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Resting pastures to improve land condition in northern Australia: guidelines based on the literature and simulation modelling

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Abstract. Pasture rest is a possible strategy for improving land condition in the extensive grazing lands of northern Australia. If pastures currently in poor condition could be improved, then overall animal productivity and the sustainability of grazing could be increased. The scientific literature is examined to assess the strength of the experimental information to support and guide the use of pasture rest, and simulation modelling is undertaken to extend this information to a broader range of resting practices, growing conditions and initial pasture condition. From this, guidelines are developed that can be applied in the management of northern Australia's grazing lands and also serve as hypotheses for further field experiments. The literature on pasture rest is diverse but there is a paucity of data from much of northern Australia as most experiments have been conducted in southern and central parts of Queensland. Despite this, the limited experimental information and the results from modelling were used to formulate the following guidelines. Rest during the growing season gives the most rapid improvement in the proportion of perennial grasses in pastures; rest during the dormant winter period is ineffective in increasing perennial grasses in a pasture but may have other benefits. Appropriate stocking rates are essential to gain the greatest benefit from rest: if stocking rates are too high, then pasture rest will not lead to improvement; if stocking rates are low, pastures will tend to improve without rest. The lower the initial percentage of perennial grasses, the more frequent the rests should be to give a major improvement within a reasonable management timeframe. Conditions during the growing season also have an impact on responses with the greatest improvement likely to be in years of good growing conditions. The duration and frequency of rest periods can be combined into a single value expressed as the proportion of time during which resting occurs; when this is done the modelling suggests the greater the proportion of time that a pasture is rested, the greater is the improvement but this needs to be tested experimentally. These guidelines should assist land managers to use pasture resting but the challenge remains to integrate pasture rest with other pasture and animal management practices at the whole-property scale.

Additional keywords: grazing systems, pasture management, productivity, spelling.

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Introduction

Extensive grazing with beef cattle is the main land use on the majority of rangelands in northern Australia. These rangelands have been grazed for over a century and during this time there has been some deterioration in land condition and there are concerns that resources and productivity are not being maintained. This concern about Australia's rangelands led to the development of a rangelands issues paper and a subsequent rangeland strategy aimed at improving the condition of the Australia's rangelands (ANZECC and ARMCANZ 1996, 1999).

Tothill and Gillies (1992) interviewed technical experts throughout Queensland, the Northern Territory and Western Australia and concluded that 12% of these northern grazing lands were in a degraded state (severe soil deterioration and a predominance of undesirable species) and 32% were in a deteriorating state (slight soil deterioration and increased presence of undesirable pasture species and/or woody weeds). In a survey of 375 northern beef properties, Bortolussi *et al*. (2005) reported 48% of properties had land degradation (erosion, salinity and weeds) and 68% had woody weeds. Although deterioration in pasture condition has occurred across northern Australia, most documentation of this has occurred in Queensland. Field investigations of 260 sites in the Northern Gulf region of Queensland during 2003–04 indicated that the potential carrying capacity of 25% of these sites was less than half of its original capacity (Shaw *et al*. 2007). Clearly there is scope for considerable improvement in the condition of pastures in this region.

The climate in northern Australia is characterised by hot, wet summers (wet season – typically from December to May) and dry, cool-warm winters (dry season). Pasture growth commences with the first rains of the wet season or as temperatures rise after winter in southern areas if soil water is available. Growth rates are highest during the summer and decline later as water supply diminishes, temperatures decline and available nutrients (particularly nitrogen) become limiting (Mott *et al*. 1985).

The northern rangelands are mostly open woodlands and grasslands where the herbaceous layer is dominated by perennial tussock grasses. These grasses provide the bulk of forage for grazing livestock, are important sources of ground cover to protect the soil surface from raindrop impact and to reduce run-off and erosion, and provide habitat and food for soil animals and microorganisms. Although these tussock grasses have persisted in most areas, the proportions of the favoured 3P species (perennial, palatable and productive) in pastures have sometimes declined either as patches within the pastures or as whole pasture areas in response to high grazing pressures (Mott 1987; Gardener *et al*. 1990; McIvor and Orr 1991; Tothill and Gillies 1992; McIvor *et al*. 2005). This loss of perennial grasses causes a decline in land condition (more bare ground, lower cover, greater run-off, increased soil loss and more weeds, annual grasses and forbs) and results in lower forage production. In a study at 10 sites in northern Australia, herbage yields on land in poor condition was only 10–20% of that from the same land type dominated by perennial grasses (McIvor *et al*. 1995).

Pasture resting or spelling (i.e. leaving an area ungrazed for a specific period) has been recommended to reduce the adverse impacts of grazing (e.g. Pratt and Gwynne 1977; Tainton 1999). Resting prevents or delays defoliation, allowing perennial grass tussocks to expand their basal area, and to reproduce by setting seeds with the seeds subsequently germinating and establishing new plants. There have been several experimental studies examining various resting treatments in several vegetation types. Rest periods can vary from annual to season long to durations of a few days or weeks: the work in this paper is for longer rest periods and is not relevant to short-duration grazing systems. We review the results from Australian studies and relevant international material, and, although these tend to be site or vegetation-type specific, we develop general guidelines for the use of pasture resting to improve land condition. In almost all cases, the experimental evidence does not cover all factors of interest. To address this, we use simulation modelling to extend this evidence to a wider range of conditions (length of rest periods, initial land condition and growing season conditions) and over longer time periods.

Methods

Our literature review revealed that stocking rates, three components of pasture resting (season of rest, duration of rest and frequency of rest), initial land condition and seasonal growing conditions determine how effective rest will be in improving land condition: these factors are used to form the structure of this paper. Some aspects of pasture rest have been examined by O'Reagain *et al*. (2014). For each factor we present the results of the literature review and the conclusions that we have drawn from that information.

The next step was to investigate the issues raised by the review of literature through simulation modelling using the GRASP model (McKeon *et al*. 2000). GRASP is a dynamic, soil–pasture–animal growth model that has been widely used to evaluate the effects of grazing management practices in Australia. These uses include safe stocking rate estimation (e.g. Johnston *et al*. 1996) and potential impacts of climate change (e.g. McKeon *et al*. 2009). The original version of GRASP was unable to model the full impacts of pasture resting as grazing during the active growth period had the same impact on land condition as grazing during the winter period when the dominant pasture species are dormant. This is not an accurate representation of the actual situation in pastures. Ash and McIvor (1998) showed that the impact of grazing pressure on pasture composition was greatest in the early wet season, intermediate in the late wet season, and that there was no significant effect in the dry season. Mott *et al*. (1985) have shown that during the growing season, excessive grazing causes perennial grasses to decline, with the degree of decline being related to the degree of utilisation of growth in the growing season. In the GRASP model, utilisation[1] is used to estimate the change in pasture condition state and, following Mott *et al*. (1985), we used a modification of GRASP developed in the study by Scanlan *et al*. (2013) to account for the known biological response to grazing during the growing season (Appendix 1). The major modification involved weighting the impact of utilisation depending on the month in which that utilisation occurred. Grazing during the growing period is weighted such that it has a greater impact on change in condition than does grazing during the dry season. In our modelling, we weighted the wet-season utilisation to have 75% of the annual impact of grazing. Recently, this approach was used successfully to model changes in perennial grasses in north Queensland (Scanlan *et al*. 2013).

Simulation methodology

Detailed modelling has recently been done for the major land type within the Wambiana grazing trial in north Queensland (Scanlan *et al*. 2013). As this grazing experiment is one of the major study sites in northern Australia, we chose to use the dominant Reid River box (*Eucalyptus brownii* Maiden & Cambage) land type from that study for all of our simulations here. Other land types and other locations may give different responses to those reported here. The most important way in which this could occur relates to the rates of recovery and decline in pasture condition as a function of utilisation. The rates for the box land type would be typical of

[1]Utilisation as used in this paper is defined as the percentage of pasture growth over a year that is consumed by livestock.

many moderately fertile land types within Queensland. The faster the change in condition as a function of utilisation, the more rapid will be the response to resting (or heavy utilisation). It is unlikely that this pattern of change will differ across land types although there will be quite a range in terms of the rates of change across land types. The sensitivity to grazing during the growing season will also differ between land types, especially between monsoonal climates in far northern Australia and the more southerly areas of northern Australia where growth is less concentrated in the main summer growing season.

Simulation studies by McKeon *et al*. (2009) have shown that different pasture types respond differently to climate change depending on whether they are water or nitrogen limited. The pattern of response was not greatly influenced by location. Studies of stocking rate and climate variability showed relatively small differences due to land type and appeared to have little influence on the recommended stocking rate strategies derived from simulations at 28 locations across northern Australia (Pahl *et al*. 2013; L. I. Pahl, unpubl. data). Further testing of the influence of land type on simulated changes is warranted. Field studies in Queensland of grazing impacts in subcoastal *Heteropogon*-dominated pasture and inland *Astrebla*-dominated pasture have shown the dominating influence of level of utilisation with both areas showing a safe utilisation level of 30% (Orr *et al*. 2010; Orr and Phelps 2013). Such generalities support our approach of examining in detail the response to pasture rest at one location for one land type and suggesting that the principles derived should apply to broadly similar land types across northern Australia. However, specific combinations of land types and locations may give different results.

Land type description

Mean long-term annual rainfall (July–June) for the Wambiana grazing experimental site (O'Reagain *et al*. 2007) is ~640 mm with over 80% falling in the November–April summer period. Annual rainfall has been highly variable over the period of the experiment varying from 380 mm (2001–02) to 1232 mm (2010–11). The site is an open eucalypt woodland with the dominant (~55%) vegetation being Reid River box; there are also significant areas of silver-leaf ironbark (*E. melanophloia* F. Muell.) and brigalow (*Acacia harpophylla* F. Muell. ex Benth.). The soils are brown sodosols and chromosols, moderately fertile and support a pasture layer containing *Bothriochloa ewartiana* Domin C.E.Hubb, *Chrysopogon fallax* S.T. Blake, *Aristida* spp. L. and a variety of other perennial and annual grasses.

Modelling change in the percentage of perennial grasses

Pasture productivity in this land type is strongly positively correlated with the percentage of perennial grasses in the pasture and it is essential to be able to model changes in perennial grasses in order to model changes in pasture productivity. Within GRASP, the percentage of perennial grasses is a non-linear function of pasture 'state' with State 0 having 90% perennial grasses and State 11 having 1% perennial grasses – see Appendix 2, Fig. *c*. The general relationships between condition states in GRASP and other terms used in this paper are given in Table 1. A key feature for every land type is the safe utilisation level [see Hunt (2008) for a review of utilisation rates as a management tool in northern Australia]. At the safe utilisation rate, the simulated percentage of perennial grasses does not change. If pasture utilisation is higher than the specified safe utilisation level for that pasture type, pasture state deteriorates; if pasture utilisation is lower than the safe utilisation level, then pasture state improves. For the box land system, the safe utilisation level is 30%.

Table 1. Percentage of perennial grasses in GRASP states, and comparison of these states with the ABCD condition framework and general descriptions of land condition

GRASP state[A]	% perennial grasses[A]	ABCD condition[B]	ECOGRAZE state[C]	General condition[D]
0	90	A	–	Good
1	88	A	–	Good
2	84	A	State I	Good
3	70	B	State I	Fair
4	50	B	–	Fair
5	32	C	State II	Fair
6	20	C	State II	Poor
7	15	C	–	Poor
8	10	C	–	Poor
9	5	D	–	Poor
10	2	D	–	Poor
11	1	D	–	Poor

[A]As used by McKeon *et al*. (2000).
[B]As in Quirk and McIvor (2003).
[C]As used in the ECOGRAZE trial – Ash *et al*. (2011).
[D]These are general terms used to describe condition. These terms are indicative only and are not meant to be a definition. Some readers may use slightly different categorisations.

The greatest change in pasture state and, therefore, percentage of perennial grasses, occurs at 100% utilisation or 0% utilisation (see Appendix 2, Fig. *b*). The increase in pasture state in GRASP at zero utilisation was set to 0.65 and the annual rate of deterioration in state at 100% utilisation was set to 0.75. If the pasture was in State 4 (Appendix 2, Fig. *c*), then the percentage of perennial grasses could increase by ~15% at zero utilisation and decrease by about the same amount under 100% utilisation. Within 10% of the safe utilisation, the change in state occurs more slowly than at higher or lower utilisation rates. The change in state at safe utilisation ± 10% is set to 0.15 (see Appendix 2, Fig. *b*). Key parameters within GRASP relevant to our simulations of pasture rest are listed in Table 2.

Climate windows

The climate windows over which field and modelling studies are done can have a major influence on results [see O'Reagain *et al*. (2011) for field studies and Table 1 in Scanlan *et al*. (2013) for a simulation study]. We chose 10 climate windows (one starting in each decade from 1890s), each of 30 years from the full Wambiana climate record and conducted simulations over each of these windows. The mean results from the 10 climate windows were used to produce overall responses to the pasture rest options being simulated.

Table 2. Key variables and parameter values within the GRASP model relating specifically to simulations of effect of resting on pasture condition for the box land type in north Queensland

Parameter description	Parameter value
Stocking rate during non-resting period	14.5 AE 100 ha^{-1}
Land condition state at start of simulation	6 (20% of perennial grasses)
Utilisation level at which state does not change	30%
Increase in state due to 100% utilisation	0.65
Decrease in state due to 0% utilisation	0.75
Change in state at safe utilisation ± 10%	0.15
Commencement of rest	1 December
Weighting (proportion) of effect of utilisation during the wet season	0.75
Month for maximum effect of grazing on state	December

Maintenance stocking rate

For all simulations, we needed to use a stocking rate that would maintain the percentage of perennial grasses at about the initial level when averaged across the simulation period for the 10 climate windows. We term this the maintenance stocking rate. To determine this, we simulated the percentage of perennial grasses over a range of fixed stocking rates in GRASP from very low (3 AE 100 ha^{-1}) to very high (50 AE 100 ha^{-1}). [All stocking rates are given in AE (adult equivalents) per 100 ha with an AE being a 450-kg non-pregnant, non-lactating beef animal.] We selected the stocking rate that maintained the percentage of perennial grasses at about the same mean level over the 30-year simulation period: some departure from the initial percentage of perennial grasses was observed, but the mean percentage of perennial grasses was similar to the starting percentage. Considerable variation between climate windows was observed with a decline in some windows and an improvement in other windows. In most of the simulation studies examining resting options, the initial percentage of perennial grasses was set at 20% of pasture biomass to represent poor or C condition (see Table 1). With this starting point, the maintenance stocking rate was 14.5 AE 100 ha^{-1}. As pasture productivity is related to the percentage of perennial grasses and stocking rates depend on pasture production, a different maintenance stocking rate will apply when the starting percentage of perennial grasses differs from 20%. For example, a pasture with 50% of perennial grasses on this land type would have a maintenance stocking rate of 20 AE 100 ha^{-1} when modelled over the same 10 climate windows.

Stocking rate definitions

The studies use fixed stocking rates from year to year, except when a pasture rest is scheduled; where necessary for clarity, this is referred to as the initial stocking rate. To take into account varying lengths and frequencies of pasture rest periods, we use the term adjusted stocking rate to refer to the mean stocking rate over the simulation period. When pastures are rested, there is effectively a reduced stocking rate. A pasture with a fixed stocking rate for 3 years and given a 6-month rest in the fourth year has 12.5% fewer grazing days than a pasture continuously grazed throughout the entire period. This can be accounted for by converting the number of grazing days in the rested pastures over the rest-graze cycle to an adjusted stocking rate value, e.g. for a pasture rested for 6 months every 4 years and then grazed at 10 AE 100 ha^{-1} for the other 42 months of the cycle over 10 cycles, there would be 10 * (183 + 365 + 365 + 365) = 12 780 grazing days per 100 ha over the cycle. The equivalent stocking rate on a pasture grazed continuously for 48 months is 8.75 AE 100 ha^{-1} [12 780/(365 + 365 + 365 + 365)]. In this case, the adjusted stocking rate would be 8.75 AE 100 ha^{-1}. When no resting is simulated, the adjusted stocking rate is the same as the initial stocking rate.

Response to pasture rest

Percentage of perennial grasses is used as the indicator of pasture condition in GRASP and varies between a maximum of 90% and a minimum of 1% (see Table 1 and Appendix 1). Although the percentage of perennial grasses is only one aspect of land condition, it provides a simple and easy-to-understand measure and the proportion is widely known to decrease as condition declines (McIvor and Orr 1991; Tothill and Gillies 1992; O'Reagain *et al*. 2009; Ash *et al*. 2011) and to increase as condition improves (McIvor 2001; Orr *et al*. 2006). We defined the response to pasture rest as the difference in the percentage of perennial grasses in pastures that were rested compared to the proportion in pastures without any rest periods.

When a pasture is already in very good condition (say 85% of perennial grasses), then there is little scope for improvement by resting – in this case a maximum of 5% improvement (given that the maximum percentage of perennial grasses is 90% in GRASP). If the initial percentage of perennial grasses is only 20%, then there is potential for an improvement of 70% in the percentage of perennial grasses.

The potential response to rest is defined as the difference between the percentage of perennial grasses in a continuously grazed pasture and 90%. Thus, there is a low potential response if pastures are in good condition with perennial grasses already making up a high percentage in the pasture. The nominal response to rest is the comparison of a rested pasture and a pasture continuously grazed at the same stocking rate, e.g. a rested pasture grazed at 10 AE 100 ha^{-1} during the non-rest period and a pasture continuously grazed at 10 AE 100 ha^{-1}. The actual response is the difference between the percentage of perennial grasses in rested and continuously grazed pastures when compared at the same adjusted stocking rate.

Stocking rate simulations

To examine the impact of stocking rate on the percentage of perennial grasses, we did simulations for each climate window using stocking rates ranging from 3 AE 100 ha^{-1} to 30 AE 100 ha^{-1}. The values of the percentages of perennial grasses for each stocking rate for different climate windows were then averaged. These simulations were repeated using a 6-month rest (starting 1 December) every 4 years. Again, the percentage of perennial grasses for different climate windows was averaged. For some cases, we report only the results of 1982–2011 where we are interested in the change through the simulation period rather than the mean for the whole simulation period. Results were plotted against both the initial and adjusted stocking rates. The initial percentage of perennial grasses was 20%.

Timing of pasture resting

All wet-season pasture resting commenced on 1 December. In one series of simulations, resting in winter was simulated and, in this case, resting commenced at the beginning of June and ended at the start of December. The wet-season rest was from the beginning of December to the beginning of June. Resting was once in 4 years.

Duration and frequency of rest

Pasture rest was simulated for 1–11 months with frequencies from annual to once in 5 years. The duration and frequency of rest were used to calculate the proportion of time that the pasture was rested. As an example, a proportion of rest of 0.25 can be achieved by a 6-month rest every 2 years or a 3-month rest every year. Again, all rest periods commenced on 1 December.

Initial land condition

To examine the effect of initial condition on the improvement due to pasture resting, we started simulations in all states, representing from 1% to 90% of perennial grasses (Table 1). The pasture rest was for 6 months, starting in December with a range of frequencies from annual to once in 5 years at a stocking rate of 14.5 AE 100 ha^{-1}. These results are presented as the mean percentage of perennial grasses compared with the starting percentage of perennial grasses as well as the change during the simulation period.

Growing seasons

To examine the influence of rainfall conditions over the entire simulation period, we selected sequences of years when annual rainfall was above average, near average and below average. There were three sequences for each category with some overlap between sequences – non-overlapping sequences could not be selected as the 120-year climate sequence is not long enough. For each of the climate windows, we ran simulations with a wide range of rest periods, from a low of a 2-month rest every 4 years to a maximum of a 6-month rest every 2 years.

Results

Importance of correct stocking rate in association with pasture rest

Literature

Many studies show that land condition deteriorates (loss of perennial grasses and reduced basal area, increase in weeds, low cover and more bare ground, increased run-off and soil loss) as stocking rate increases (McIvor and Orr 1991; Tothill and Gillies 1992; O'Reagain *et al*. 2009; Orr *et al*. 2010; Ash *et al*. 2011). All the above studies used continuous grazing and we are aware of only one study where the effects of both pasture resting and stocking rate or utilisation rate were investigated. In the ECOGRAZE experiment conducted at three sites near Charters Towers in north Queensland, the response to 8 weeks' rest at the start of each growing season was compared to no rest for plots grazed to utilise 25, 50 or 75% of the annual pasture growth (Ash *et al*. 2011). The comparisons were made on plots in two initial land condition states – plots in State I were dominated by 3P grasses, such as black spear grass [*Heteropogon contortus* (L.) P.Beauv. ex Roem. and Schult.], desert blue grass (*Bothriochloa ewartiana*) and Queensland blue grass [*Dichanthium sericeum* (R. Br.) A. Camus]; plots in State II had some 3P grasses but greater quantities of less desirable perennial grasses [e.g. wire grasses (*Aristida* spp.)], annual grasses and forbs (see Table 1 for the relationship between these states and other pasture condition terms). The study showed that a pasture utilisation level of 25% with no rest or a pasture utilisation level of 50% with rest enabled land condition to be maintained where the land was initially in good condition, and restored condition when land was in poor initial condition. With 75% utilisation, land condition declined (good initial condition) or remained poor (poor initial condition) despite receiving a rest period.

Modelling

To expand on the ECOGRAZE study, we simulated the pasture response to resting across a wide range of stocking rates in the Reid River box land type in a similar environment. One of the obvious aspects of pasture resting is that the number of livestock carried over a resting cycle is lower than if a continuous grazing system was used. In Fig. 1*a*, there is a large nominal improvement in the percentage of perennial grasses due to wet-season resting. However, this is in part due to the stocking rate for the pasture-resting situation being less (12.5% lower) than for the fixed stocking rate situation. When this difference in stocking rate is taken into account by using the adjusted stocking rate (Fig. 1*b*), the actual advantage of pasture resting is reduced, though it is still

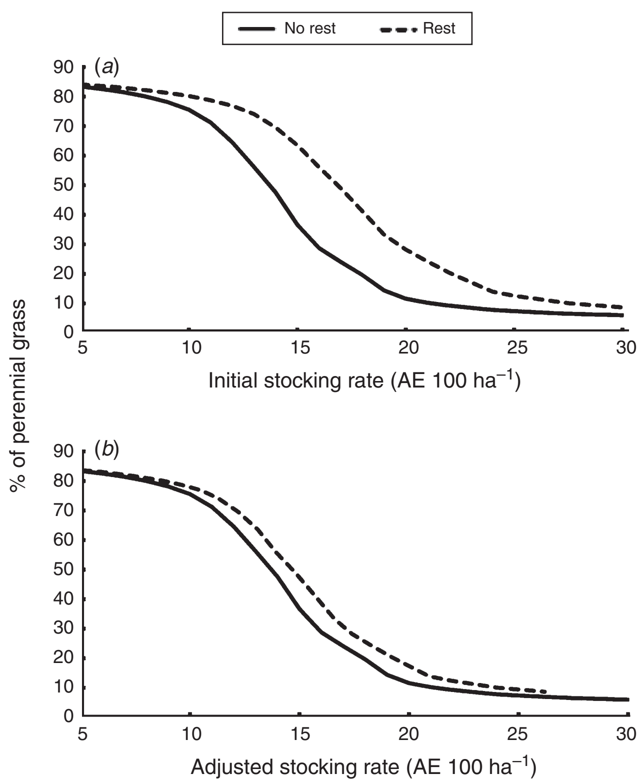

Fig. 1. The percentage of perennial grasses under a range of fixed stocking rates, with and without pasture resting for 6 months in wet season, once every 4 years. (*a*) Perennial grasses plotted against the stocking rate during the non-rest period, (*b*) perennial grasses plotted against the adjusted stocking rate.

evident. The maximum benefit from wet-season resting occurred when pastures were stocked neither heavily (>25 AE 100 ha^{-1}) nor lightly (<10 AE 100 ha^{-1}).

The response of pastures in poor condition that are rested for 6 months every 4 years depends on the stocking rate during the non-rest period (Fig. 2). Condition declined further at the highest stocking rate, was maintained at the second highest stocking rate, and improved at the lower stocking rates. When the stocking rate is high (20 AE 100 ha^{-1}), any benefits from pasture resting cannot counteract the negative effects of the excessive stocking rate. If stocking rate is very low (8 AE 100 ha^{-1}), then there is rapid improvement in land condition in rested pasture. However, at the lower stocking rates there is also improvement in non-rested areas (data not shown), though the rate of recovery is more rapid in the rested pasture.

The potential response to rest shows that there is little to be gained from resting at low stocking rates (as the pastures recover under continuous gazing at these levels); the potential response increases as stocking rate increases (Fig. 3). The greatest nominal response to resting was at intermediate stocking rates of 10–15 AE 100 ha^{-1}. At higher stocking rates, resting did not improve condition and both rested and non-rested pastures had low percentages of perennial grasses. At low stocking rates, the percentages of perennial grasses increased irrespective of whether or not the pastures were rested.

The highest actual response to resting was at 13 AE 100 ha^{-1} where there was an average improvement in the percentage of perennial grasses of 8% (Fig. 3) when the rested pastures and continuously pastures were compared at the same stocking rate (the adjusted stocking rate). This actual benefit is much less than the nominal benefit of nearly 25% as the latter includes an effect of lowering the overall stocking rate in addition to the pasture rest; the actual benefit of resting is greatest at intermediate stocking rates and the actual values are always greater than zero.

Season of rest

Literature

Tropical and subtropical perennial grasses are most sensitive to defoliation early in the growing season (Smith 1960; Norman 1965; Tainton *et al*. 1977; Mott 1987; Ash and McIvor 1998) and rest at this time of the year could be expected to give greater responses than rest at other times. Several studies at sites in south, central and north Queensland have shown that pastures rested during the early growing season had higher yields and percentages of perennial grasses than similar pastures that were grazed during this time (Paton and Rickert 1989; Orr *et al*. 1991; Orr and Paton 1997; Paton 2004; Ash *et al*. 2011). There have been few studies comparing resting at different times of the year. In a multi-site comparison in Queensland, Orr *et al*. (2006) found the only substantial improvement occurred with rest during the growing season; there was little or no improvement with rest at other times. However, a comparison of wet-season versus dry-season resting in the Kimberley region of Western Australia found little difference between the two treatments (Hacker and Tunbridge 1991).

The experimental results support resting during the growing season, particularly during the early growing season when grasses are most susceptible to defoliation. Although rest during the dry or non-growing season may have little direct impact on the growth of grasses, it can have benefits by: increasing cover levels by avoiding consumption of herbage; preventing the repeated grazing of regrowing shoots if there are small falls of rain sufficient to initiate some growth but not enough to start the growing season; and preventing the removal of aerial buds so that more growing points are available at the start of the following growing season.

Modelling

To assess the relative benefits of wet-season and dry-season resting over a wider range of climate conditions than covered in the field studies, we simulated the response to a 6-month pasture rest every 4 years for all 10 climate windows.

In general, the response to pasture rest simulated by GRASP arises due to increased growth during the rest period and the improved pasture condition. In the absence of grazing, a larger photosynthetically active leaf area is produced, which gives rise to increased growth. In the period following resting, percentage of perennial grasses increases, leading to further increased growth. Under the same environmental conditions, the modelled growth

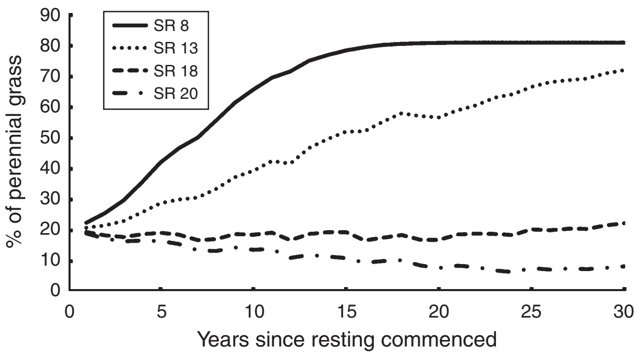

Fig. 2. Changes over 30 years (1982–2011) in the percentage of perennial grasses in pastures initially in poor condition (20% of perennial grasses) that were rested for 6 months every 4 years and grazed at four different fixed stocking rates (8, 13, 18 and 20 AE 100 ha^{-1}) during the non-rest periods.

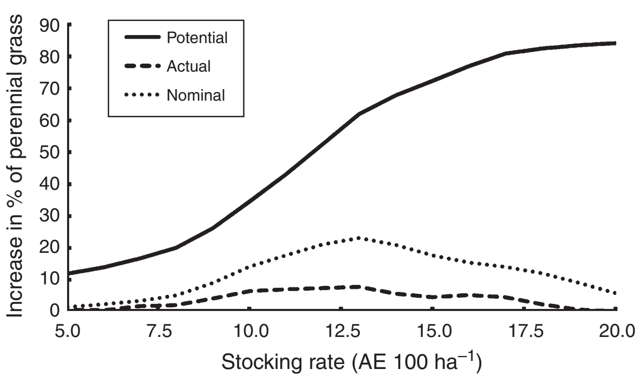

Fig. 3. The effect of stocking rate during the non-rest period on the increase in the percentage of perennial grasses in rested pastures compared to that in continuously grazed pastures during the 1982–2011 simulation period. Note: for potential and nominal responses the stocking rate is the stocking rate during non-rest periods, whereas for actual responses, the stocking rate is the adjusted stocking rate, which takes into account the period of rest.

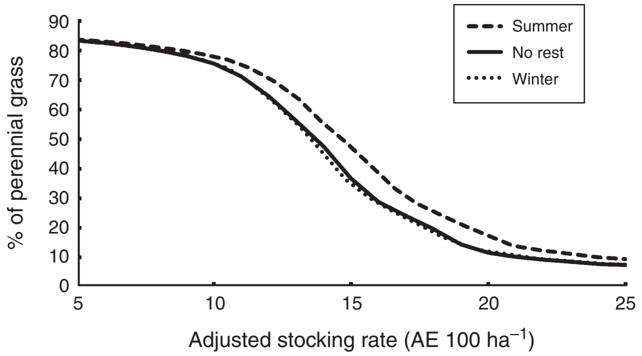

Fig. 4. Comparison of wet-season and dry-season pasture resting showing the percentage of perennial grasses in pastures in relation to adjusted stocking rate (rests were for 6 months once in 4 years starting in December and June for wet-season and dry-season rests, respectively).

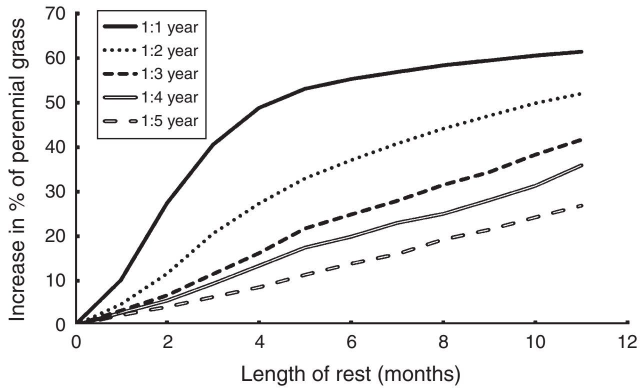

Fig. 5. The effect of duration (0–11 months) and frequency (once every 1, 2, 3, 4 or 5 years) of rest periods on the response of percentage of perennial grasses to resting. Note that all pasture rests, irrespective of length, commenced on 1 December and the stocking rate was 14.5 AE 100 ha^{-1} during the non-rest period.

from a pasture will be higher when the pasture has a higher percentage of perennial grasses. Resting during the dry season will not generally increase growth during the rest period as soil water is generally limiting and, therefore, the percentage of perennial grasses does not increase (Fig. 4). There is little difference between continuously grazed pastures and pastures rested in winter, but an increase in the percentage of perennial grasses does occur when pastures are rested during the wet season.

A notable feature of this result is that the same percentage of perennial grasses can be achieved at a higher adjusted stocking rate when pastures are rested than when the pasture is continuously grazed. For example, a pasture with 50% of perennial grasses will result from continuous grazing at 13.8 AE 100 ha^{-1} whereas the same percentage of perennial grasses will result from a pasture rest system where the adjusted stocking rate is 14.8 AE 100 ha^{-1} (interpolated from Fig. 4).

Duration and frequency of rest periods

Literature

Most studies have compared rest with no rest rather than different durations of rest. An exception is the study of Orr and Paton (1997) in south-east Queensland where plots were rested annually for 0, 2, 4 or 6 months after an annual burn during spring for 5 years. The yield of the desirable black spear grass was higher with rests of 4 and 6 months than with 0 or 2 months. In the final year, the basal area of black spear grass was higher in plots with 6 months' rest compared with those with no rest, but the total basal area, including all grass species, was the same. Although the evidence is limited, we suggest pastures should be rested for the whole of the growing season rather than only for a short period at the start of the growing period. The rest for a full growing season has the following advantages: it is a longer period so the probability of having some good growing conditions during the rest are increased; it provides rest during the early growing season when grasses are sensitive to grazing and also later when they are setting seed and accumulating reserves; it allows new seedlings to establish, grow and set seed, and existing plants to expand; it covers a range of flowering times; and cattle do not need to be moved during the growing or wet season when the logistics of doing so can be difficult. Despite the biological benefits being greater with longer rest periods, the duration of the rest period must balance the benefit to the pasture with the loss of grazing during the rest period. The loss of grazing during the rest period reduces the number of animals that can be carried through the entire year. An additional impact of resting is a reduction in the nutritive value of the forage (digestibility and crude protein concentration) as a greater proportion of the pasture is able to mature before being available for grazing.

Modelling

There are no experiments in northern Australia dealing explicitly with comparisons of frequency of rest periods. To partially address this, we simulated a wide range of lengths and frequencies of rests to quantify the impacts of these on the percentage of perennial grasses in rested pasture. Resting for periods of 1–11 months and at frequencies from every year to once in 5 years was modelled in a factorial combination. Figure 5 shows the increase in perennial grasses in relation to length and frequency of rest periods. The percentage of perennial grasses increased with both longer and more frequent rests.

An annual rest of 4 months produced an increase of 50% in perennial grasses (from ~20% to ~70% of the pasture). When the rest occurred every second year, the increase was ~30%, and when the rest occurred only every 5 years, the increase was less than 10% over the simulation period.

An annual rest of 4 months gave about the same increase in the percentage of perennial grasses as a 10-month rest every second year. However, these responses all essentially represent different proportions of the year during which the pasture is rested. The duration and frequency of resting can be combined into a single value expressed as the mean proportion of time during which resting occurs. When this is done (Fig. 6), there is a linear increase up to ~33% (equivalent to a 4-month rest annually or 12-month rest every third year), after which there was little further increase. Modelling suggests that it is the total length of time a pasture is rested that drives the increase in the percentage of perennial grasses rather than any particular duration or frequency (for situations where all resting commences on 1 December). This is a response derived from the model rather than a relationship

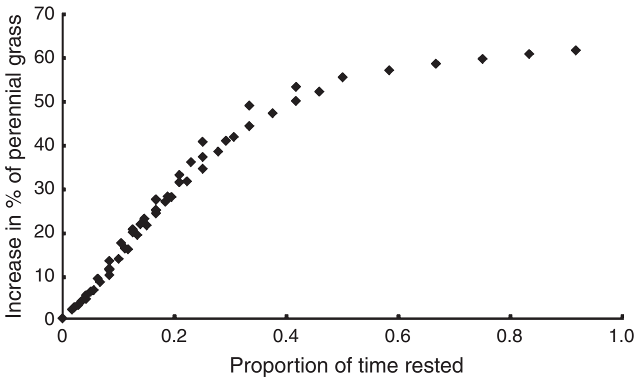

Fig. 6. The increase in percentage of perennial grasses in pastures rested for different average proportions of the 30-year simulation period (compared with pasture continuously grazed at 14.5 AE 100 ha^{-1}). Different combinations of duration and frequency of rest periods give rise to the same or similar proportions of rest.

built into the model. The key relationship within GRASP is that 75% of the impact of grazing during the year occurs during the 6 months from October to March (Appendix 2, Fig. *a*). A result of this is that resting solely during the non-growing winter period appears to have little benefit (Fig. 4). Combinations that include a low frequency of long rest periods where a substantial part of the rest period occurs during the non-growing season produce a lower response than when the resting occurs during the growing season – this is the reason for the lower values for the range of 0.2–0.4 rest in Fig. 6.

An associated question is what is the impact of a one-off heavy utilisation? The change in percentage of perennial grasses depends on the condition of the pasture at the time of a heavy utilisation as well as the level of that utilisation. In this version of GRASP, the maximum change in pasture condition state for the box land type was set to 0.75. If the pasture is in very good condition, a single heavy utilisation may result in a decline in perennial grasses of only a few per cent; if the pasture is in very poor condition, the decline again may only be a few per cent – see the changes in Appendix 2, Fig. *c* for State 1 and State 10, respectively, when the state (on *x*-axis) increases by 0.75 units. By comparison, a change of 0.75 along the *x*-axis will produce a decline of almost 15% in perennial grasses if the initial state is State 4, which has 50% of perennial grasses.

Impact of initial land condition

Literature

The condition of pasture at the time of rest will have an influence on some aspects of the response to that rest, e.g. pastures with a higher percentage of perennial grasses will be more productive and can carry more livestock. The ECOGRAZE study is the only experiment to explicitly study the effect of initial land condition on response to pasture rest (Ash *et al*. 2011) but the comparison is of little use to this question as one of the two states was a good initial condition pasture that had little scope for improvement.

There are several experiments where exclosures were used to exclude grazing for varying periods that provide useful information although they are not specific studies of pasture resting (McIvor 2010). All the exclosure studies had no grazing at any time during the year and hence are not the same as a pasture-resting system with alternating periods of grazing and rest. Care is needed when extrapolating such results to frequency of rest periods as modelling reported in an earlier section showed that grazing during the inter-rest periods can have significant effects depending on the stocking rate (e.g. Fig. 2). Two sites (Hillgrove near Charter Towers and Kerale near Collinsville) in north Queensland where pastures in a range of initial conditions were exclosed for 1 (Kerale) or 3 years (Hillgrove) with good growing conditions provide some relevant information. Using the ABCD condition classification (Quirk and McIvor 2003), four of the eight plots at Hillgrove (McIvor 2001, 2010) initially in B condition recovered to A condition after 1 year and the other four after 2 years of rest. For the two plots initially in C condition, one plot recovered to A condition after 2 years, and the other plot after 3 years of rest. All four plots initially in D condition remained in D condition. At Kerale where the plots were exclosed for 1 year only (McIvor and Gardener 1990; McIvor 2010), all three plots initially in B condition recovered to A condition; for the plots initially in C condition, three plots recovered to B condition, and three plots remained in C condition. All six plots initially in D condition remained in D condition. At both these sites with good growing conditions, it took longer for the plots to recover condition and/or the amount of recovery during any period was less when the initial condition was poorer.

Recovery under grazing can be very slow, especially in degraded and low productivity rangelands (Bartley *et al*. 2014). In this study in north Queensland, reduced stocking rate and rotational wet-season resting led to ground cover increasing from ~35% to ~80% over a 10-year period. Most of that increase was due to the stoloniferous *Bothriochloa pertusa* (L): deep-rooted perennial grasses increased from ~7% to ~15% of pasture composition over the same period. They conclude that more than 10 years is needed to restore healthy eco-hydrological function to pastures in poor condition.

Modelling

From the available field studies, we can tentatively conclude that, as land condition declines, pasture rests need to be more frequent or for a longer period if land condition is to be improved for a given sequence of seasonal conditions. To examine both the rate and magnitude of recovery for a wide range of initial land condition, we simulated a range of frequencies of resting for a range of initial percentages of perennial grasses in the pasture.

At a stocking rate of 14.5 AE 100 ha^{-1}, there was little actual response to pasture rest where the initial land condition that was either good (70% of perennial grasses) or poor (5% of perennial grasses). For good initial condition, the percentage of perennial grasses increased in both rested and non-rested pasture and was at the maximum of 90% by the end of the 30-year simulation period. When the initial percentage of perennial grasses was low, there was only a very small increase in percentage of perennial grasses as both rested and continuously grazed pastures had less than 5% of perennial grasses by the end of the 30 years. The biggest response was for pastures in intermediate condition – see the line of 32% of perennial grasses in Fig. 7. For this starting condition, rested pasture showed an increase in the percentage of

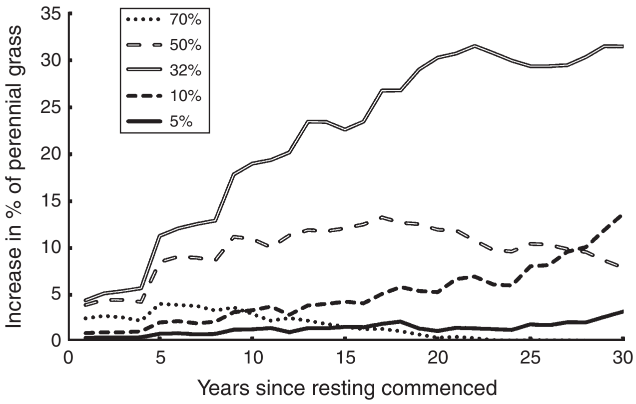

Fig. 7. The increase in percentage of perennial grasses over the 30-year simulation period for rested pasture compared with continuously grazed pasture. Simulations were for initial pasture composition ranging from 5% of perennial grasses to 70% of perennial grasses with rests being for 6 months every 4 years and grazed at 14.5 AE 100 ha^{-1} during the non-rest period. Note the rapid increase in percentage of perennial grasses every 4 years in some treatments is the response to the pasture rest in the preceding wet season.

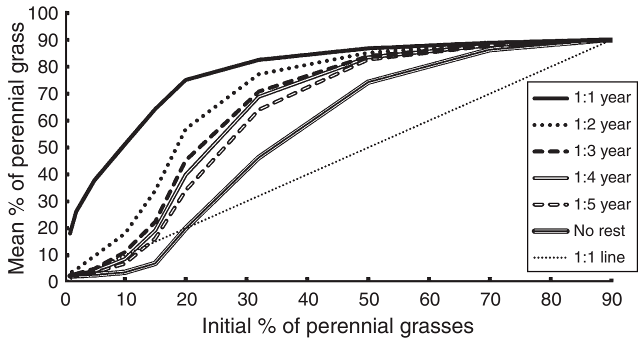

Fig. 8. The influence of initial percentage of perennial grasses and frequency of 6-month rest in the wet season on the percentage of perennial grasses in rested pasture compared with no rest when grazed at 14.5 AE 100 ha^{-1} during the non-rest period.

perennial grasses whereas the continuously grazed pasture showed little change (data not shown).

Figure 8 shows the impact of different frequencies of rest in relation to initial percentage of perennial grasses. Where the initial percentage of perennial grasses was above 20%, there was an increase with no rest but where the initial percentage of perennial grasses was below 20%, there was a decrease in the percentage of perennial grasses with no rest. With rest, the percentage of perennial grasses increased and the more frequent the rest, the greater the response but where the initial percentage of perennial grasses was less than 20%, the percentage of perennial grasses did not reach the maximum values even with resting every year for 30 years. Part of the reason for this pattern is that frequent rests effectively give rise to a lower overall stocking rate, when the same stocking rate is used for all grazing in the non-rest period.

Impact of growing conditions

Literature

Pasture recovery with rest is limited if growing conditions are poor (Orr *et al*. 2006; O'Reagain *et al*. 2007). In the ECOGRAZE study, there were some increases in the perennial grasses with resting during the early years under drought conditions at two of the three sites but there were much larger increases in later years when rainfall was higher (Ash *et al*. 2011). In Mitchell grass pastures at Blackall and Toorak in western Queensland, effects of exclosure were small and the growth of *Astrebla lappacea* (Lindl.) was mainly dependent on the wet-season growing conditions (Orr 1980; Orr and Evenson 1991; Orr and Phelps 2013).

Modelling

The field studies recorded responses under the prevailing climate conditions of the study period. Simulation analyses enabled us to examine responses under a wider variety of climatic conditions.

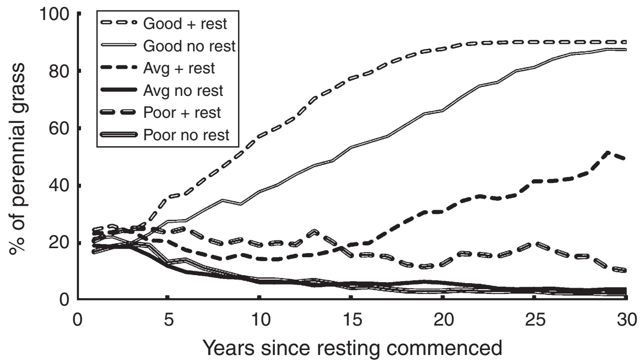

Fig. 9. The influence of growing conditions and pasture resting on the changes in the percentage of perennial grasses in pastures. Growing conditions are defined by rainfall as good, average and poor. The resting regime was a 6-month rest every 4 years and the stocking rate was 14.5 AE 100 ha^{-1} during the non-rest period.

When rainfall during the 30-year simulation period was above average, the percentage of perennial grasses increased in both the rested and the continuously grazed pastures (Fig. 9) when grazed at the maintenance stocking rate. The rested pasture approached the maximum of 90% perennial grass ~10 years earlier than the continuously grazed pasture. When rainfall was below average, the percentage of perennial grasses declined in both rested and continuously grazed pastures although the rested pastures always had slightly higher percentages of perennial grasses (Fig. 9). Under intermediate rainfall conditions, resting led to an increase in the percentage of perennial grasses compared to a decline in the continuously grazed pastures.

In poor and intermediate seasons, there was considerable potential improvement as grazing at a fixed stocking rate of 14.5 AE 100 ha^{-1} simulated a pasture with very low percentage of perennial grasses (Fig. 10). Small amounts of rest for poor condition pastures under poor seasonal conditions did not result in marked improvements but, when the proportion of time the pasture was rested exceeded 0.125, the responses increased rapidly; this is equivalent to a 6-month rest at a frequency of once in 4 years. The reason for this is that once the rest exceeded 0.125,

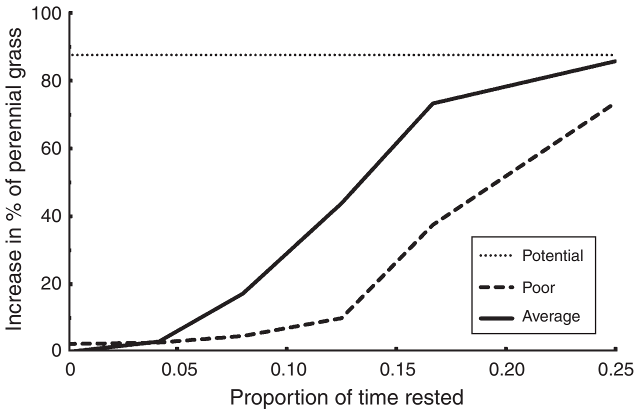

Fig. 10. Increase in percentage of perennial grasses as influenced by the proportion of the 30-year simulation period that a pasture was rested under poor and average growing conditions when stocked at 14.5 AE 100 ha^{-1} during non-rested periods.

the utilisation rate was lower than the safe utilisation rate (30% in this case) and this allowed increases in the percentage of perennial grasses. A similar pattern existed for intermediate conditions although a substantial increase was observed once the proportion of rest increased above 0.08. Longer or more frequent resting regimes (or lower stocking rates) are needed to increase the percentage of perennial grasses in poor seasons than in intermediate or average conditions in our simulations.

Discussion

The combination of synthesis of experimental results and simulation modelling used in this study strengthens existing guidelines on how resting can be used to improve land condition. The synthesis of experimental results provides the knowledge base but, because resources limit the size (number of treatments, locations, vegetation types, soil types and initial land condition) and duration of experiments, this knowledge base will always be limited. Despite the years of rangeland research in northern Australia, relatively little is known from field experiments about pasture resting; what is known is almost entirely from Queensland with little from Western Australia and the Northern Territory. However, representing the knowledge that we do have in models, enables a wider range of treatments, durations and seasonal conditions to be examined, and builds upon the empirical studies. As the prospects for major field work to fill knowledge gaps are limited, there is a need to use modelling to developed guidelines/hypotheses in relation to pasture resting.

Both the experimental results (Ash *et al.* 2011) and the modelling show the importance of stocking rate during non-rest periods to any pasture-resting regime. If the stocking or utilisation rate is too high, then rest will be ineffective in preventing further pasture deterioration for pastures already in poor condition. Conversely, at low stocking rates, grazing pressure over the year may be well below the safe utilisation rate on both continuously grazed and rested pastures and hence there would be relatively small differences in the increase in the percentage of perennial grasses in the pasture. However, pasture resting will generally lead to a more rapid improvement in land condition. When trying to recover C condition pastures with 20% of perennial grasses, adjusting (usually lowering) stocking rate to match pasture growth is a first, pre-requisite step. Resting will then be effective and lead to more rapid recovery than if the stocking rate exceeded the sustainable level. If stocking rates are left high in degraded paddocks, resting will not promote recovery – at best it may slow the rate of deterioration.

The ECOGRAZE study near Charter Towers (Ash *et al.* 2011) found that, when pastures were rested, the utilisation rate during the time between rest periods could be increased to 50% compared to the 25% utilisation that could be sustained with continuous grazing. However, in that study the livestock from the rested paddocks were not grazed on the other paddocks during the rest period but were grazed on non-experimental pastures. The current modelling suggests that rest can enable a small increase during the remainder of the year while achieving the same composition of perennial grasses but the increase is modest (see Fig. 4); further work is required on this aspect where the livestock from rested pastures are redistributed across the remainder of the property, increasing the short-term stocking rate on those areas during the active growing period when most damage can be done to the pasture. Some potential problems with implementing pasture resting where cattle from rested paddocks are spread across the grazed paddocks are identified in Fig. 4 in Scanlan *et al.* (2011). That study showed that a rigidly applied resting regime could actually lead to further deterioration of at least one of the four paddocks in a four-paddock system where each paddock received one 6-month rest over the wet season during the cycle. The implementation of a resting regime will need to take this possibility into account.

The present study has concentrated on land in C condition, which can be recovered by management and shows resting has a role. Land in D condition (with significant surface soil degradation and a very low percentage of perennial grasses) is a different situation and it is unlikely that resting will lead to rapid or even moderate recovery rates. Overgrazing often results in changes in soil, vegetation and landscape patterning (Friedel *et al.* 2003; Sparrow *et al.* 2003; Tongway *et al.* 2003) that are not easily reversed, especially in the short to medium term. Changes in resource patterning can result in a net loss of water and nutrients from the system (Sparrow *et al.* 2003), with resulting declines in landscape productivity. Land can degrade rapidly but complete recovery, where top soil has been lost, is often very slow. As the rate of soil formation is low [e.g. Edwards and Zierholz (2001) suggest rates ranging from 0.5 to 1 t ha^{-1} $year^{-1}$ in Australia], centuries may be required for soil to be reformed. These degraded systems also have depleted seed banks (Kinloch and Friedel 2005*a*), and a lack of safe sites for plant establishment (Kinloch and Friedel 2005*b*). Severely degraded (D condition) country often requires mechanical intervention such as pondage banks to stabilise severely eroded landscapes to control water flow (Bastin *et al.* 2001) before recovery processes can start. Open woodland country on Woodgreen Station in the Northern Territory in D condition took 50 years to recover, with the first 25 years destocked and the next 25 years with light stocking and regular resting (Bastin *et al.* 2001). Similar results have been reported from Western Australia in the Ord River catchment (Payne *et al.* 2004) where a combination of fencing, reduced stocking rates and mechanical rehabilitation restored degraded areas. Studies in north Queensland indicate that more than

10 years are required to restore healthy eco-hydrological function to a site that had considerable loss of top soil (Bartley *et al*. 2010, Bartley *et al*. 2014). During their 10-year study, deep-rooted perennial grasses increased from 7% to only 15%, despite several wet-season rests. This is consistent with our modelling results and highlights that for pastures in very poor initial condition, frequent pasture rests for long periods are required to get large increases in the percentage of perennial grasses; in fact in the modelling, pastures with this low initial percentage of perennial grasses and grazed at 14.5 AE 100 ha^{-1} had still not recovered after 30 years even with resting every year.

Although results have varied between experiments, we can be reasonably confident that rest during the wet season will give a greater response than rest during the dry season and that longer rests will give a greater response than shorter rests. There are no experiments in northern Australia that have studied frequency of rest. This remains a knowledge gap although a present study in north Queensland (Jones *et al*. 2012) will provide important information on this topic for pastures where *Bothriochloa ewartiana* is the most important perennial grass. In the meantime, the modelling suggests that it is the combination of duration and frequency of rest that is important, with the response being largely determined by the proportion of time during the rest-graze cycle that the pasture is rested.

Pasture rest during the growing season may play a role in recovery after drought or other periods of pasture deterioration. In the period of growth immediately after the breaking of a drought, high grazing pressure on the new growth can lead to further pasture deterioration. There are likely to be fewer benefits from resting pasture during the dormant phase (winter) although destocking during drought is still beneficial as post-drought recovery will be more rapid if pastures are not immediately exposed to grazing.

One-off events can have a considerable impact on the health of a pasture. A relevant example comes from the Wambiana grazing experiment where a fire followed by a poor growing season necessitated pasture resting during the wet season for three consecutive years to encourage pasture recovery (O'Reagain *et al*. 2009). Such combinations of events can be modelled within GRASP but there is not sufficient ecological understanding to capture the complete impacts of such events at present. At the extremes of complete removal of all pasture by grazing and complete rest for the whole growing season, the maximum possible simulated change in the percentage of perennial grasses is ~15% if the pasture initially had ~50% of perennial grasses. It is likely that greater changes than this could be observed in the field and further study on this aspect would improve our capability to model such changes.

The modelling assumes all parts of the area being modelled respond the same, i.e. the paddock or the land type within the paddock is uniform. In reality, paddocks are mosaics of land types, condition and grazing pressure. It is hard to accurately model what is happening under these circumstances. Generally, the responses will be 'more buffered' under such circumstances i.e. changes (either up or down) will be harder to make and slower to occur. Whether A condition is reachable for a whole paddock that was previously degraded is an open question. It is more likely that paddocks may become 'stabilised' with a mix of C, B and A condition patches. Pastures in higher condition will have a greater proportion of the area in A and B condition. At the landscape level, Bartley *et al*. (2014) reported marked differences between the rate of increase of grass cover on upper slopes and lower slopes which supported different vegetation types on different soil types.

A recent paper by Hunt *et al*. (2014) presented a set of principles and guidelines for managing grazing land in northern Australia, including the use of pasture rest. Our results are generally consistent with their principles and guidelines – rest during the growing season is superior to rest during the dry season, longer rests are more effective than short rests, and as the initial pasture condition declines longer rest periods are needed to improve condition. However, Hunt *et al*. (2014) may have been overly optimistic about rates of recovery of land in C condition – they suggested such land would need resting for four good growing seasons to recover to A condition but our modelling results suggest such recovery may take longer.

Another feature of the results presented in this paper is that few rapid or abrupt changes are presented. At least in part, this is due to the averaging of results over 10 different climate windows; results in any one of those windows can be quite dynamic. Another factor is that all rests commenced on 1 December, irrespective of seasonal conditions and this may tend to dampen responses compared with what could be achieved if rest was commenced under good growing conditions. Finally, the change in percentage of perennial grasses in the pasture is essentially a continuous function (Appendix 2, Fig. *c*) whereas McIvor and Scanlan (1994) suggested that four distinct pasture condition states exist and suggested possible factors involved in the transitions between these states. We do not have a full understanding of the complexities involved in all of these transitions despite the northern spear grass region being well studied by comparison with some other regions such as the *Aristida-Bothriochloa* region [see Weston *et al*. (1981) for detailed descriptions of these]. The work of Watson and Novelly (2012) is one of the few studies that have attempted to assess when sites have crossed a threshold to a different vegetation state.

This modelling study used the box land type at Wambiana (near Charters Towers, Queensland). This is the first land type for which the rates of recovery and degradation (as defined following recent changes to the GRASP model) have been derived from experimental data (Scanlan *et al*. 2013). Future research needs to include an improved understanding of how rates of recovery and degradation might vary between land types and regions.

There are still gaps in field experiments looking at aspects of timing and frequency of pasture resting. The work of Jones *et al*. (2012) addresses this in part. Information from that work could lead to refinements of the GRASP model or at least to better parameterisation of the model for two land types in north Queensland. Desirable model enhancements include combining flexible stocking rates with pasture resting. Recently, Pahl *et al*. (2013) simulated the biological responses of some flexibility in stocking rate, and MacLeod *et al*. (2013) have shown the potential economic benefits of such a strategy. Pasture resting could reinforce the benefits of flexible stocking rates and these may combine to achieve a more rapid recovery than either alone. The potential responses to pasture resting at the paddock level should be extended to a whole property level to examine the likely economic impacts of pasture resting.

Acknowledgements

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Appendix 1. Modifications to the GRASP model to simulate pasture resting

The major modification involved weighting the impact of utilisation depending on the month in which that utilisation occurred (Appendix 2, Fig. *a*). At one extreme, the impact of grazing in each month is equal (as may be the case in a seasonal locations) and at the other extreme, 100% of the impact occurs during the wet season of northern Australia. For simulations in the present study, 75% of the grazing impact occurred during the 6-month wet season.

Utilisation is used to estimate the change in pasture condition state (Appendix 2, Fig. *b*). There are several critical parameters: the magnitude of change at 0% and 100% utilisation; the utilisation rate at which there is no change in condition (the safe utilisation rate where the line crosses the *x*-axis); and variation in the rate of change in pasture condition (small change when the utilisation rate is close to the safe utilisation rate, and larger change when utilisation rates are considerably lower or higher than the safe utilisation rate). This differs from the original GRASP model in which there was no change of state within safe utilisation level ± 10%, and a fixed change of 1 (or a larger integer) above or below these thresholds, irrespective of the actual utilisation rate.

In the original GRASP model, pasture condition state was represented as an integer value from 0 (excellent condition) to 11 (very poor condition) (Fig. 1 in McKeon *et al*. 2000). In the modified model, state can be represented by any real value between 0 and 11 and the relationship between state and percentage perennial grasses is shown in Appendix 2, Fig. *c*. In an ungrazed pasture (0% utilisation), the state can decrease (i.e. pasture condition can improve) by a specified maximum; at 100% utilisation the state can increase (i.e. pasture condition can degrade) by a specified maximum as shown in Appendix 2, Fig. *b*. State does not change when utilisation is at the specified safe level (30% in Appendix 2, Fig. *b*). Within ± 10% of the safe utilisation rate, the rate of change is generally lower than outside this range.

Percentage of perennial grasses varies between a maximum of 90% and a minimum of 1% in the model. Although some land types may not have 90% of perennial grasses even when in excellent condition, in this representation of condition, pasture in its maximum possible condition will be represented as 90% of perennial grasses.

Appendix 2. Fig. Elements in the calculation of the percentage of perennial grasses within the GRASP model: (*a*) weighting applied to utilisation per month, (*b*) change in pasture condition state as a function of utilisation percentage where the safe utilisation rate is 30%, and (*c*) percentage of perennial grasses as a function of pasture condition state