CSIRO PUBLISHING

The Rangeland Journal, 2016, **38**, 85–102
http://dx.doi.org/10.1071/RJ15045

Comparing fixed and flexible stocking as adaptations to inter-annual rainfall variability in the extensive beef industry of northern Australia

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Abstract. Many beef producers within the extensive cattle industry of northern Australia attempt to maintain a constant herd size from year-to-year (fixed stocking), whereas others adjust stock numbers to varying degrees annually in response to changes in forage supply. The effects of these strategies on pasture condition and cattle productivity cannot easily be assessed by grazing trials. Simulation studies, which include feedbacks of changes to pasture condition on cattle liveweight gain, can extend the results of grazing trials both spatially and temporally. They can compare a large number of strategies, over long periods of time, for a range of climate periods, at locations which differ markedly in climate.

This simulation study compared the pasture condition and cattle productivity achieved by fixed stocking at the long-term carrying capacity with that of 55 flexible stocking strategies at 28 locations across Queensland and the Northern Territory. Flexible stocking strategies differed markedly in the degree they increased or decreased cattle stocking rates after good and poor pasture growing seasons, respectively. The 28 locations covered the full range in average annual rainfall and inter-annual rainfall variability experienced across northern Australia.

Constrained flexibility, which limited increases in stocking rates after good growing seasons to 10% but decreased them by up to 20% after poor growing seasons, provides sustainable productivity gains for cattle producers in northern Australia. This strategy can improve pasture condition and increase cattle productivity relative to fixed stocking at the long-term carrying capacity, and its capacity to do this was greatest in the semiarid rangeland regions that contain the majority of beef cattle in northern Australia. More flexible stocking strategies, which also increased stocking rates after good growing seasons by only half as much as they decreased them after poor growing seasons, were equally sustainable and more productive than constrained flexibility, but are often impractical at property and industry scales. Strategies with the highest limits (e.g. 70%) for both annual increases and decreases in stocking rates could achieve higher cattle productivity, but this was at the expense of pasture condition and was not sustainable. Constrained flexible stocking, with a 10% limit for increases and a 20% limit for decreases in stocking rates annually, is a risk-averse adaptation to high and unpredictable rainfall variability for the extensive beef industry of northern Australia.

Additional keywords: grazing management, pastoral industry, perennial grasses, rangeland management.

Received 29 May 2015, accepted 15 February 2016, published online 11 March 2016

Introduction

The extensive beef industry of northern Australia (Queensland, Northern Territory and the northern half of Western Australia) consists of ~15 million cattle (MLA 2012) distributed over 2.8 million km^2 of grazing lands (Tothill and Gillies 1992). Native pastures are the main source of forage for cattle in northern Australia, where forage availability is predominantly determined by rainfall (McKeon *et al*. 1990; O'Reagain and Bushell 2011). Rainfall across northern Australia varies enormously in amount and reliability. Regional mean annual rainfall ranges from <200 to >1500 mm, between 70% and 90% falls between October and March (pasture growing season), and inter-annual variability is among the highest in the world (O'Rourke *et al*. 1992; Nicholls *et al*. 1997; McKeon *et al*. 1998; Hunt 2008; Fatichi *et al*. 2012). Although cattle producers can adapt to high spatial variability in mean annual rainfall by setting stocking rates according to the long-term carrying capacity of their country (Scanlan *et al*. 1994; Johnston *et al*. 1996), it is more difficult to adapt to high inter-annual variability in rainfall and forage supply. As McKeon *et al*. (2004) wrote, the 'challenge is to achieve a balance between economic performance and the sustainability of the resource-base by matching stock numbers to forage availability, in environments that are highly variable and unpredictable'.

Cattle producers generally use either of two broad stocking rate approaches to manage for temporal variability in forage supply. Many attempt to maintain a relatively constant stocking rate from year-to-year (defined here as fixed stocking even though numbers are often reduced during severe droughts) whereas other producers proactively vary stocking rates between years (flexible stocking) (Stafford Smith 1992; Buxton and Stafford Smith 1996; Johnston *et al*. 2000; Hunt 2008; O'Reagain *et al*. 2011). Due to marked variation in rainfall, and hence pasture production and short-term carrying capacity experienced in rangelands globally, Illius *et al*. (1998) and Higgins *et al*. (2007) wrote that it is intuitively appealing to conclude that fixed stocking will be inappropriate. In support of this, several simulation studies found that the productivity of livestock enterprises in highly variable environments could be improved by adopting some form of flexible stocking (Foran and Stafford Smith 1991; Stafford Smith and Foran 1992; Ash *et al*. 2000; McKeon *et al*. 2000; Lodge and Johnson 2008; Díaz-Solís *et al*. 2009; Torell *et al*. 2010). Although the flexible stocking strategies simulated in these studies varied in the number of occasions and the degree which stocking rates were adjusted annually, they were generally more sustainable and productive than fixed stocking, and the relative performance of flexible stocking increased with increasing forage variability (Ash *et al*. 2000; Torell *et al*. 2010). However, the better performance of flexible stocking, particularly when this involved large changes in stocking rates, often required accurate climate forecasts or multiple annual adjustments in stocking rates, or land not prone to degradation (Campbell *et al*. 2006; Higgins *et al*. 2007; Lodge and Johnson 2008; Díaz-Solís *et al*. 2009; Torell *et al*. 2010). Given these conditions are rarely met in northern Australia, it is not surprising that a review of field studies by Scanlan and McIvor (2010) and Hunt *et al*. (2014) concluded that fixed stocking at close to the long-term carrying capacity was more profitable and less ecologically risky than flexible stocking. Even so, they acknowledged some annual variation in stocking rates could still be advantageous, but the degree of variation that is most beneficial was unclear, and may differ with differences in annual rainfall (O'Reagain and Scanlan 2013).

The study reported here differs from other simulation studies in that it did not use perfect climate forecasts or multiple annual adjustments in stocking rates to constantly align cattle demand for pasture with the supply of pasture. Instead, stocking rates were adjusted on one occasion at the end of the summer growing season in accordance with the amount of forage present at that time, and the resultant stocking rate was maintained for a further 12 months. The simulation study reported here also contrasted with others in that it compared strategies which differed markedly in the degree they could decrease or increase stocking rates annually, and did this for 10 overlapping 30-year periods of actual climate between 1890 and 2012, at locations which differed greatly in annual rainfall amount and variability. Hence, this simulation study had two objectives, which were to determine:

(1) If some degree of flexible stocking can achieve higher cattle productivity than fixed stocking at the long-term carrying capacity, and whether this differs with amount and variability of annual rainfall; and
(2) The impact of varying degrees of flexible stocking on pasture condition, and whether this differs with amount and variability of annual rainfall.

Methods

Simulation model

A range of stocking rate strategies, varying in the extent that stocking rates could be changed annually, were simulated at 28 locations in Queensland and the Northern Territory using a version of GRASP reported in Scanlan *et al*. (2011). This is a dynamic, deterministic, point-based model that simulates soil moisture, pasture growth and animal production from daily inputs of rainfall, temperature, humidity, pan evaporation and solar radiation (Littleboy and McKeon 1997; McKeon *et al*. 2000; Rickert *et al*. 2000). The GRASP pasture model has been extensively calibrated and validated in over 40 native Australian pasture communities in Queensland and Northern Territory over many years (McKeon *et al*. 1990; Day *et al*. 1997; Hall *et al*. 1998; Hassett *et al*. 2000; Walsh and Cowley 2011; Webb and Stokes 2012), and has been used to evaluate many different management options in the cattle-grazed rangelands of northern Australia (Johnston *et al*. 1996; Hall *et al*. 1998; McKeon *et al*. 2009; Cowley *et al*. 2012; Scanlan *et al*. 2014; Whish *et al*. 2014).

The GRASP model, calibrated by Scanlan *et al*. (2013) to represent the Reid River box (*Eucalyptus brownii*) woodland land type at the Wambiana grazing trial site near Charters Towers in north-eastern Queensland (O'Reagain *et al*. 2011), was used for all simulations of stocking rate strategies at all locations. The performance of stocking rate strategies was compared using the same Reid River box model so not to confound land-type impacts with the effects of differences in mean annual rainfall and inter-annual rainfall variability. This is consistent with Webb and Stokes (2012) and Scanlan *et al*. (2014) who limited their evaluations of adaptation options for livestock industries in north Australian rangelands to a single land type, so as not to complicate assessments of their effectiveness. Although using a single land-type model may reduce the accuracy of simulations of pasture growth for individual locations, the dominating influence of rainfall and pasture utilisation on pasture and livestock productivity means that the principles derived from this approach should be applicable across the rangelands of north Australia (Illius *et al*. 1998; Sandford and Scoones 2006; Orr and Phelps 2013; Scanlan *et al*. 2014). In support of this, Pahl *et al*. (2013) found that differences in land types had little influence on the relative performance of stocking rate strategies at individual locations in Queensland and the Northern Territory.

Two pasture condition states for the Reid River box land type were used in this simulation study. When pasture condition was excellent, 88% of the pasture consisted of perennial grasses. When pasture condition was moderate, 60% of the pasture was perennial grass. The initial grass basal area for locations ranged from 1.5% and 9.0%, and increased with increases in median annual pasture growth.

Stocking rate strategies compared

A total of 56 stocking rate strategies were compared during this simulation study. These differed greatly in the degree to which stocking rates could be adjusted each year in response to changes in the amount of forage (standing dry matter) available for consumption at the end of the pasture growing season (May). The unit of stocking rate used in this study is AE km^{-2}, where an AE is an adult equivalent, comparable with a 450-kg dry beast.

Fixed stocking did not allow any change in stocking rate at the end of May, and kept the stocking rate constant over the entire simulation period. The constant stocking rate used in simulations was the maximum stocking rate which maintained the average pasture condition over each simulation period (see Scanlan *et al*. 2010, 2011). The constant stocking rate identified in this way for each simulation period was called the maintenance stocking rate.

Fixed stocking was then compared with 55 strategies with varying levels of flexibility. Under the most flexible strategy, full flexibility, stocking rates were adjusted so that 30% of the pasture present at the end of May would be consumed over the following 12 months. To achieve this utilisation rate, there was essentially no limit to the degree which stocking rates could be either increased or decreased annually. To ensure this occurred, full flexibility could potentially increase stocking rates by up to 1000% or decrease them by up to 99% annually, but these rates of change never occurred during simulations. A further 54 strategies with lower levels of flexibility were simulated, again commencing with the maintenance stocking rate in the first year. This included six core strategies, which set different limits (5%, 10%, 20%, 30%, 50% and 70%) to the degree which stocking rates could be increased annually, providing forage availability increased by at least these amounts. Each of these core strategies were simulated with different limits to the degree which stocking rates could be decreased annually (5%, 10%, 20%, 30%, 40%, 50%, 60%, 70% and 80%), providing forage availability decreased by at least these amounts. Strategies are defined by the combination of rates of annual increases and annual decreases. For example, *10*, *30* is a strategy which has a maximum allowable increase of 10% and a maximum possible decrease of 30% in any year.

Simulation locations

Locations were selected so that all combinations of the mapped zones of average annual rainfall (BOM 2013*a*) and inter-annual rainfall variability (BOM 2013*b*) in northern Australia were included in this simulation study. Mean annual rainfall zones ranged from 0–300 mm to 1200–2000 mm, and rainfall variability zones ranged from low to very high. Across the 28 locations, mean annual rainfall varied 11-fold, from 139 mm at Bedourie to 1602 mm at Heathlands (Table 1). The range in median rainfall was even higher (13-fold), varying from 122 mm at Birdsville to 1584 mm at Heathlands.

Annual rainfall metrics for the period 1892 to 2012, calculated for each location using the records from SILO (2013), were examined for their correlation with percent perennial grass composition and cattle liveweight gain (LWG) achieved by stocking rate strategies. Each year commenced on 1 June and finished on 31 May, corresponding with the years used in the GRASP simulations of stocking rate strategies. Several annual rainfall metrics are reported in Table 1, being the mean, median, standard deviation (s.d.), the percent coefficient of variation, and the mean minus the standard deviation (M_s.d.). Other annual rainfall metrics also examined for their correlation with percent perennial grass composition and cattle LWG were the median minus s.d., the BOM (2013*b*) index of annual rainfall variability ((90th percentile–10th percentile)/50th percentile), and the mean percent change in rainfall between successive years.

Simulation periods

Previous modelling studies (Foran and Stafford Smith 1991; Illius *et al*. 1998; Sandford and Scoones 2006; Pahl *et al*. 2013) observed that the outcomes of stocking rate strategies at a single location often varied substantially between simulation periods, due to differences in the amount and sequences of annual rainfall. Also, Illius *et al*. (1998) and Orr and Phelps (2013) observed that annual rainfall sequences had more impact on cattle productivity and plant dynamics than did grazing strategies. These effects were limited in this simulation study by averaging the outcomes of strategies across multiple simulation periods, covering the entire period for which climate records were available. Accordingly, stocking rate strategies were simulated for 10 separate simulation periods at each location during this study, with each simulation period being 30 years. The starting year of the first nine simulation periods was randomly chosen from the 10 years in each decade, beginning with the decade 1890–1899. The starting year of the 10th simulation period, being 1983, was chosen so that the end year of that simulation period was 2012. Different maintenance stocking rates were calculated and used for each of the 10 simulation periods, for excellent and moderate starting pasture condition.

The simulated annual outputs used in this study were kilograms of cattle LWG per hectare per year (LWG ha^{-1}) and the percent of pastures consisting of perennial grasses. At each location, these annual outputs were averaged for each 30-year simulation period, and then averaged again for the 10 simulation periods. For each stocking rate strategy at each location, this provided single values for annual percent perennial grass composition and cattle LWG ha^{-1}.

Comparing the performance of stocking rate strategies

Statistical analyses were performed on the two sets of simulated data. The first dataset was 3136 values for average annual percent perennial grass composition, being a factorial of 56 stocking rate strategies, 28 locations and two initial pasture conditions. The second was the same number of values for average annual LWG ha^{-1}. First, variation in average annual percent perennial grass composition or LWG ha^{-1} achieved by the 56 stocking rate strategies were analysed using ANOVA

Table 1. The nearest town, coordinates (latitude and longitude in decimal degrees), the mean, median, standard deviation (s.d.), the % CV of annual rainfall, actual mean minus the standard deviation (M_s.d.) rainfall, and the M_s.d. rainfall group for 28 locations at which stocking rate strategies were compared

Nearest town (State)	Coordinates	Metric of annual rainfall					
		Mean (mm)	Median (mm)	s.d. (mm)	% CV	M_s.d. (mm)	M_s.d. group
Simpson Desert (NT)	–24.40, 137.05	144	131	105	73.1	39	1
Bedourie (Qld)	–24.70, 138.20	139	124	99	71.1	40	1
Ghan (NT)	–25.50, 134.50	166	133	121	72.8	45	1
Birdsville (Qld)	–25.70, 139.05	151	122	103	68.4	48	1
Boulia (Qld)	–23.25, 140.25	223	183	140	62.8	83	2
Hart (NT)	–22.30, 136.85	221	197	138	62.3	83	2
Hungerford (Qld)	–28.80, 143.50	216	200	110	50.9	106	2
Longreach (Qld)	–23.70, 142.85	329	287	174	52.7	155	2
Yowah (Qld)	–27.80, 144.80	317	287	150	47.2	167	2
Tablelands (NT)	–18.75, 135.70	392	335	210	53.6	182	2
Boatman (Qld)	–27.25, 146.80	430	412	161	37.4	269	2
Aramac (Qld)	–23.00, 145.10	454	424	183	40.3	271	3
Dirranbandi (Qld)	–28.35, 148.15	453	429	160	35.4	293	3
Gidya (Qld)	–19.50, 139.60	505	466	208	41.1	297	3
Lake Woods (NT)	–17.55, 132.50	506	480	193	38.1	313	3
Nicholson (Qld)	–18.00, 138.55	605	567	253	41.9	352	3
Alton (Qld)	–27.80, 149.45	550	520	170	31	380	4
Mackenzie Rr (Qld)	–23.30, 148.70	570	556	190	33.4	380	4
Einasleigh (Qld)	–18.15, 143.95	766	722	306	39.9	460	4
Rawbelle (Qld)	–24.95, 150.55	683	672	184	26.9	499	4
Gregory (NT)	–15.60, 131.20	750	734	230	30.6	520	4
Maramie (Qld)	–16.30, 142.30	990	925	346	34.9	644	4
Beswick Ck (NT)	–14.20, 133.35	919	915	256	27.8	663	5
East Alligator Rr (NT)	–11.80, 133.00	1252	1221	271	21.7	981	5
Kakadu (NT)	–13.35, 132.25	1267	1286	279	22	988	5
Mt Bundy (NT)	–12.75, 131.70	1369	1349	300	21.9	1069	5
Wenlock (Qld)	–12.50, 142.50	1420	1436	309	21.7	1111	5
Heathlands (Qld)	–11.65, 142.30	1602	1584	349	21.8	1253	5

in GENSTAT (2015). However, when interpreting ANOVA results from data generated by models, particularly when this involves large datasets derived from deterministic models such as GRASP, the relative sizes of treatment mean squares is more important than calculated probability levels (Mayer *et al.* 1994). For this reason, differences between the mean squares were used to show the degree of variation in the mean values for percent perennial grass composition and LWG ha^{-1} due to initial pasture condition, limits for annual increases in stocking rates, limits for annual decreases in stocking rates, and M_s.d. rainfall.

The more extreme treatments of fixed stocking and full flexibility could not be included in the analyses of the 54 strategies with intermediate flexibilities, and hence were analysed separately. Also, preliminary ANOVA considered locations separately to identify the annual rainfall metric which most influenced pasture condition and cattle productivity. The annual rainfall metric, which had by far the largest influence on LWG ha^{-1} was M_s.d. and this also was among the dominant rainfall metrics for percent perennial grass composition. Accordingly, further ANOVA used only M_s.d. as the metric for annual rainfall. Locations were then pooled into five groups according to their M_s.d. rainfall, where the range for each M_s.d. group was determined using KnowledgeSEEKER version 2.1 decision-tree model (FirstMark Technologies 1990). The M_s.d. rainfall ranges in mm for these five groups are 39–48; 83–269; 271–352; 380–644 and 664–1253. The M_s.d. rainfall group to which each location is assigned to is shown in Table 1.

Results

Cattle productivity and pasture condition for fixed stocking and full flexibility

The ANOVA showed significant effects ($P \leq 0.01$) of initial pasture condition, the two stocking strategies and M_s.d. rainfall groups on LWG ha^{-1}. The mean squares (MS) were used to identify the relative impact of each factor. The very large MS for M_s.d. rainfall (MS = 10 376) showed it to be by far the dominant source of variation in simulated average annual LWG ha^{-1}. As such, LWG ha^{-1} varied from 0.4 kg for locations in M_s.d. rainfall Group 1 to 53 kg for locations in M_s.d. rainfall Group 5. Initial pasture condition (MS = 852) was also responsible for differences in LWG ha^{-1}, being 22 kg when moderate and 27 kg when excellent. To a lesser degree (MS = 163), differences in LWG ha^{-1} were due to the two stocking rate strategies, with the mean for full flexibility stocking being 26 kg and that for fixed stocking being 23 kg. The dominant two-way interaction was that between initial pasture condition and M_s.d. rainfall (MS = 78). When initial pasture condition was excellent, the kg difference in LWG ha^{-1} between full flexibility and fixed stocking increased as M_s.d. rainfall increased (Fig. 1). In comparison, when initial pasture condition was moderate, the difference in LWG ha^{-1} between full flexibility and fixed stocking increased as M_s.d. rainfall increased to 352 mm, then declined with further increases in M_s.d. rainfall.

Variations in percent perennial grass composition due to initial pasture condition, the two stocking strategies and M_s.d. rainfall groups were all significant (ANOVA $P < 0.01$). Initial pasture condition was by far the dominant source of variation in simulated average annual percent perennial grass composition (MS = 19 787). When moderate, the average annual percent perennial grass composition was 54% (initial value was 60%), and when excellent it was 80% (initial value was 88%). The two strategies, fixed and full flexibility stocking, were also responsible for considerable variation in perennial grass composition (MS = 6142). The mean was 74% for fixed stocking at the long-term carrying capacity and 59% for full flexibility. In comparison, M_s.d. rainfall groupings had a relatively minor influence (MS = 190), where percent perennials varied from 63% to 70%.

The dominant two-way interaction was between the M_s.d. rainfall groups and the two stocking strategies (MS = 169), indicating that the influence of these strategies on perennial grass composition varied with M_s.d. rainfall (Fig. 2). The extent that percent perennial grass composition for fixed stocking was higher than that for full flexibility was greatest for the three groups with the lowest M_s.d. rainfall.

Cattle productivity and pasture condition for intermediate flexibilities

Trends in the variation of simulated average annual LWG ha^{-1} for the 54 intermediate flexibilities were similar to those observed earlier for fixed stocking and full flexibility. Variations in LWG ha^{-1} due to initial pasture condition, limits for decreases in stocking rates and M_s.d. rainfall were all significant (ANOVA $P < 0.01$), but those for the limits for annual increases were not (ANOVA $P = 0.09$). The very dominant source of variation was again due to differences in M_s.d. rainfall (MS = 302 840). Initial pasture condition was also a large source of variation in LWG ha^{-1} (MS = 26 470), followed by the limits for annual decreases (MS = 556). In relation to the two-way interactions, by far the greatest variation in LWG ha^{-1} occurred for the interaction between initial pasture condition and M_s.d. rainfall (MS = 3355). The next largest amount of variation was due to the interaction between limits for annual decreases and M_s.d. rainfall (MS = 79), and was followed by the interaction between limits for increases and limits for decreases in stocking rates (MS = 68).

Across all locations and initial pasture conditions, the maximum average annual LWG ha^{-1} of 26 kg was achieved by 12 of the 54 intermediate flexibilities, which was equal to that

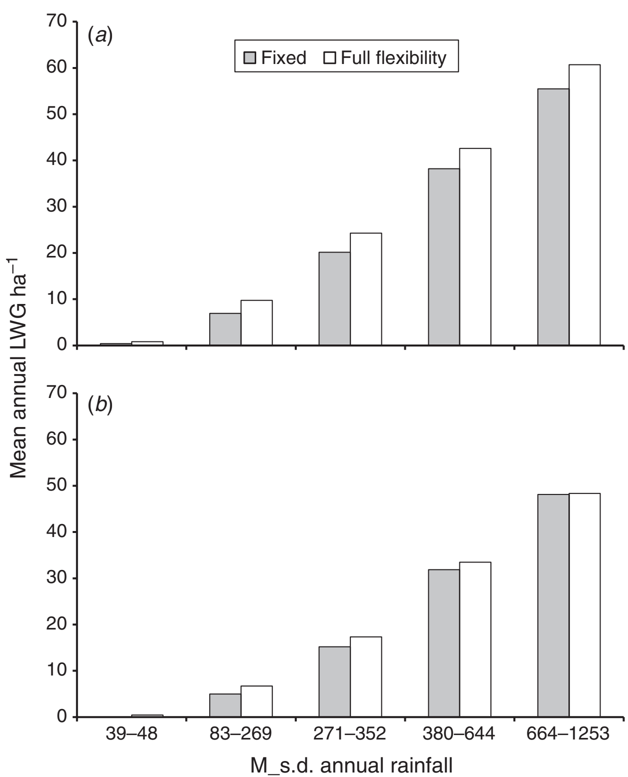

Fig. 1. The LWG ha^{-1} (kg) achieved by fixed stocking at the long-term carrying capacity and full flexibility for each M_s.d. rainfall group, when initial pasture condition was (*a*) excellent and (*b*) moderate.

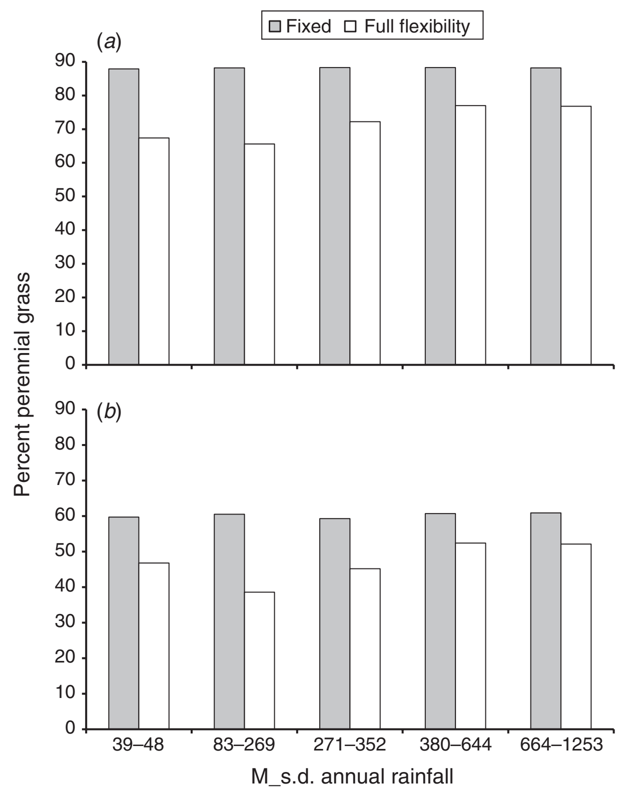

Fig. 2. The percent perennial grass composition achieved by fixed stocking at the long-term carrying capacity and full flexibility for each M_s.d. rainfall group, when initial pasture condition was (*a*) excellent and (*b*) moderate.

of full flexibility. These intermediate flexibilities had 30–70% limits for increases in combination with 50–80% limits for decreases in stocking rates. However, annual LWG ha^{-1} averaged in the same way for 14 other intermediate strategies, those with 10–20% limits for increases in combination with 20–80% limits for decreases, was 25 kg, and hence were only 1 kg lower than that for the more flexible strategies.

Similarly, there was little difference in the LWG ha^{-1} achieved by a range of flexible strategies for each initial pasture condition in each M_s.d. rainfall group. When initial condition was excellent, there was less than 1 kg difference in the LWG ha^{-1} achieved by a range of flexible strategies in each M_s.d. rainfall group. These included two with a 20% limit for increases and 30% or 40% limits for decreases, three with a 30% limit for increases and 50–80% limits for decreases, four with 50–70% limits for increases and 50–80% limits for decreases in stocking rates annually, and full flexibility. For M_s.d. Group 5 locations, there was less than 1 kg difference between all flexible strategies. The same trend occurred when initial pasture condition was moderate, with the only difference being that the 20–70% limits for increases were accompanied by higher 70–80% limits for decreases in stocking rates.

These trends in variation of LWG ha^{-1} identified by ANOVA are illustrated in Fig. 3, where a constant range in kg of LWG ha^{-1} on all graphs was used to enable observation of trends across locations, which varied greatly in the their amount of LWG ha^{-1}. Although LWG ha^{-1} varied greatly between M_s.d. rainfall groups, they also varied with the combinations of limits for annual increases and decreases in stocking rates. For locations within M_s.d. rainfall Groups 1–4, strategies with $\geq$20% limits for increases and only 5% or 10% limits for decreases in stocking rates resulted in the lowest LWG ha^{-1}. However, the LWG ha^{-1} achieved by strategies with $\geq$20% limits for annual increases improved markedly as the limits for decreases in stocking rates rose. Hence, it was these strategies which achieved the highest LWG ha^{-1} for M_s.d. rainfall Groups 1–4. In comparison, the LWG ha^{-1} of strategies with 5% or 10% limits for increases dropped as the limits for decreases in stocking rates rose. At the locations within the highest M_s.d. rainfall Group 5, LWG ha^{-1} varied little for all 54 flexible strategies.

The trends in variation of LWG ha^{-1} described above were similar for both initial pasture conditions. However, a notable difference was that strategies which achieved the highest LWG ha^{-1} for each M_s.d. rainfall group differed with initial pasture condition (Table 2). When initial pasture condition was excellent, and for all M_s.d. rainfall groups except 5, the strategies which achieved the highest LWG ha^{-1} were either full flexibility or a similarly very high flexibility. In comparison, when initial pasture condition was moderate, it was often the less flexible strategies which achieved the highest LWG ha^{-1}, and they mostly had limits for annual decreases which were considerably higher than the limits for annual increases in stocking rates.

Variations in perennial grass composition for the 54 intermediate flexibilities due to each factor were all significant (ANOVA $P < 0.01$), and the trends were very similar to those observed earlier for fixed and full flexibility. Relative differences in the MS indicated that by far the largest source of variation in perennial grass composition was due to differences in initial pasture condition (MS = 317 231). Although the limits for annual increases and decreases in stocking rates were responsible for less variation in perennial grass composition (MS = 32 331 and 26 470, respectively), this variation was still high, and much higher than that due to M_s.d. rainfall (MS = 823). The strong two-way and three-way interactions, which occurred between the limits for annual increases and decreases in stocking rates, M_s.d. rainfall and with initial pasture condition are illustrated in Fig. 4.

At mesic locations within the highest M_s.d. rainfall Group 5, the different combinations of increases and decreases in stocking rates varied little in their influence on percent perennial grass composition (Fig. 4). The divergence in impacts of the combinations of limits for increases and decreases was greatest at locations in M_s.d. rainfall Groups 2 and 3. At these locations, strategies with high limits for annual increases and low limits for annual decreases in stocking rates caused large declines in percent perennial grass composition. However, percent perennial grass composition increased quickly with rises in the limits for annual decreases in stocking rates.

The improvement in perennial grass composition with rises in the limits for annual decreases in stocking rates was greatest when initial pasture condition was moderate. With moderate initial pasture condition, strategies with 5–30% limits for increases, mostly in combination with high limits for decreases in stocking rates, improved percent perennial grass composition for all locations except those in M_s.d. Group 5. Hence, these strategies achieved higher average annual percent perennial grass composition than fixed stocking (60%) for M_s.d. Groups 1–4. When initial pasture condition was excellent, strategies with a 5% limit for increases and $\geq$30% limits for decreases in stocking rates achieved similar percent perennial grass composition (88%) to fixed stocking, which is almost the maximum value (90%) achievable within the GRASP model (Scanlan *et al*. 2014). Locations within M_s.d. rainfall Group 5 were again the exception, where all flexibilities varied little in their impact on pasture condition and mostly achieved perennial grass composition less than that of fixed stocking. Overall, it was fixed stocking or strategies with a 5% or 10% limit for increases and $\geq$30% limit for decreases in stocking rates which achieved the highest percent perennial grass composition for each M_s.d. rainfall group.

Cattle productivity at the expense of pasture condition

At all except the wettest locations within M_s.d. rainfall Group 5, full flexibility or other very high flexibilities achieved the highest cattle productivity (Table 2), whereas fixed stocking at the long-term carrying capacity or strategies with a 5% limit for increases and $\geq$30% limits for decreases in stocking rates achieved the best pasture condition (Figs 2 and 4). This suggests that achieving the highest average annual LWG ha^{-1} may occur at the expense of pasture condition.

A conflict between cattle productivity and pasture condition is evident in Fig. 5, which shows the differences in LWG ha^{-1} and perennial grass composition between fixed stocking, which maintains pasture condition and the flexible strategy, which achieved the highest average annual LWG ha^{-1} (Table 2).

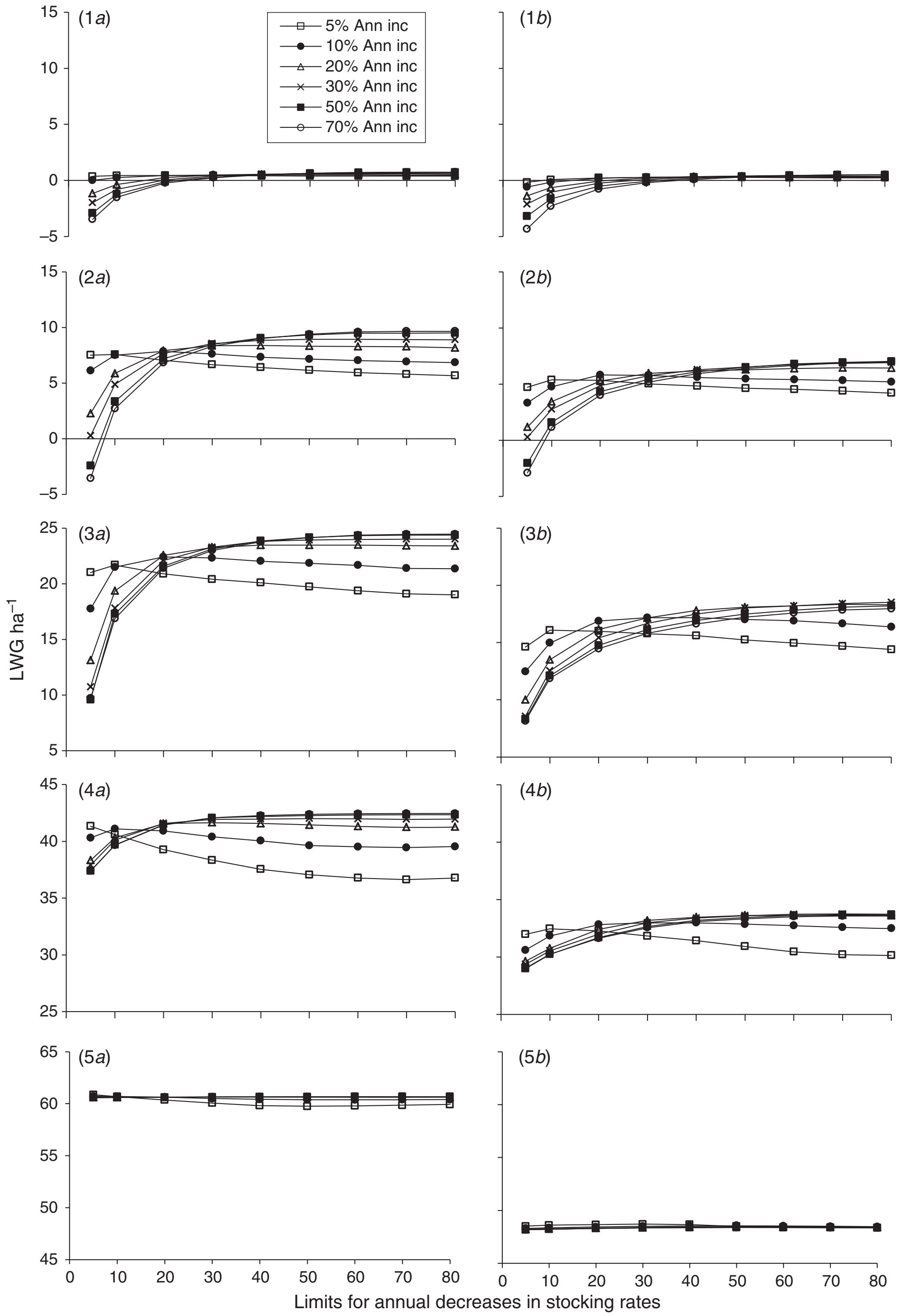

Fig. 3. The average annual LWG ha^{-1} (kg) achieved by the intermediate flexibility stocking rate strategies for the five M_s.d. rainfall groups, when initial pasture condition was (*a*) excellent and (*b*) moderate.

When initial pasture condition was excellent (Fig. 5*a*), flexible stocking achieved from 0.4 to 5.4 kg of LWG ha^{-1} more than fixed stocking annually, and when initial pasture condition was moderate (Fig. 5*b*), it achieved 0.5–3.3 kg more. These improvements in LWG ha^{-1} achieved by flexible stocking, for both excellent and moderate initial pasture condition, were

Table 2. The stocking rate strategies which achieved the highest liveweight gain ha^{-1} for each mean minus the standard deviation (M_s.d.) rainfall group, for excellent and moderate initial pasture conditions (limits of none are for full flexibility)

Group	M_s.d. rainfall (mm)	Starting pasture condition			
		Excellent		Moderate	
		Limit for increases	Limit for decreases	Limit for increases	Limit for decreases
1	39–48	None	None	70	80
2	83–269	None	None	50	80
3	271–352	70	80	30	80
4	380–644	None	None	30	70
5	664–1253	5	5	5	30

often associated with losses in percent perennial grass composition relative to fixed stocking. Losses in perennial grasses, ranging from 10% to 23%, always occurred when initial pasture condition was excellent (Fig. 5*a*). Except for locations within M_s.d. rainfall Group 5, these losses occurred for either full flexibility or a strategy with a 70% limit for increases and an 80% limit for decreases in stocking rates. In comparison, when initial pasture condition was moderate, the flexible strategies which produced the highest LWG ha^{-1} also improved the percentage of perennial grasses for M_s.d. rainfall Groups 2, 3 and 4, by 1–5%. These flexible strategies had lower limits of 30% and 50% for annual increases but still high 70% and 80% limits for annual decreases respectively in stocking rates. For Groups 1 and 5, losses in percentage of perennial grass were 13% and 2%, respectively. The highest loss of 13% perennial grasses occurred with the most flexible strategy, again with a 70% limit for increases and an 80% limit for decreases in stocking rates.

The trade-off between cattle productivity and pasture condition is also observed in the graphs of percent perennial grass composition and the corresponding LWG ha^{-1} for the 56 stocking rate strategies at locations representing the five M_s.d. groups (Fig. 6). Again, the range in LWG ha^{-1} for each location was kept constant to enable comparisons between them. For M_s.d. rainfall Groups 1–4, strategies with high limits for increases and low limits for decreases in stocking rates almost always produced both the lowest perennial grass composition and LWG ha^{-1}. An example of this is a strategy with a 70% limit for increases and only a 5% limit for decreases. As the size of the limits for decreases rose relative to the limits for increases in stocking rates, there was a gradual improvement in both pasture condition and cattle productivity. For example, cattle productivity and pasture condition were improved by a strategy with a 20% limit for increases and a 10% limit for decreases, and were improved further by full flexibility (Fig. 6). Strategies like full flexibility, with very high limits for both increases and decreases in stocking rates, achieved the highest LWG ha^{-1} at locations within MS_D rainfall Groups 1–4. When initial pasture condition at these locations was excellent, this maximum LWG ha^{-1} was achieved when percent perennial grass composition was 10–22% below the maximum value of close to 90% achieved by other strategies. Similarly, when initial pasture condition was moderate, the highest LWG ha^{-1} occurred when perennial grass composition was 15–25% below the maximum values of ~80%. With further rises in the limits for decreases relative to the limits for increases in stocking rates, percent perennial grass composition gradually increased and LWG ha^{-1} gradually declined. An example of this in Fig. 6 is a strategy with a 10% limit for increases and a 20% limit for decreases, which achieved higher perennial grass composition but lower LWG ha^{-1} than the strategies which achieved maximum cattle productivity. This trend culminated in a strategy such as that with a 5% limit for increases and a 70% limit for decreases, which achieved close to the maximum value for percent perennials, but its LWG ha^{-1} was ~5 kg lower than its maximum for M_s.d. rainfall Groups 2–4, and marginally lower for Bedourie (Group 1).

At East Alligator River in M_s.d. rainfall Group 5, strategies with very high limits for increases relative to decreases in stocking rates caused less declines in pasture condition and cattle productivity. At this location, the differences in percent perennial grass composition and LWG ha^{-1} between strategies were small, and it was a strategy with only 5% limits for both increases and decreases in stocking rates, which achieved the highest LWG ha^{-1}.

The trade-off between cattle productivity and pasture condition was also apparent within 30-year simulation periods for the locations representing all M_s.d. rainfall groups (Fig. 7). Three strategies that were shown in Fig. 6 to vary in their impact on perennial grass composition were chosen to demonstrate how the use of average annual values for entire 30-year simulation periods can mask the decline in pasture condition at the end of these periods. These strategies were fixed stocking, a 10% limit for increases with a 20% limit for decreases, and full flexibility. The graphs in Fig. 7 show the percent perennial grass composition for each year of the 30-year simulation period, with the values for each year being an average for that year for the 10 different climate periods simulated at each location. Although percent perennial grass composition for fixed stocking remained constantly high, that for the two flexibilities declined steadily over time. Of the two flexibilities, the decline for full flexibility was much greater than that for the strategy with a 10% limit for increases and a 20% limit for decreases.

When initial pasture condition was excellent, the average annual percent perennial grass composition across the five M_s.d. groups for full flexibility of 67–76% (Table 3) is not indicative of the perennial grass composition of 43–61% at the end of 30-year simulation periods (Fig. 7; *1a*–*5a*). The decline in pasture condition that can occur is also evident in the average annual percent perennial grass compositions for the two flexible stocking strategies during the second half of simulations (Table 3). Average annual perennial grass composition for the strategy with a 10% limit for increases and a 20% limit for decreases during the second 15-year periods were less than those for the first 15 years, but the decline during the second 15 years was much greater for full flexibility.

The average annual LWG ha^{-1} for each year of the 30-year simulation period, averaged over the 10 different simulation periods, is shown for the same M_s.d. groups (Fig. 7; *1b*–*5b*). Annual LWG ha^{-1} for the two flexible strategies was much more dynamic than that for fixed stocking, and was generally higher during the first half of the simulation period. The relatively constant LWG ha^{-1} over 30 years for fixed stocking is

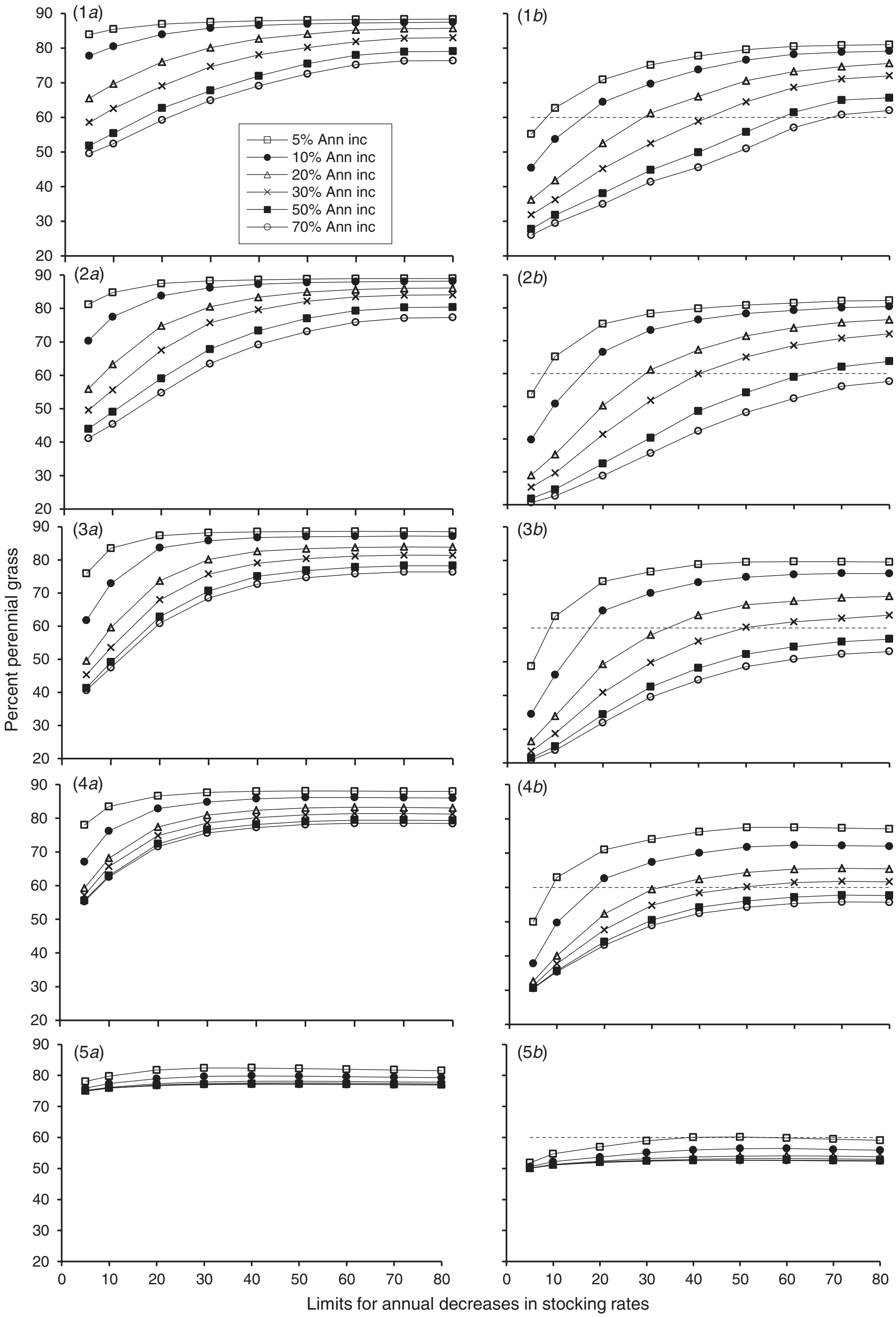

Fig. 4. The average annual percent perennial grass composition achieved by the intermediate flexibility stocking rate strategies for the five M_s.d. rainfall groups, when initial pasture condition was (*a*) excellent and (*b*) moderate. Perennial grass composition at the beginning of simulations when initial condition was moderate is shown by the dashed line.

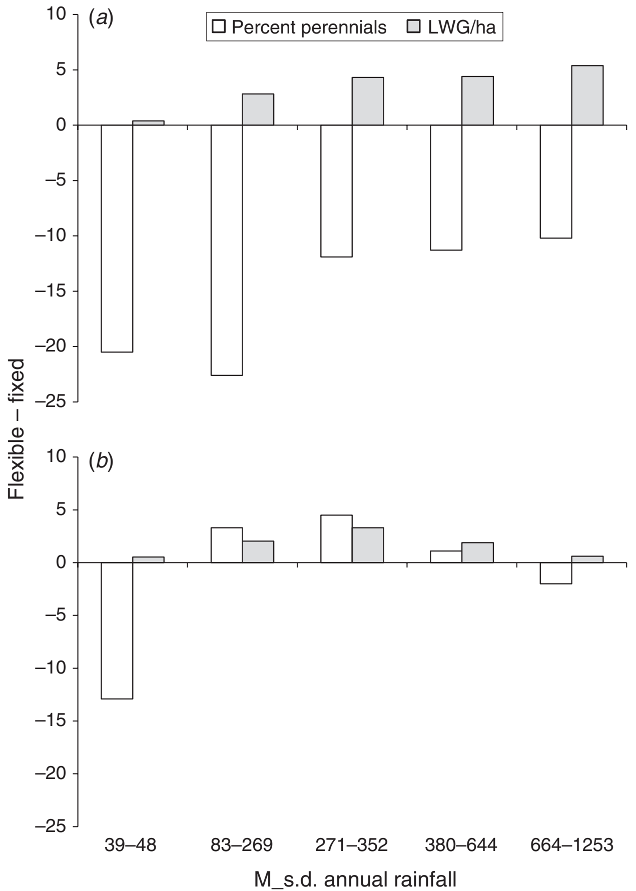

Fig. 5. Differences in percent perennial grass composition and LWG ha^{-1} between fixed stocking at the long-term carrying capacity and the flexibility which achieved the highest LWG ha^{-1} for each M_s.d. rainfall group, when initial pasture condition was (*a*) excellent and (*b*) moderate.

also evident in Table 3, where average LWG ha^{-1} for the whole 30 years and the first and second 15-year periods were very similar for all M_s.d. rainfall groups (Table 3). The same is not true for the two flexible strategies. In particular, the average LWG ha^{-1} for full flexibility was highest in the first 15 years, and then declined considerably during the second 15 years, which is similar to the trend observed for percent perennial grass composition.

Discussion

This simulation study identified the potential for short-term high cattle productivity to occur at the expense of pasture condition. Full flexibility and flexible strategies with very high limits for increasing stocking rates annually achieved the highest average annual cattle productivity, but they caused large declines in pasture condition and were unsustainable. However, fixed stocking at the long-term carrying capacity and strategies with a low 5% limit for increases and ≥30% limits for decreases in stocking rates maintained or improved pasture condition, but their cattle productivity was relatively low.

A balance between high cattle productivity and good pasture condition was achieved at all but the wettest locations by flexible strategies which could increase stocking rates by around half of what they could decrease them annually. The cattle productivity of these strategies was still considerably higher than that of fixed stocking at the long-term carrying capacity, and occurred with minimal loss or even improvement in pasture condition. Some of these strategies, such as that with a 30% limit for increases and a 60% limit for decreases, involved large changes in stocking rates annually, whereas a less flexible strategy, one with a 10% limit for increases and a 20% limit for decreases, may be more practical at property and industry scales. The balance between high cattle productivity and good pasture condition was most apparent when initial pasture condition was moderate, and for locations within M_s.d. rainfall Groups 2, 3 and 4, which contain the majority of beef cattle in northern Australia.

Can flexible stocking achieve higher cattle productivity than fixed stocking?

Fixed stocking at a conservative stocking rate can maintain land in good condition, but Higgins *et al*. (2007) and Torell *et al*. (2010) claimed this can be at the expense of cattle productivity. Furthermore, the more rainfall and forage supply is variable and unpredictable, the more conservative fixed stocking rates need to be (Ash *et al*. 2000; McKeon *et al*. 2000; Higgins *et al*. 2007). It is for these reasons that Ash *et al*. (2000) believed, theoretically, flexible stocking should achieve higher cattle productivity than fixed stocking.

This is consistent with the findings of this simulation study, where a range of flexible stocking strategies achieved higher cattle productivity than fixed stocking, when the latter was simulated at the maximum stocking rate which maintained pasture condition. However, many of the flexible strategies which achieved maximum cattle productivity caused large declines in pasture condition and were unsustainable. When average annual rainfall decreases and inter-annual variability increases, periods of high pasture growth tend to be of short duration, and occur irregularly in a background of low pasture growth. At these locations, more flexible strategies were required to rapidly increase stocking rates to take advantage of the short annual pulses in pasture growth. In comparison, strategies with low annual limits for increasing stocking rates were unable to fully utilise short pulses in forage supply.

In this simulation study, a wide range of flexible strategies achieved close to the maximum cattle productivity for all M_s.d. rainfall groups. When initial pasture condition was excellent, for M_s.d. Groups 2–4, there was less than 1 kg or 2–10% difference in the LWG ha^{-1} achieved by the 23 most flexible strategies. These included those with 20–70% limits for increases and 20–80% limits for decreases, and full flexibility. For M_s.d. Group 1 locations where the maximum LWG ha^{-1} was only 0.8 kg, a similar range of strategies achieved at least 0.6 kg LWG ha^{-1}. For M_s.d. Group 5 locations, there was less than 1 kg or 2% difference between all flexible strategies. Hence, the most flexible strategies delivered only small gains in cattle productivity relative to that with a 20% limit for increases and a 40% limit for decreases in stocking rates. A very similar trend was observed when initial pasture condition was moderate, with the main difference being that strategies

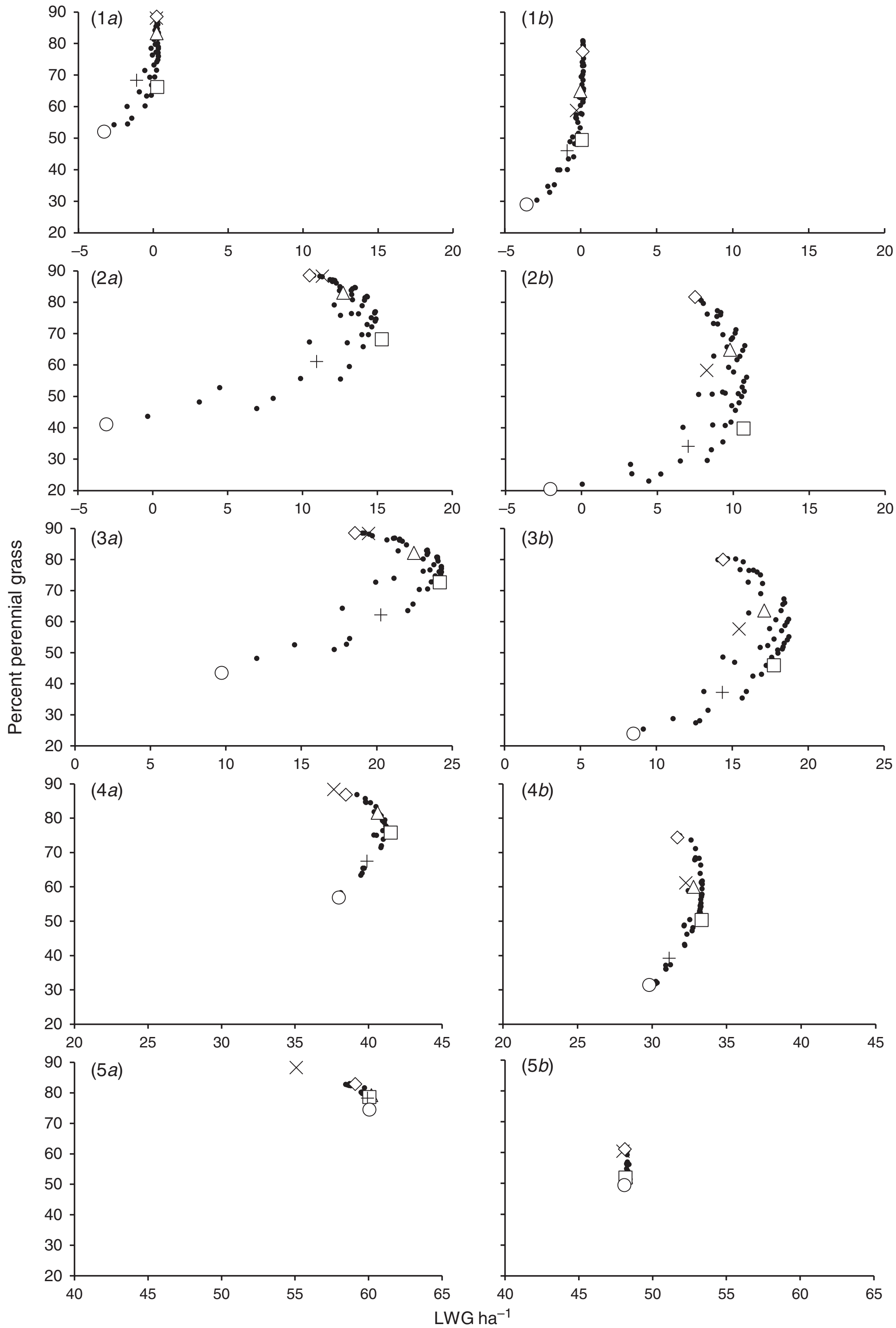

Fig. 6. Average annual percent perennial grass composition and the corresponding LWG ha^{-1} for each of the 56 stocking rate strategies at one location in each of the five M_s.d. rainfall groups (Bedourie (1), Tablelands (2), Lake Woods (3), Gregory (4) and East Alligator River (5)), when initial pasture condition was (*a*) excellent and (*b*) moderate. (O = 70:5; + = 20:10; □ = full flexibility; Δ = 10:20; × = fixed stocking; ◇ = 5 : 70).

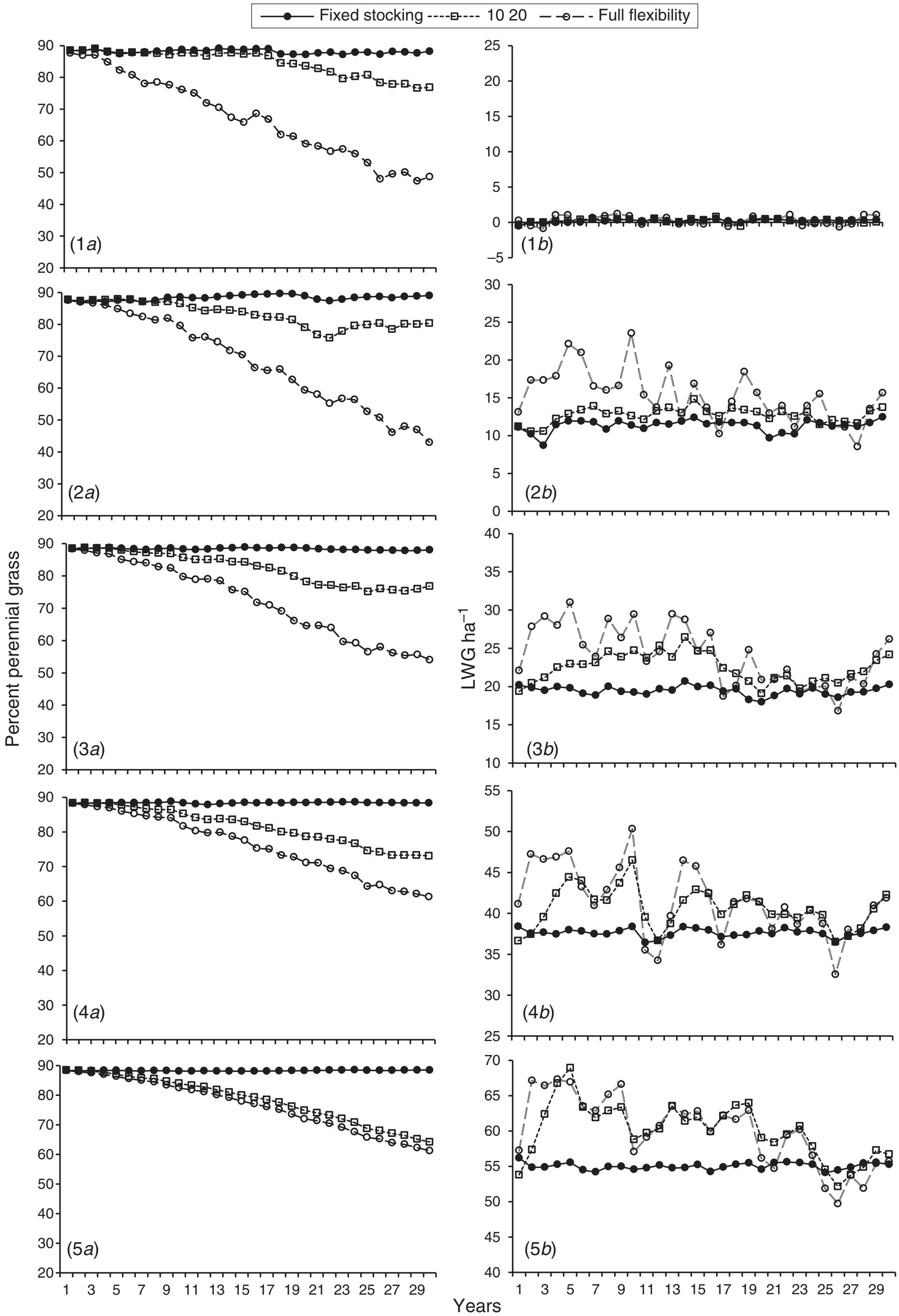

Fig. 7. (*a*) Average annual percent perennial grass composition and (*b*) LWG ha^{-1} for three stocking rate strategies at one location in each of the five M_s.d. rainfall groups (Bedourie (1), Tablelands (2), Lake Woods (3), Gregory (4) and East Alligator River (5)), when initial pasture condition was excellent.

Table 3. Average annual percent perennial grass composition and liveweight gain ha^{-1} achieved by fixed stocking at the long-term carrying capacity, a strategy with a 10% limit for increases and a 20% limit for decreases, and full flexibility for the entire 30-year simulation period and for the first and second 15-year periods, for each mean minus the standard deviation (M_s.d.) group, when initial pasture condition was excellent

Location strategy	% Perennials			Liveweight ha^{-1}		
	Mean 30-year	Mean 1st 15-year	Mean 2nd 15-year	Mean 30-year	Mean 1st 15-year	Mean 2nd 15-year
M_s.d. 1: Bedourie						
Fixed stocking	88	88	88	0.2	0.1	0.3
10 20	85	88	81	0.2	0.2	0.2
Full flexibility	67	78	56	0.3	0.4	0.2
M_s.d. 2: Tablelands						
Fixed stocking	88	88	89	11	11	11
10 20	83	86	80	13	13	13
Full flexibility	68	81	56	15	17	13
M_s.d. 3: Lake Woods						
Fixed stocking	88	89	88	20	20	19
10 20	82	87	78	23	23	22
Full flexibility	72	82	62	24	27	22
M_s.d. 4: Gregory						
Fixed stocking	88	88	88	38	38	38
10 20	82	86	77	41	41	40
Full flexibility	76	84	68	42	44	39
M_s.d. 5: East Alligator R.						
Fixed stocking	88	88	88	55	55	55
10 20	78	85	72	60	62	58
Full flexibility	76	84	69	60	63	57

with a 10% limit for increases and 20–60% limits for decreases also achieved only 1 kg lower LWG ha^{-1} than the more flexible strategies.

The impact of flexible stocking on pasture condition

Interactions between rainfall variability and livestock grazing are known to degrade rangelands in northern Australia (McKeon *et al*. 2004; Hunt 2008; O'Reagain *et al*. 2011; Orr and Phelps 2013). A key symptom of this is loss of perennial grasses, which play a crucial role in fostering long-term economic and resource sustainability (Tothill and Gillies 1992; Scanlan *et al*. 1994; Johnston *et al*. 2000; McKeon *et al*. 2000, 2004; Bortolussi *et al*. 2005). In this simulation study, the flexible strategies which produced the highest average annual cattle productivity resulted in 10–25% lower average annual perennial grass composition than what was possible with strategies which achieved the best pasture condition (Figs 5 and 6). Also, the average annual values for a 30-year simulation period often masked the poor state of both pasture condition and cattle productivity at the end of that period, especially when initial pasture condition was excellent (Fig. 7*a* and *b*). Hence, this maximum average annual cattle productivity occurred at the expense of pasture condition and was unsustainable.

Strategies with very high limits for annual increases in stocking rates often raised stocking rates markedly after seasons with high rainfall, resulting in high cattle productivity (Fig. 7; *2b*). If stocking rates are raised substantially after a very good growing season at locations with high rainfall variability, then it is likely they will be excessive during the following growing season (Hunt 2008), resulting in high utilisation rates and a decline in pasture condition. The more that stocking rates are raised in response to a good growing season, the greater the risk that grazing will cause a decline in pasture condition during the next year. Under these circumstances, it is not surprising that this study found that the more stocking rates were increased after a good growing season, the more pasture condition declined, and particularly when strategies were able to increase stocking rates faster than they could decrease them (Figs 4 and 6). This cost to pasture condition associated with achieving the highest cattle productivity is consistent with the findings of several grazing trials and/or simulation studies (Buxton and Stafford Smith 1996; Day *et al*. 1997; McKeon *et al*. 2000; O'Reagain *et al*. 2011; Orr and Phelps 2013).

When initial pasture condition was moderate, the strategies which produced the highest cattle productivity caused less pasture damage or even improved pasture condition relative to fixed stocking at the long-term carrying capacity (Fig. 5). These strategies mostly had lower limits for increases in stocking rates compared with those which achieved maximum cattle productivity when initial pasture condition was excellent, but had similarly high limits for decreasing stocking rate (Table 2). In three of the five M_s.d. rainfall groups, the limits for increasing stocking rates were less than half of the accompanying limits for decreasing them. Consequently, these strategies were more constrained in their capacity to raise stocking rates after a good season, but still had the ability to markedly lower them after a poor growing season. This more conservative approach to adjusting stocking rates in response to rainfall variability still achieved higher cattle productivity than fixed stocking, but with little loss or even improvement in pasture condition (Fig. 4*b*). Similarly, when initial pasture condition was excellent (Fig. 4*a*), strategies which could increase stocking rates less than half they could decrease them annually caused the least reductions in pasture condition.

Achieving a balance between cattle productivity and pasture condition

Strategies with limits for increasing stocking rates that were half those for decreasing them (e.g. 10%, 20% and 30% limits for increases accompanied by 20%, 40% and 60% limits for decreases, respectively), achieved high cattle productivity for all M_s.d. rainfall groups (Fig. 3), mostly improved pasture condition when initial condition was moderate, and caused relatively small declines in pasture condition when initial condition was excellent (Fig. 4). It is these strategies which appear to best meet the challenge identified by McKeon *et al*. (2004), which is to achieve a balance between economic performance and the sustainability of the resource-base, by matching stock numbers to forage availability, in environments that are highly variable and unpredictable.

The performance of one of these strategies, with a 30% limit for increasing and a 60% limit for decreasing stocking rates, is shown in Fig. 8. This strategy increased cattle productivity

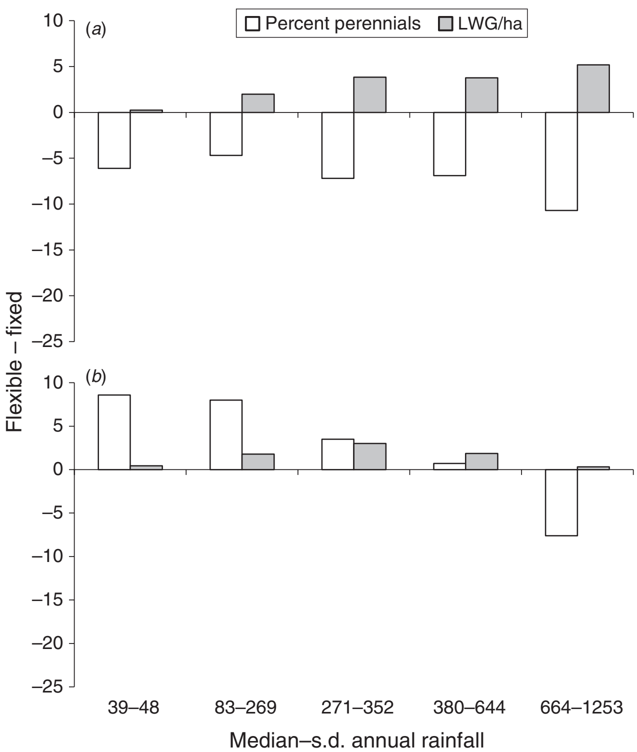

Fig. 8. Differences in percent perennial grass composition and LWG ha^{-1} between a strategy with a 30% limit for increases and an 80% limit for decreases in stocking rates and fixed stocking for each M_s.d. rainfall group, when initial pasture condition was (*a*) excellent and (*b*) moderate.

relative to fixed stocking when initial pasture condition was excellent and moderate. When initial condition was excellent (Fig. 8*a*), productivity gains rose from 0.2 to 5.2 kg ha^{-1} annually as M_s.d. rainfall increased. This was accompanied by a decline in perennial grass composition of between 4% and 10%, which generally increased with increasing M_s.d. rainfall. These declines in pasture condition may not make them unsustainable, and especially when these were only ≤7% for all locations except those in M_s.d. rainfall Group 5 (664–1253 mm). When initial pasture condition was moderate (Fig. 8*b*), productivity gains from this strategy ranged from 0.3 to 3.0 kg ha^{-1}, and were greatest for locations within M_s.d. rainfall Group 2, 3 and 4. Again, with the exception of locations within M_s.d. rainfall Group 5, these cattle productivity gains were accompanied by improvements in average annual perennial grass composition of between 1% and 9%.

Although a strategy with a 30% limit for increases and a 60% limit for decreases in stocking rate is more conservative than the highly flexible strategies which generally achieved maximum cattle productivity, it would often be impossible or financially risky for individual cattle producers to change cattle numbers to this degree annually, and it would also not be possible for the entire north Australian beef industry to adopt this strategy at the same time. For this reason, the industry may prefer a more constrained approach for coping with rainfall variability.

Due to the sustainability and financial risks associated with highly flexible stocking, several authors have recommended that annual changes in stocking rates be constrained (Stafford Smith and Foran 1992; Illius *et al*. 1998; Díaz-Solís *et al*. 2009; O'Reagain *et al*. 2011; Hunt *et al*. 2014). A strategy with a 10% limit for annual increases and a 20% limit for annual decreases in stocking rates requires less change in herd size and still achieved higher cattle productivity than fixed stocking for all M_s.d. rainfall groups (Fig. 9). When initial pasture condition was excellent, annual cattle productivity gains relative to fixed stocking ranged from 0.1 to 5.1 kg ha^{-1}, and increased with increases in M_s.d. rainfall (Fig. 9*a*). At the same time, perennial grass composition declined by 4% or 5% at locations in M_s.d. Groups 1–4, and by 9% for M_s.d. Group 5. When initial pasture condition was moderate (Fig. 9*b*), annual cattle productivity gains ranged from 0.2 to 1.7 kg ha^{-1}, and were greatest at locations within M_s.d. rainfall Groups 2, 3 and 4. Percent perennial grass composition improved by 2–7% for M_s.d. Groups 1–4, and only declined by 7% for M_s.d. Group 5. However, compared with the strategy with a 30% limit for increases and a 60% limit for decreases in stocking rates annually (Fig. 8), this form of constrained flexibility resulted in 1–1.5 kg ha^{-1} or 41–125% lower cattle productivity for M_s.d. rainfall Groups 2–4, without providing additional improvements in pasture condition. The same trend occurred for M_s.d. rainfall Group 1, but the kg difference was much lower and the percentage difference much higher. Hence, constraining flexibility to this level for the purpose of making it more practical at the property level forfeited considerable cattle productivity gains. In comparison, these two forms of flexibility achieved similarly high cattle productivity and reduced pasture condition compared with fixed stocking at locations within M_s.d. rainfall Group 5. At these locations,

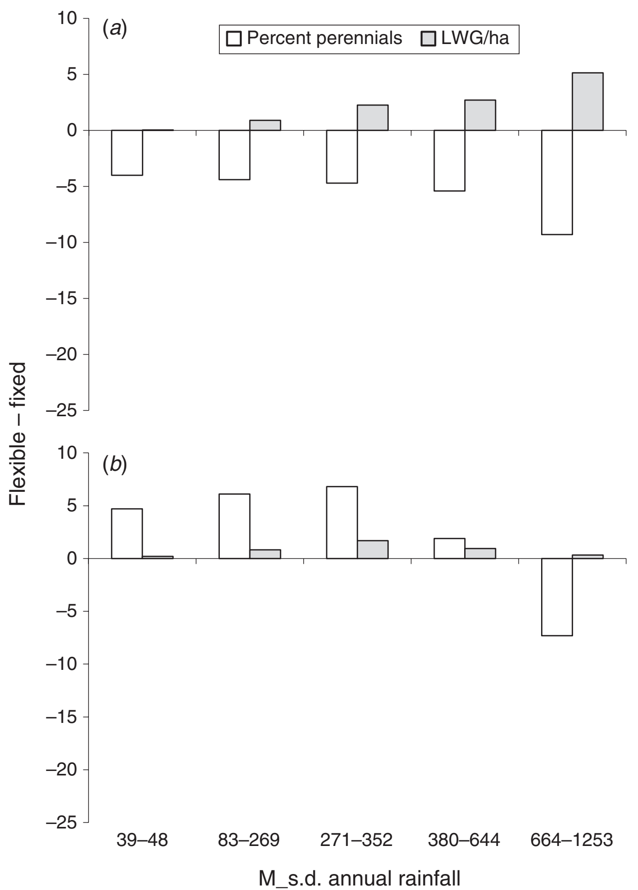

Fig. 9. Differences in percent perennial grass composition and LWG ha^{-1} between a strategy with a 10% limit for increases and an 20% limit for decreases in stocking rates and fixed stocking for each M_s.d. rainfall group, when initial pasture condition was (*a*) excellent and (*b*) moderate.

an even more constrained strategy with only a 5% limit for increases in stocking rates annually appears to provide higher and more sustainable cattle productivity gains (Table 2, Figs 3 and 4).

The capacity of these forms of flexible strategies to improve pasture condition is significant, given that large proportions of cattle-grazed rangelands in northern Australia show signs of pasture degradation (Tothill and Gillies 1992; Karfs *et al*. 2009; Beutel *et al*. 2014). Also, the capacity of these strategies to improve both pasture condition and cattle productivity was most apparent for locations within M_s.d. rainfall Groups 2, 3 and 4. Again this is significant, given that these three zones contain the majority of beef cattle in northern Australia (ABS 2006; Bastin 2008).

Implementing stocking rate strategies

This simulation study compared the performance of flexible stocking with fixed stocking, where fixed stocking occurred at the maximum stocking rate possible without causing a decline in pasture condition. Hence, fixed stocking performed to its maximum capability, as it was simulated with a stocking rate which was determined using 30 years of historical rainfall figures. In reality, a cattle producer could not do this without the detailed knowledge of future climate that would come from a perfect climate forecast. Furthermore, it would be practically impossible for cattle producers to maintain the same stocking rate over 30 years, due to annual variation in cattle liveweight and rates of mortality and weaning. For these reasons it would not be possible for cattle producers to implement the optimal fixed stocking strategy simulated in this paper. Hence, an important advantage of the form of flexible stocking simulated in this study is its application does not require knowledge of long-term carrying capacity and how this differs with land types, land condition and climatic periods. As such, constrained flexibility appears to meet the challenge identified by Hunt *et al*. (2014), which was to ensure stocking rates were consistent with maintaining good land condition when this varies with land type, land condition and climate. Although Hunt *et al*. (2014) claimed that using appropriate stocking rates was the most critical element of grazing land management, they also recommended wet-season pasture resting for maintaining or improving pasture condition. However, effective implementation of pasture resting can be difficult, as above-average seasonal conditions are often needed for pasture recovery, and pasture condition and cattle productivity can decline in the paddocks that receive cattle from the rested paddocks (Scanlan *et al*. 2011; Hunt *et al*. 2014).

The conclusions of this study were predicated on a single annual adjustment in stocking rates. Further adjustments, and particularly leading into the next pasture growing season, would greatly improve the sustainability and long-term cattle productivity of the more flexible strategies (Hunt 2008). Even so, the single annual adjustment simulated here appears consistent with the operations of many extensive cattle properties in northern Australia. Due to wet summers, which restrict access to herds within properties and between properties and markets, the presence of heavily pregnant cows or cows with young calves at foot, high temperatures and the large expense and long periods of time required to muster cattle herds, many cattle producers in northern Australia muster their stock on only two occasions annually, during the drier and cooler months (April–September). From this perspective, the best time to adjust stocking rates would coincide with the first muster during the early dry season, when calves are weaned, non-productive cows are culled, and surplus heifers and steers sold. This muster coincides with the recommended time for conducting a forage budget (Stocktake 2014), which is the time flexible strategies adjusted stocking rates in this simulation study. However, although the forage budgeting technique in Stocktake (2014) applies only to the dry season, the strategies simulated in this study were based on a 12-month forage budget, consistent with their conservative approach to coping with high and unpredictable rainfall variability.

At the beginning of the dry season, cattle producers make decisions about stocking rates with little knowledge of the climatic conditions that will unfold over the following 12 months. At this time, forecasts of the amount of rain likely to fall during the next wet season have low levels of confidence (Cobon and Toombs 2013), and hence stocking rate decisions are more easily based on the amount of forage available at the end of the previous wet season. But, as pointed out by Hunt

(2008), livestock numbers based on the amount of standing forage present at the end of one pasture growing season are unlikely to be appropriate for the next growing season, leading to over- or under-utilisation of pastures. The results of this simulation study, using 30-year simulation periods, suggest that the adverse long-term impacts of episodes of over-utilisation are greater than those of under-utilisation. Although an occasional inappropriately low utilisation rate is a lost opportunity for short-term high cattle productivity, this is partially compensated by higher productivity per individual animal and by improvements in pasture condition, both of which can drive higher cattle productivity in the future. Occasional inappropriately high stocking rates that cause a decline in pasture condition in a small number of years can drive a decline in cattle productivity over many years. This is apparent in Fig. 7 and Table 3, where full flexibility achieved high productivity during the first 15 years, but pastures damaged during this time supported lower cattle productivity in subsequent years. It is for these reasons that flexible strategies, which could decrease stocking rates much more rapidly than increase them, achieved better long-term balances between cattle productivity and pasture condition.

Highly variable and unpredictable annual rainfall in arid and semiarid rangelands is a major challenge for beef producers who often have limited capacity to adjust cattle numbers throughout the year. Under these circumstances, and especially where adjustments in stocking rates are mostly confined to the dry season, sustainable cattle production occurred when decreases in cattle numbers after poor growing seasons were much higher than increases in numbers after good seasons. As such, a rule-of-thumb arising from this simulation study is that increases in cattle numbers after good growing seasons should be only half the magnitude of decreases after poor growing seasons. This is a risk-averse adaptation to high and unpredictable inter-annual rainfall variability, in regions where cattle producers do not have access to accurate climate forecasts and have limited capacity to change stocking rates during the wet season.

Conclusions

When stocking rates were adjusted once annually at the beginning of the dry season, maximum short-term (<15 years) cattle productivity occurred at the expense of pasture condition. This occurred with flexible strategies which had very high limits for both increases and decreases in stocking rates annually. Although they achieved high cattle productivity during the first 15 years of simulations, this could not be maintained, and hence they were unsustainable. The opposite occurred for fixed stocking and strategies with a low 5% limit for increases and $\geq$30% limits for decreases in stocking rates. These maintained pasture condition when initial condition was excellent, and considerably improved condition when initial condition was moderate. However, this occurred at the expense of cattle productivity in the majority of locations.

A balance between cattle productivity and pasture condition occurred when flexible strategies had limits for increases that were only half the limits for decreases in stocking rates. Three examples of these strategies, with increasing levels of flexibility, are: a 10% limit for increases and 20% for decreases; 20% limit for increases and 40% limit for decreases; and 30% limit for increases and 60% limit for decreases. These strategies achieved high cattle productivity for all M_s.d. rainfall groups, and good pasture condition for all M_s.d. groups except Group 5. They were able to do this without knowledge of long-term carrying capacity or reference to climate forecasts.

These forms of flexibilities performed best when initial pasture condition was moderate. Relative to fixed stocking at its optimum stocking rate, they improved pasture condition, and in doing so, improved cattle productivity. This capacity is significant, given that large parts of the cattle-grazed rangelands show signs of pasture degradation. The capacity of these strategies to improve both pasture condition and cattle productivity was most apparent for locations within M_s.d. rainfall Groups 2, 3 and 4. This is also significant, given that the majority of beef cattle in northern Australia occur within these three zones. A constrained form of these strategies, with a 10% limit for increases and a 20% limit for decreases, is likely to be more practical at property and industry scales, as it requires less change in stocking rates and herd size.

Strategies with annual limits for increases that are half those for decreases in stocking rates appear to improve cattle productivity and pasture condition relative to fixed stocking in the majority of the cattle-grazed rangelands of northern Australia. However, their impact on herd productivity and enterprise profitability need to be assessed before they could be recommended for adoption by industry.

Acknowledgements

This simulation of stocking rate strategies commenced during the Northern Grazing Systems project that was funded by Meat and Livestock Australia and the Australian Government Department of Agriculture, Fisheries and Forestry, and was continued through support from the Queensland Government Department of Agriculture and Fisheries. The authors also thank Dr Greg McKeon for his ongoing encouragement of this work and his comments on a draft manuscript. The authors are also very grateful to Dr David Mayer for guiding and conducting the analysis of variance of simulated data, and for the constructive comments of the reviewers.

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