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Review

Sustainable grazing management for temporal and spatial variability in north Australian rangelands – a synthesis of the latest evidence and recommendations

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Abstract. Rainfall variability is a major challenge to sustainable grazing management in northern Australia, with management often complicated further by large, spatially-heterogeneous paddocks. This paper presents the latest grazing research and associated bio-economic modelling from northern Australia and assesses the extent to which current recommendations to manage for these issues are supported. Overall, stocking around the safe long-term carrying capacity will maintain land condition and maximise long-term profitability. However, stocking rates should be varied in a risk-averse manner as pasture availability varies between years. Periodic wet-season spelling is also essential to maintain pasture condition and allow recovery of overgrazed areas. Uneven grazing distributions can be partially managed through fencing, providing additional water-points and in some cases patch-burning, although the economics of infrastructure development are extremely context-dependent. Overall, complex multi-paddock grazing systems do not appear justified in northern Australia. Provided the key management principles outlined above are applied in an active, adaptive manner, acceptable economic and environmental outcomes will be achieved irrespective of the grazing system applied.

Additional keywords: grazing distribution, multi-paddock systems, pasture spelling, rainfall variability, simulation modelling, stocking rates.

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Introduction

The rangelands of northern Australia occupy a vast area stretching from Queensland to Western Australia with the majority of these lands used for extensive beef production (Mott *et al*. 1984). How these rangelands are managed thus has important ecological, economic and social implications. Poor water quality emanating from grazing lands for example has been identified as a major threat to the Great Barrier Reef and associated fishing and tourism industries (Furnas 2003).

A major challenge for the sustainable and profitable management of all rangelands is that of inter-annual rainfall variability. In Australia, rainfall variability is extreme and occurs at annual, decadal and generational time-scales (McKeon *et al*. 1990). This leads to major temporal variability in forage supply, with significant risks of resource degradation and economic loss in below-average rainfall years if not managed appropriately. Eight major regional degradation events have been documented in Australia: all followed a similar pattern of above-average rainfall years followed by drought and overstocking, leading to catastrophic overgrazing, degradation and a shift to lower, less productive rangeland states (McKeon *et al*. 2009). Since the 1960s the introduction of improved supplementation, hardier *Bos indicus* cattle, the provision of new water-points and the ability to truck cattle rapidly over long distances have significantly increased the capacity of graziers to manage for drought (Gardener *et al*. 1990). However, these changes have also allowed high grazing pressures to be maintained both during and after droughts by some producers, increasing the risk of severe resource degradation.

Spatial variability is a further complicating factor for sustainable management in northern Australia. Properties and paddocks are generally very large, have few water-points and are often spatially heterogeneous. In the Northern Territory and Western Australia for example, paddocks can be 13 000–16 000 ha with only two or three water-points (Oxley 2006). Despite low stocking rates of paddocks, area-selective overgrazing is thus common around water-points or in the most productive parts of the landscape, with other distant or less preferred areas seldom utilised (Andrew 1988).

The challenges of managing for a variable environment are not new: for example, the legendary Australian grazier, Sir Sidney Kidman, utilised spatial variability via an extensive network of grazing properties to both integrate breeding and fattening operations and buffer temporal variability in forage supply (Dobes 2012). This strategy is still successfully employed by large cattle companies but most graziers are restricted to using agistment (leased grazing) or forced sales to cope with rainfall variability (McAllister 2012). While the use of spatial variability may buffer localised or regional droughts, it is of little use for droughts at state or national scales (Dobes 2012).

The inherent nature of the grazing industry in northern Australia also makes managing for variability difficult. Most properties have limited fencing and water-points, labour is expensive and returns on investment are extremely low (McCosker *et al*. 2010). Large distances, limited markets and the seasonal inaccessibility of many roads also restrict the ability of managers to respond rapidly to changing conditions. Most property management systems accordingly have to be relatively simple and inexpensive, which tends to preclude more intensive grazing management systems.

The challenges of managing for temporal and spatial variability in Australian rangelands have been addressed previously, notably by McKeon *et al*. (1990) and Stafford Smith and Foran (1993). Since then a significant amount of research involving both grazing experiments and modelling has been conducted. The objective of this paper is to review the latest evidence available and the extent to which it supports current recommendations on grazing management to manage for variability in northern Australia, highlight deficiencies in knowledge and practical difficulties in their application, and synthesise the latest findings into an updated set of recommendations for managing temporal and spatial variability.

In the first section of this paper, key recommendations and associated research for managing temporal variability in northern Australia are presented. Thereafter, strategies for managing spatial variability are addressed. The following section then briefly considers recent research on the contentious issue of multi-paddock grazing systems. Finally, the key recommendations for managing temporal and spatial variability are summarised based on the available grazing experiment and modelling evidence.

Managing for temporal variability in forage supply

Temporal variability in forage supply occurs at two scales: in the shorter term, intra-annual variability in supply (and particularly nutritive value) occurs due to the pronounced seasonal distribution of rainfall in northern Australia (Ash *et al*. 1997). Although a major constraint on animal production, such seasonal variation is fairly predictable and thus relatively easy to manage (Danckwerts *et al*. 1993). In the longer term, inter-annual variability in forage supply occurs in response to rainfall fluctuations between years. Although the coefficient of variation (CV) in annual rainfall can be up to 40% or more for some areas (Ash *et al*. 1997) the variability in forage production is invariably markedly higher. For example, at an experimental site in north Queensland the variability in annual pasture production (CV of 55%) over 16 years was markedly greater than that for rainfall (CV of 38%) with forage availability varying by up to 12-fold between years, even under moderate stocking rates (P. O'Reagain, unpubl. data). This paper focuses on the problem of inter-annual variability of forage supply which is far less predictable and hence far more difficult to manage than that at the intra-annual scale. The three major management recommendations for managing for inter-annual variability in forage supply are to (1) stock at long-term carrying capacity, (2) match stocking rates with forage supply and (3) apply wet-season spelling. These recommendations are discussed below.

Stock at long-term carrying capacity

The most basic recommendation to manage for rainfall variability is stocking at the long-term carrying capacity. Depending upon vegetation type, this is defined as an average annual utilisation of 15–30% of the pasture growth expected in most years with the level of 'safe' utilisation increasing with rainfall and soil fertility (Scanlan *et al*. 1994). Stocking at the long-term carrying capacity should ensure sufficient forage in all but the driest years and maintain resource condition, ensuring long-term profitability (Wilson and MacLeod 1991). In northern Australia, the GRASP model has been used extensively to estimate the potential long-term carrying capacity of individual land types (McKeon *et al*. 2009; Walsh and Cowley 2011). Although the GRASP model is the most objective method of estimating the long-term carrying capacity currently available, given the complexity of the systems and landscapes involved, these, and indeed all, estimates of the long-term carrying capacity are not infallible and, hence, must be applied cautiously and in an adaptive fashion.

Empirical evidence for stocking at the long-term carrying capacity

There is substantial evidence that low to moderate rates of pasture utilisation maintain or improve land condition (McKeon *et al*. 2009). For example, in a 26-year study on *Astrebla* grasslands, pasture condition was maintained at a 30% utilisation rate of dry-season standing forage while 50% utilisation proved unsustainable with a marked decline in pasture condition after 20 years (Orr and Phelps 2013). There is, however, a lack of direct empirical evidence showing that stocking at the long-term carrying capacity is more profitable in the longer term than heavy stocking. Most grazing studies have focussed on pasture dynamics, e.g. McIvor and Gardener (1995) and Ash *et al*. (2011), been relatively short-term and/or used relatively small, uniform paddocks, e.g. Gillard (1979) and Burrows *et al*. (2010), restricting the relevance of their results to commercial management. The extent to which relationships derived from steers and wethers extend to breeding animals has also been questioned (Ash and Stafford Smith 1996). This basic lack of evidence of relevance to the grazing industry has limited the adoption of lower, more sustainable stocking rates in northern Australia.

Results from a 13-year stocking rate experiment using paddock sizes of 10–40 ha in central Queensland showed that profitability was greatest at the highest stocking rate with an average pasture utilisation rate of ~61% (Burrows *et al*. 2010).

Although rainfall over the period of the experiment was generally well below average, no major change in pasture composition occurred. Nevertheless, some preliminary degradation was recorded indicating that the highest stocking rates were not sustainable (Orr *et al*. 2010).

Conversely, in an experiment using larger (~100 ha), spatially heterogeneous paddocks over 15 years in north Queensland (O'Reagain *et al*. 2009; O'Reagain and Bushell 2011), constant moderate stocking at around the long-term carrying capacity maintained pasture condition, gave better liveweight gain per head and was far more profitable than heavy stocking. Although heavy stocking gave the highest liveweight gain per ha and was very profitable in the initial high-rainfall years, pasture condition declined markedly in the first drought. In the long term, profitability was severely reduced relative to stocking at the long-term carrying capacity due to higher interest costs and drought-feeding costs and reduced product value in drier years. Importantly, this difference in overall profitability and pasture condition was not reversed despite five later above-average rainfall years.

Limitations of the application of the latter results to commercial properties include the relatively small scale of the experimental area relative to commercial paddocks and the use of steers as opposed to breeders (Ash and Stafford Smith 1996). The results are also somewhat place- and time-specific with different outcomes potentially possible given a different sequence of rainfall years. Despite this, these results are the first empirical evidence in northern Australia showing that in the longer term (>8 years) stocking at the long-term carrying capacity is more profitable than heavy stocking.

Bio-economic modelling of different stocking rates

Simulation modelling provides a means to overcome some of the limitations of grazing experiments and has been widely used to compare the performance of different management strategies, e.g. Buxton and Stafford Smith (1996). Recent models simulate grazing systems far more realistically than previous versions; significant progress has also been made in simulating property-level outcomes with breeding cattle (MacLeod and Ash 2001; Scanlan and McIvor 2010).

In a recent study, different grazing management strategies were simulated for nine regions across northern Australia using historic rainfall data (Scanlan and McIvor 2010). In each region a 'typical' model property was developed to simulate a beef breeding herd with followers and fattening stock grazing up to 20 individual paddocks. Simulated properties contained a representative mix of the relevant regional land types but paddocks contained only one land type.

Results across all nine regions indicated that pasture condition declined as stocking rates increased above the long-term carrying capacity, eventually resulting in reduced liveweight gain per ha at high stocking rates. Over 25 years, stocking at the long-term carrying capacity was more profitable than heavy stocking, although the length of time that this took to occur varied with region, starting conditions and the sequence of rainfall years encountered (Scanlan and McIvor 2010).

Simulations have also been run to extend the outcomes of the grazing experiment of O'Reagain *et al*. (2009, 2011) to a representative commercial property in the same area with breeding cattle (Scanlan *et al*. 2013). Increasing stocking rates up to nine 450 kg animal equivalents (AE) per 100 ha had little adverse impact on pasture condition or individual animal performance, leading to an increase in overall liveweight gain per ha and economic returns (Fig. 1). However, at stocking rates above 12 AE per 100 ha, there were adverse impacts on soil loss, pasture growth, land condition and liveweight gain per head, leading to an overall reduction in liveweight gain per ha, increased supplementary feeding and an associated decline in profit. While economic returns peaked at stocking rates between 9 and 12 AE per 100 ha, at higher stocking rates liveweight gain per head began to decline and there were potentially large impacts on pasture condition, both of which increase risk and vulnerability in a variable climate. Accordingly, it would be prudent to operate at stocking rates below those that yield maximum economic returns. Importantly, these outcomes suggest that the overall principles elucidated with steers (O'Reagain *et al*. 2009, 2011) may also hold with breeding cattle at a commercial scale.

One weakness of these simulations is the assumption of a single soil or land type in each paddock. However, realistically modelling the performance of different management strategies in large heterogeneous paddocks is a major challenge given the interactions between foraging behaviour, spatial heterogeneity and vegetation dynamics that occur in a complex and highly variable environment.

Matching stocking rates to seasonal forage supply

Varying stocking rates to match forage supply is another key recommendation for managing rainfall variability e.g. Ash *et al*. (2000). Variable stocking should minimise overgrazing and feed shortages in low-rainfall years while taking advantage of high-rainfall years. Closer coupling of stocking rates with forage supply might thus potentially give greater total production than constant stocking at the long-term carrying capacity, without causing pasture degradation. In northern Australia, the logical time to adjust stock numbers is at the end of the wet season (April/May) as further pasture growth is unlikely for the next 6–9 months. Stocking rates may be set to utilise a percentage of standing pasture e.g. 20–30% (Hunt 2008), or adjusted using a forage budgeting system like Stocktake (Aisthorpe *et al*. 2004). The use of seasonal climate forecasts, such as the Southern Oscillation Index (SOI), are also sometimes recommended to inform stocking-rate decisions and make adjustments more proactive (McKeon *et al*. 1993).

Empirical evidence for variable stocking

The only long-term empirical evidence on the relative performance of variable relative to constant stocking at the long-term carrying capacity is that of O'Reagain *et al*. (2009, 2011). Here stocking rates were varied over 15 years based on either (1) end-of-wet season (May) standing pasture or (2) end-of-dry season (October) standing pasture and an SOI-based climate forecast for the approaching wet season. Stocking rates in these two treatments varied 3-fold over the period of 15 years in response to large variations in rainfall. Over 15 years, the overall profitability of both variable strategies was slightly higher but

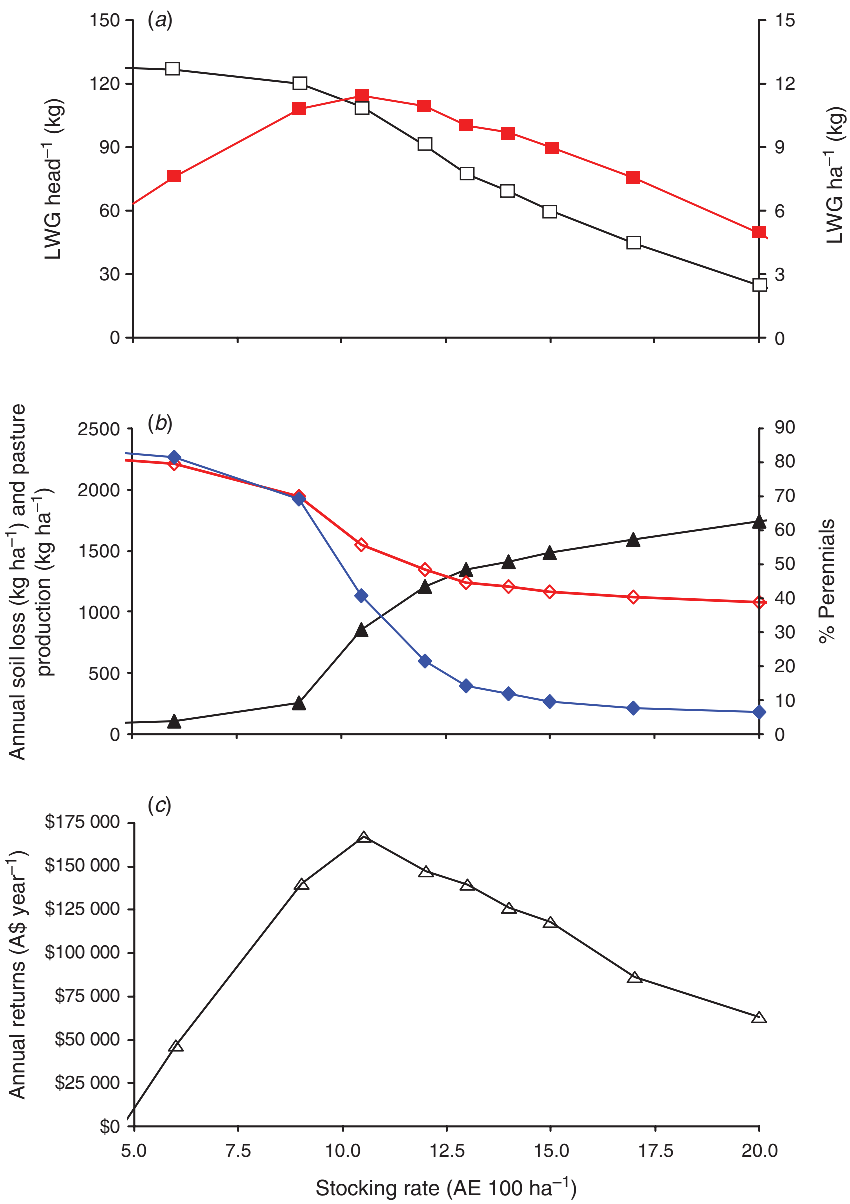

Fig. 1. Simulated effect of increasing stocking rate on (*a*) liveweight gain per head (LWG head^{-1}, open squares) and liveweight gain per ha (LWG ha^{-1}, closed squares) (*b*) annual soil loss (closed triangles), annual pasture production (open diamonds) and per cent desirable perennials (closed diamonds) in the pasture and (*c*) return on capital, labour and management in relation to stocking rate [animal equivalents (AE) 100 ha^{-1}] for a *Eucalyptus brownii* woodland in north Queensland.

showed greater inter-annual variability than constant stocking at the long-term carrying capacity. However, pasture condition was significantly poorer after 15 years under variable stocking relative to constant stocking at the long-term carrying capacity (O'Reagain and Bushell 2011). This occurred due to the carry-over of high stocking rates in the variable strategy into a drought period after a sequence of previous wet years. Despite a rapid reduction in stocking rates in these dry years, the adverse effects of this short-term overgrazing on pasture condition were still evident years later. Similar effects have also been observed with simulation modelling of variable stocking (Scanlan *et al.* 2011).

The use of the SOI in combination with standing pasture to adjust stocking rates at the start of an extended dry period in 2002 did result in stocking rates being reduced 6–7 months earlier than would otherwise have happened. However, this had no discernable effect on pasture condition relative to simply adjusting numbers based on standing pasture alone. This indicates that the reduction in stocking rates was too late in both strategies to prevent degradation in the subsequent drought. The timing of the reduction in stock numbers in the SOI strategy (late in the dry season) also resulted in an economic loss through the sale of cattle in poor condition. Both factors indicate the need for seasonal forecasts with a longer lead time i.e.

>6 months, to allow adjustments of stocking rate earlier in the season.

These results indicate that, while variable stocking is a valid strategy in managing for rainfall variability, changes in stocking rate need to be made in a risk-averse manner (i.e. decreases faster than increases and with upper limits set on the maximum stocking rate allowed in even the best years e.g. 1.5 times the long-term carrying capacity). Although the end of the wet season should be the primary time for adjustments of stocking rate, other secondary adjustment points, such as the end of the dry season, or mid-wet season, should also be used (O'Reagain and Scanlan 2013). These recommendations are currently being tested in ongoing research at this experimental site (O'Reagain and Bushell 2011).

Two large-scale but relatively short-term (<6 years) assessments of variable stocking with breeding cattle were also conducted in the Northern Territory at Mount Sanford and Pigeon Hole cattle stations (Cowley *et al*. 2007; Hunt *et al*. 2013). Here stocking rates were adjusted annually based on end-of-wet season standing pasture to achieve target utilisation rates of between 12 and 40% depending on treatment. Importantly, conditions at both sites were comparable to commercial breeder properties; with 5000 cattle grazing a combined area of 35 000 ha, the Pigeon Hole experiment is one of the largest grazing experiments ever conducted.

At both Pigeon Hole and Mount Sanford, land condition was unaffected by increasing utilisation rate of the pasture. Although unexpected, this undoubtedly reflects the relatively short period of study, the robust, productive land types involved and the seasons of high rainfall encountered. In some high-rainfall years, the intended higher utilisation rates of pasture were also not achieved (Hunt *et al*. 2013).

Superficially, the Mount Sanford and Pigeon Hole results appear to suggest that profitability is maximised at high rates of utilisation of pasture. However, the maximum utilisation rates of pasture at both sites were relatively low compared with those sometimes observed in commercial practice (Walsh and Cowley 2011). Further, although liveweight gain per ha increased with utilisation rate, at Mount Sanford reproductive indices like inter-calving interval and cow condition began to decline at higher utilisation rates (Cowley *et al*. 2007). In the longer term, given the droughts associated with a variable climate, the adverse effects of higher utilisation rates would undoubtedly emerge, as observed in the Queensland experiments. The Pigeon Hole and Mount Sanford results thus cannot be interpreted as contradicting the general principle that high utilisation rates lead to pasture degradation and an associated decline in profitability.

Both Pigeon Hole and Mount Sanford highlighted the practical difficulties in varying stock numbers to achieve set targets of pasture utilisation. For example, to achieve 20% utilisation at Pigeon Hole, stocking rates had to be varied from 10 to 20 AE per 100 ha between some years. This would be almost impossible to achieve in commercial practice, especially with breeding cattle. Recommended utilisation rates of pasture should thus be considered a long-term target average rather than attempting to achieve a specific rate each year by sharply varying livestock numbers (Hunt *et al*. 2013).

Bio-economic modelling of variable stocking

Scanlan and McIvor (2010) compared a range of annual stocking rate changes from no change i.e. constant stocking, to fully flexible stocking to match forage supply. Only one stocking rate change was allowed each year based on end-of-wet-season standing pasture. In most regions, variable strategies that allowed relatively small (10–20%) increases in stocking rate in high-rainfall years relative to larger decreases (30–40%) in low-rainfall years out-performed set stocking at the long-term carrying capacity. However, highly variable strategies with large fluctuations in stocking rate had a large number of years with negative gross margins. Importantly, when high stocking rates were carried into a dry year following high-rainfall seasons, pasture condition invariably declined leading to a long-term decline in cattle and pasture productivity.

Wet-season spelling

Although secondary to stocking rate management, wet-season spelling (resting) is a key principle of sustainable pasture management (Ash *et al*. 1997), and is also important for managing rainfall variability. In the short term, spelling can buffer intra- and inter-annual variations in feed supply by providing a bank of ungrazed fodder (Danckwerts *et al*. 1993). However, this depends upon forage persistence, weather and potential losses to other herbivores. In the longer term, periodic wet-season spelling maintains land in good condition which, by definition, has a high proportion of perennial grasses. Perennials directly reduce inter-annual variability in forage supply due to their superior productivity and longevity (Orr and O'Reagain 2011). Perennial grass patches also have higher rainfall infiltration rates and hence rainfall-use efficiency than those patches dominated by annuals or shorter-lived perennial grasses (Roth 2004).

Empirical evidence for wet-season spelling

There is extensive anecdotal evidence, e.g. Landsberg *et al*. (1998), and experimental evidence, e.g. McIvor (2001) and Ash *et al*. (2011), on the benefits of wet-season spelling on pasture condition. However, there is very little evidence to assess the actual economic costs or benefits of spelling. This is a significant impediment to adoption: although most managers recognise the benefits of spelling for pasture condition, many regard spelling as an expensive loss of grazeable forage (Walsh and Cowley 2014).

In a recent smaller-scale study over 8 years on three land types in north Queensland (Ash *et al*. 2011), pastures in good condition were maintained at a 25% pasture utilisation rate without spelling. However, with annual early wet-season spelling, 50% utilisation was possible without pasture degradation occurring. More importantly, pastures in poor condition improved with annual spelling and a 50% utilisation rate (Ash *et al*. 2011). Annual early wet-season spelling thus buffered the effects of higher utilisation rates on pasture condition. Although annual spelling of a commercial paddock is impractical, these results suggest that utilisation rates of pasture could be increased slightly above recommended levels, provided regular spelling occurred. However, a limitation of the experiment was that the impact of these treatments on cattle production was not assessed.

There appears to be only one study where the long-term effects of spelling on cattle production and profitability were also quantified (O'Reagain *et al*. 2009, 2011). Here constant, moderate stocking at the long-term carrying capacity without spelling was compared with moderate–heavy stocking with a third of the pasture spelled annually. In contrast to Ash *et al*. (2011), spelling did not appear to buffer the impacts of higher stocking rates on either pasture condition or cattle production, necessitating a reduction in stocking rate after 7 years to moderate levels. This suggests that the detrimental effects of increased stocking rates on the grazed (non-spelled) areas during the wet season may outweigh the benefits of spelling if overall stocking rates are not close to the long-term carrying capacity.

Nevertheless, after 15 years, the last 8 of which involved moderate stocking at the long-term carrying capacity, the profitability of the moderate stocking-spelling treatment was similar to that under constant moderate- or under variable stocking. Pasture condition was, however, better than under constant moderate stocking without spelling and markedly superior to the variable treatments (O'Reagain and Bushell 2011).

Bio-economic modelling of wet-season spelling

Bio-economic modelling (Scanlan and McIvor 2010; Scanlan *et al*. 2011) indicated that the percentage of perennial grasses in the pasture increased with the duration and frequency of spelling. However, this response was dependent on stocking rate: even with a full wet-season spell every 4 years, land condition declined under heavy stocking (Fig. 2). Again, this occurred because the impact of higher stocking rates on the grazed areas outweighed the benefits of spelling. Spelling frequency was also important for land condition with a 3-month spelling every second year superior to a 6-month spelling every 4 years.

In terms of cattle production, simulations for *Astrebla* grasslands in the Northern Territory for example, suggested that the highest liveweight gain per ha and the fastest land condition recovery occurred with stocking at the long-term carrying capacity with full wet-season spelling every fourth year (Walsh and Cowley 2014). This strategy outperformed both light stocking without spelling and heavy stocking with spelling. Spelling thus buffered the effects of a slightly higher stocking rate, allowing greater cattle production to be achieved than under low stocking without spelling. Preliminary modelling suggests that provided regular wet-season spelling occurs, stocking rates can be increased by ~10% without adversely affecting pasture condition (J. Scanlan, unpubl. data).

Managing for spatial variability

A key management principle for the large, spatially-heterogeneous paddocks of northern Australia is to increase evenness of pasture utilisation to improve forage-use efficiency and prevent degradation through selective grazing of preferred areas. Fencing to separate different land types and/or to make smaller paddocks or installing additional water-points are all partial solutions but in extensive, spatially-complex paddocks may be impractical and uneconomic. In the Pigeon Hole study, reducing paddock size was the most effective method of improving grazing distribution across the broader landscape

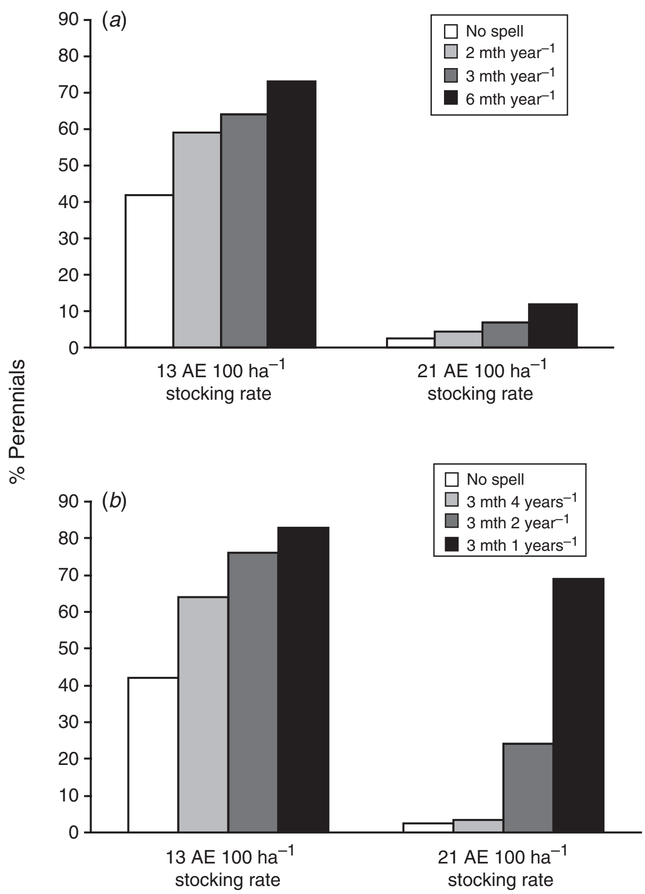

Fig. 2. Simulated mean percent desirable perennials in the pasture showing the influence of (*a*) stocking rate and length of spell period (0, 2, 3 or 6 months) for a 1 in 4-year rest, and (*b*) stocking rates and frequency of a 3-month spell (applied every 1, 2 or 4 years) for a grano-diorite (goldfields) land type in north Queensland (means are for 20 different climate windows each of 30 years).

(Hunt *et al*. 2007). Establishing additional water-points in large paddocks was less effective, partly because cattle still had considerable choice in where they grazed. While reducing paddock size improved the evenness of landscape use, uneven grazing still occurred within paddocks that were small (900 ha) by regional standards (Hunt *et al*. 2007). There were no consistent effects of paddock size on cattle performance or financial returns.

Although smaller paddock sizes improve grazing distributions, there is an obvious trade-off against the cost of the additional fences and water-points. Overall, these costs per ha rise disproportionally for paddocks below ~4000 ha in size (Hunt *et al*. 2014). At Pigeon Hole, paddocks smaller than 4000 ha were not justified as they provided no significant improvement in financial return or evenness of use. Optimum paddock size will, however, vary substantially depending upon carrying capacity and potential improvements in overall production and economic performance. Hence in more productive and intensively managed regions of Queensland, smaller paddocks can probably be justified (e.g. ~2000 ha with two water-points).

The sequential opening and closing of water-points to rotate grazing pressure has also been investigated in a large demonstration paddock (30 000 ha) in the Northern Territory. Unfortunately, a significant number of cattle continued to return to water-points that had been turned off (Scott *et al*. 2010). These cattle had to be repeatedly herded to the new, open water-points requiring a significant input of labour. Overall, both cattle and management took 2–3 years to adjust to the new system. Although an increase in overall paddock carrying capacity occurred due to the increased number of water-points, the effects on cattle production and pasture condition were not assessed. In summary, while the opening and closing of water-points has potential to spread grazing pressure and avoids the costs of fencing, cattle behaviour obviously needs to be managed for it to be successful.

Fire is another tool that has been suggested to change grazing distribution, although its efficacy can vary (Danckwerts *et al*. 1993). In a 4-year study in the Northern Territory (Dyer *et al*. 2003), rotational burning eliminated or greatly reduced grazing gradients away from water-points except when burnt areas were located very close to water-points or when most of the paddock was burnt. Although unreplicated, these results demonstrate the potential of fire to increase evenness of grazing in large paddocks.

Burning has also been recommended to reduce selective grazing at the patch scale. However, the only long-term empirical data available are from a fire-grazing experiment near Katherine in the Northern Territory (Andrew 1986). Here, burning alternate halves of individual paddocks each year successfully moved cattle off previously overgrazed patches, allowing recovery. This strategy was sustainable in terms of maintaining the percentage of perennial grasses in the pasture and maintaining liveweight gains of cattle over 18 years (Ash *et al*. 1997). However, this region has relatively dependable rainfall and the regular use of fire to improve grazing distribution in areas with lower and/or more variable reliable rainfall requires extreme caution: here the conjunction of patch-burning, drought and overgrazing can easily cause serious degradation. Further research is needed on how and to what extent spelling and fire interact to affect grazing patterns at different spatial and temporal scales and the resultant impacts upon land condition.

Is there a case for multi-paddock grazing systems?

Intensive, multi-paddock rotational grazing systems are sometimes recommended to increase the productivity of cattle, profitability and land condition in northern Australia (McCosker 2000). This is at variance with evidence from grazing experiments (O'Reagain and Turner 1992; Briske *et al*. 2008) which show little, if any, advantage of multi-paddock rotational grazing over continuous grazing.

The relevance of research based on grazing experiments for land managers has however been challenged (Teague *et al*. 2011) with a comparison of ranches in Texas using multi-paddock rotational grazing showing significantly better land condition than those continuously grazed. Importantly, the authors emphasised that the multi-paddock rotational grazing systems were applied adaptively with, among other things, stocking rates being matched to forage supply. In contrast, a recent 4-year study across several regions in Queensland showed little, if any, difference in terms of pasture or soil surface condition between established multi-paddock rotational grazing and continuously grazed paddocks (Hall *et al*. 2011). Significantly, unlike the Texas study, individual comparisons of multi-paddock rotational grazing and continuous grazing were made within rather than between properties. Thus both systems were run by the same managers who adjusted stocking rates and grazing periods as conditions changed i.e. applied adaptive management. These results and those of Teague *et al*. (2011) appear to suggest that, as long as stocking rates are appropriate and adaptive management is applied, acceptable outcomes will be achieved irrespective of the grazing system used.

Importantly, neither of the above studies quantified the relative profitability and productivity of multi-paddock rotational grazing relative to continuous grazing. In the Pigeon Hole study, the economics and productivity of a large (27 paddock) multi-paddock rotational grazing system was assessed at a commercial scale with cows and calves albeit over only 3 years (Hunt *et al*. 2013). Overall, multi-paddock rotational grazing was less profitable than continuous grazing or a simple three-paddock spelling system, all of which were adaptively managed (Hunt *et al*. 2013). The multi-paddock rotational grazing system was also labour-intensive, logistically difficult, and had no apparent benefits for cattle production or land condition. Although the study was unreplicated and was only for 3 years it was significant because of its large commercial scale. In northern Australia, the economics of multi-paddock rotational grazing systems are thus questionable given the high costs versus the relatively uncertain benefits of these systems.

Key recommendations for managing temporal and spatial variability

Overall, the available evidence shows that in the extensive grazing lands of northern Australia stocking at the long-term carrying capacity will maintain and/or improve land condition. In the longer term, profitability will also be higher relative to stocking rates above these levels due to lower costs and market premiums for cattle in better condition. There are, however, some obvious shortcomings of a long-term strategy of constant stocking even at the long-term carrying capacity in a variable climate. In particular, overgrazing can occur in dry years depressing liveweight gain and potentially causing degradation (O'Reagain and Bushell 2011). Some flexibility in stocking rate is thus required as rainfall and pasture availability varies between years. Selective grazing of preferred areas or patches is also inevitable in heterogeneous paddocks indicating the need for some form of wet-season spelling for recovery of preferentially-grazed areas.

Modelling and research also suggests that varying stock numbers with pasture availability offers some economic, production and ecological benefits relative to constant stocking at the long-term carrying capacity but only if managed correctly (O'Reagain and Scanlan 2013). In particular, abrupt shifts from wet to dry years can easily result in overgrazing and degradation if stocking rates are not promptly reduced (McKeon *et al*. 1993; Hunt 2008). Variable stocking thus involves greater risk than stocking at the long-term carrying capacity and, accordingly, requires greater management skill. Important guidelines are that stocking rates should be varied in a risk-averse manner with relatively modest increases in years with abundant forage but far sharper decreases in poorer years with low forage availability. Maximum limits on stocking rates should also be set e.g. 1.5 times the long-term carrying capacity, irrespective of the high rainfall of particular seasons (O'Reagain and Bushell 2011). As with constant stocking, selective grazing of preferred areas will also be an issue, requiring some form of spelling as mitigation.

The practical implementation of variable stocking can also be difficult for several reasons. These include the timing and extent of adjustments to stocking rates and their impacts on herd composition (Diaz-Solis *et al*. 2006). Here, pregnancy testing and fetal ageing offer significant potential to appropriately manage and/or market breeding cattle in response to seasonal conditions (Braithwaite and de Witte 1999). Other practical difficulties associated with variable stocking include accurately assessing forage availability in large diverse paddocks and the integration of such information with market and climate signals (O'Reagain and Scanlan 2013).

There is also evidence that wet-season spelling improves pasture condition provided overall stocking rates are close to the long-term carrying capacity. However, more information is required on the length, frequency and timing of spelling required for improvement to pastures and the rainfall conditions under which this occurs. More importantly, there is a lack of data on the long-term production and financial implications of spelling versus non-spelling, and its advantages for managing rainfall variability and uneven grazing distribution. These are key issues that need addressing to increase adoption of wet-season spelling by managers.

Evenness of use of pastures within paddocks is also important to prevent localised degradation and increase forage-use efficiency, particularly in large heterogeneous landscapes. The limited data available indicate that evenness of grazing can be increased through fencing in relation to land type, smaller paddocks, correct water placement and spacing and, in some areas, appropriate fire use. However, the efficacy and economics of all these strategies will vary enormously depending upon circumstances. In reality, however, the inherent selective grazing behaviour of cattle can never be fully controlled and some form of spelling will probably always be necessary to allow recovery of overgrazed patches and land types.

The empirical evidence available does not support the contention that complex multi-paddock rotational grazing systems deliver superior outcomes for either land condition or cattle production. The economics of multi-paddock rotational grazing systems in northern Australia are also extremely doubtful given the capital and labour costs involved and the nature of the industry. So long as key principles, such as stocking at or near the long-term carrying capacity, matching stocking rates to forage availability, ensuring evenness of grazing distribution and wet-season spelling are applied and managed adaptively, acceptable outcomes will be largely achieved irrespective of the grazing system applied.

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