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Review

Principles and guidelines for managing cattle grazing in the grazing lands of northern Australia: stocking rates, pasture resting, prescribed fire, paddock size and water points – a review

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Abstract. Beef cattle grazing is the dominant land use in the extensive tropical and sub-tropical rangelands of northern Australia. Despite the considerable knowledge on land and herd management gained from both research and practical experience, the adoption of improved management is limited by an inability to predict how changes in practices and combinations of practices will affect cattle production, economic returns and resource condition. To address these issues, past Australian and international research relating to four management factors that affect productivity and resource condition was reviewed in order to identify key management principles. The four management factors considered were stocking rates, pasture resting, prescribed fire, and fencing and water point development for managing grazing distribution. Four management principles for sound grazing management in northern Australia were formulated as follows: (1) manage stocking rates to meet goals for livestock production and land condition; (2) rest pastures to maintain them in good condition or to restore them from poor condition to increase pasture productivity; (3) devise and apply fire regimes that enhance the condition of grazing land and livestock productivity while minimising undesirable impacts; and (4) use fencing and water points to manipulate grazing distribution. Each principle is supported by several more specific guidelines. These principles and guidelines, and the supporting research on which they are based, are presented.

Additional keywords: beef production, carrying capacity, grasslands, grazing distribution, sustainability, tropical savannas.

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Introduction

Grazing with beef cattle is the dominant land use in the extensive rangelands of northern Australia. In 2006, pastoral land occupied ~71, 53 and 54% of the tropical savannas of Queensland (Qld), the Northern Territory (NT) and Western Australia (WA), respectively (Holmes 2010), although these figures do not include the sub-tropical and arid regions of northern Australia where cattle grazing is also widespread. In 2010, the beef herd of northern Australia represented 59% of the national beef herd and the annual farm-gate gross value of production was estimated to be A$3.7 billion (Gleeson *et al*. 2012).

Property sizes and pasture types vary across the northern rangelands. Cattle production is largely based on unimproved native pasture, with tree clearing and use of exotic pasture species limited to certain regions of Qld. In the more productive areas of eastern Qld, properties are smaller (20–300 km^2) and have higher stocking rates and more intensive management than elsewhere. Important pasture types are black speargrass (*Heteropogon contortus*) and Aristida-Bothriochloa grasslands and woodlands. In northern and western Qld, NT and WA, cattle enterprises are generally larger and have less intensive management, with properties sometimes exceeding 2500 km^2. Important pasture types in these areas are Mitchell grass (*Astrebla* spp.) downs and perennial tallgrass (e.g. *Chrysopogon*) and shortgrass grasslands, and extensive areas of the less-favoured spinifex (*Triodia* spp.) (Tothill and Gillies 1992).

Perennial tussock grasses are an important forage resource for cattle and have a vital role in protecting and stabilising the soil, trapping and retaining litter, sediment and nutrients, and providing habitat for native fauna. Maintaining the health and productivity of the palatable, productive, perennial grasses (referred to as the 3P grasses) is thus an essential part of good management, as is maintaining adequate ground cover to protect the soil, facilitate infiltration, and reduce runoff and erosion. A four-category (ABCD) land condition system that is often used to indicate the productive potential of the land incorporates many of these features (Table 1). Some land and pasture degradation has occurred in northern Australia due to livestock grazing (Tothill and Gillies 1992). Land degradation can reduce livestock productivity since pasture growth on land in poor condition may be only 10–20% of that from the same land type in good condition (McIvor *et al*. 1995).

Balancing economically viable livestock production with sustainable use of the natural resource base is becoming more difficult for cattle producers as input costs are rising faster than prices received (McCosker *et al*. 2010). Despite the considerable knowledge gained from both research and practical experience that can help address this challenge, the adoption of improved management by producers is limited by an inability to predict how changes in practices and combinations of practices affect production and resource condition, and also to determine the economic and practical implications of implementing specific management practices. To better understand the effects of various practices, we review past Australian and international research relating to four key management factors that affect productivity and resource condition: stocking rates, pasture resting, prescribed fire, and fencing and water point development for managing grazing distribution. Our review relates predominantly to the management of native pastures although useful insights from improved pastures were also considered. On the basis of this review, we formulate four key management principles (and associated guidelines) for sound grazing management in northern Australia. We have not dealt specifically with different stocking methods, e.g. rotational stocking and deferred stocking, as defined by Allen *et al*. (2011), but we believe these principles are broadly applicable and can be used irrespective of the stocking methods used on a property. Here we present these principles and guidelines and the supporting research.

Managing stocking rates

Background

Using appropriate stocking rates (the number of livestock per unit land area for a given period) is the most critical aspect of livestock grazing (Heitschmidt and Taylor 1991; Ash and Stafford Smith 1996) as stocking rate has profound effects on livestock production, financial performance and land condition. The challenge is to ensure stocking rates are consistent with maintaining good land condition (i.e. retaining favourable pasture composition including 3P grasses) when the number of cattle that can be carried without causing a decline in land condition varies with land type, land condition, production objectives and, particularly, seasonal conditions. The following discussion provides the basis for our first principle and associated guidelines which relate to managing stocking rates.

Effect of stocking rate on land condition

Continued use of stocking rates above the long-term carrying capacity generally leads to a decline in land condition and a loss of productive capacity over the medium to long term due to adverse effects on the pasture community and the soil. For example, deleterious effects of high stocking rates have been reported for annual pasture yield (e.g. Jones 1997; Silcock *et al*. 2005), perennial grass basal area (O'Reagain *et al*. 2008; Ash *et al*. 2011), ground cover and plant longevity (e.g. Silcock *et al*. 2005; Orr and O'Reagain 2011), perennial grass abundance (Mott *et al*. 1992; MacLeod and McIntyre 1997; Orr 2005) and productivity in subsequent years (Ash *et al*. 1997). Adverse changes to the soil can include increased water and wind erosion, the formation of surface crusts and reduced water infiltration (Johns *et al*. 1984).

A common approach to determining the long-term carrying capacity for a particular land type is the use of safe pasture utilisation rates (Hunt 2008). Field studies, practical experience and modelling indicate that, for the majority of pasture types in northern Australia, safe stocking rates are those that result in the utilisation of ~20–30% of annual herbage growth (e.g. Scanlan *et al*. 1994; Johnston *et al*. 1996; Hall *et al*. 1998; Hunt 2008; Ash *et al*. 2011; Walsh and Cowley 2011), although for less productive and ecologically fragile land types safe utilisation rates will be lower. Tailoring stocking rates, and hence utilisation rates, to local conditions is crucial. Under favourable seasonal conditions, high stocking rates over the short term may have little detrimental effect, and this may explain the lack of effect of stocking rate on certain pasture attributes such as the frequency of 3P grasses or the basal area of individual grasses reported in some studies (e.g. Orr 2005; Silcock *et al*. 2005).

Effect of stocking rate on livestock production

The effect of stocking rate on livestock production in the short term has been viewed in the past in terms of the Jones and

Table 1. Characteristics of the ABCD land condition classes used to indicate the productive potential of the land (from Quirk and McIvor 2003)

Condition class	Characteristics: Pasture	Soil	Weeds
'A' (good)	Good cover of 3P perennial grasses; <30% bare ground	No erosion and good surface condition	Few weeds
'B' (fair)	Some decline of 3P grasses. Increase in less favoured grasses and weeds and/or bare ground >30% but <60%	Some decline in soil condition. Signs of past erosion or current susceptibility to erosion	Some increase in woody plants
'C' (poor)	General decline in 3P grasses. Abundant less favoured species and/or >60% bare ground	Obvious signs of past erosion or susceptibility to erosion currently high	General increase in woody plants
'D' (very poor)	General lack of perennial grasses or forbs	Severe erosion or scalding	Thickets of woody plants or weeds cover most of the area

Table 2. Average annual liveweight gain (kg) per hectare for beef cattle (steers) in relation to stocking rate for experiments with replicated treatments in northern Australia

For stocking rate, 1 = lowest stocking rate and 2, 3, . . . represent progressively higher stocking rates. Peak production for each study is shaded

Study location and reference	Pasture type (Tothill and Gillies 1992)	Duration (years)	Annual liveweight gain per hectare (kg) Stocking rate 1	2	3	4	5	6
Queensland								
Kangaroo Hills (Gillard 1979)	*Heteropogon contortus*	10	24	42	–	–	–	–
Keilambete (Silcock *et al*. 2005)	*Aristida-Bothriochloa*	8	43	61	53	–	–	–
Glentulloch (Silcock *et al*. 2005)	*Aristida-Bothriochloa*	8	37	52	59	–	–	–
Glenwood (MacLeod and McIntyre 1997)	*Heteropogon contortus*	2	26	50	90	95	–	–
Lansdown (Jones 1997)	*Heteropogon contortus*	3	35	49	46		–	–
Galloway Plains (Burrows *et al*. 2010)	*Heteropogon contortus*	13	18	28	34	37	53	–
Wambiana (O'Reagain *et al*. 2008)	*Heteropogon contortus*	10	14	21	–	–	–	–
			–	–	–	–	–	–
Northern Territory			–	–	–	–	–	–
Pigeon Hole (Hunt *et al*. 2013)	Monsoon tallgrass (*Chrysopogon*)	3	13	16	19	20	27	–
Mt Sanford (Hunt *et al*. 2013)	Monsoon tallgrass and Mitchell grass (*Astrebla*)	6	15	21	21	25	26	43

Sandland model (Jones and Sandland 1974). Under this model, production per individual animal is greatest at low stocking rates but declines at higher stocking rates as competition for forage among animals increases, while animal production per unit area increases with stocking rate to peak at intermediate stocking rates but then declines as stocking rates increase further. However, Ash and Stafford Smith (1996) showed that this model rarely applies in the rangelands. They suggested that spatial buffering and a lag between the effect of grazing on land condition and livestock production mean that a peak in production is often not observed in the relationship in rangelands.

Many studies in northern Australia have shown the expected decline in production per animal as stocking rate (or pasture utilisation rate) increased, but in only two studies (Jones 1997; Silcock *et al*. 2005) was a peak in livestock production per land area evident (see Table 2). The absence of the expected decline in production per unit area may reflect favourable seasonable conditions, low to moderate stocking (or pasture utilisation) rates, or that stocking rates were reduced or supplementary feed was provided when seasonal conditions were poor. In some cases spatial buffering and a lagged effect on livestock production might also have been influential.

The effect of stocking rate on production generally flows through to financial returns. At Galloway Plains (see Fig. 1 for the location of this and other key sites mentioned in this paper), the financial returns were greatest at the highest stocking rates as declines in individual performance at higher stocking rates were compensated for by the greater number of cattle (Burrows *et al.* 2010). However, in studies where there were market penalties (e.g. weight for age) or market incentives forgone, or where there was a need to feed the cattle in dry years, then higher stocking rates resulted in lower overall financial returns than moderate or low stocking rates (e.g. MacLeod and McIntyre 1997; O'Reagain *et al*. 2011). O'Reagain *et al*. (2011) also found that high stocking rates were less profitable in the medium to long term because pasture productivity declined substantially at high stocking rates during drought and failed to recover during their study period. This observation is consistent with a modelling study based on a property near Charters Towers where declines in land condition

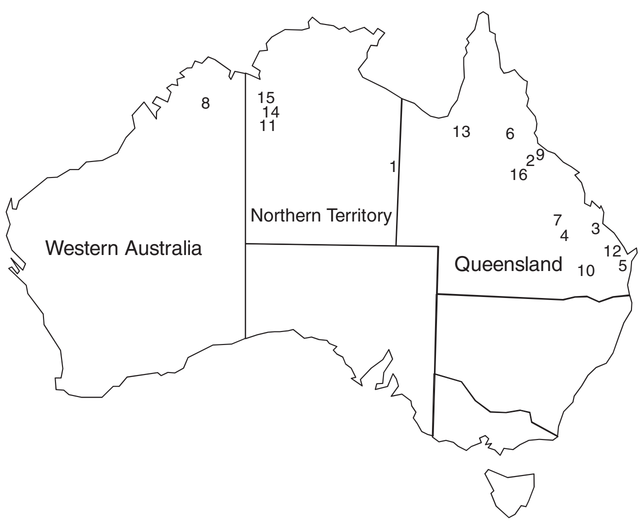

Fig. 1. The approximate location of the main sites mentioned in this paper. Where a region is referred to, the indicated location is the approximate centre of the region. 1 Barkly Tableland region, 2 Charters Towers, 3 Galloway Plains, 4 Glentulloch, 5 Glenwood, 6 Kangaroo Hills, 7 Keilambete, 8 Kimberley region, 9 Lansdown, 10 Maranoa region, 11 Mt Sanford, 12 Narayen, 13 Northern Gulf region, 14 Pigeon Hole, 15 Victoria River District (region) and 16 Wambiana.

associated with high stocking rates meant that in future the land could only support much lower stocking rates, with consequent declines in financial returns (MacLeod *et al*. 2004).

The relationship between stocking rate and livestock production is not constant but varies with seasonal conditions, and changes in land condition can bring about a shift in the relationship. Burrows *et al*. (2010) reported that variation in the amount and timing of rainfall (and management factors) resulted in a large variation between years in liveweight gain of cattle at all stocking rates. This can be partly attributed to the positive relationship between the availability of green plant material and livestock production (Gillard 1979). In the Wambiana study (O'Reagain *et al*. 2009), cattle production per square kilometre

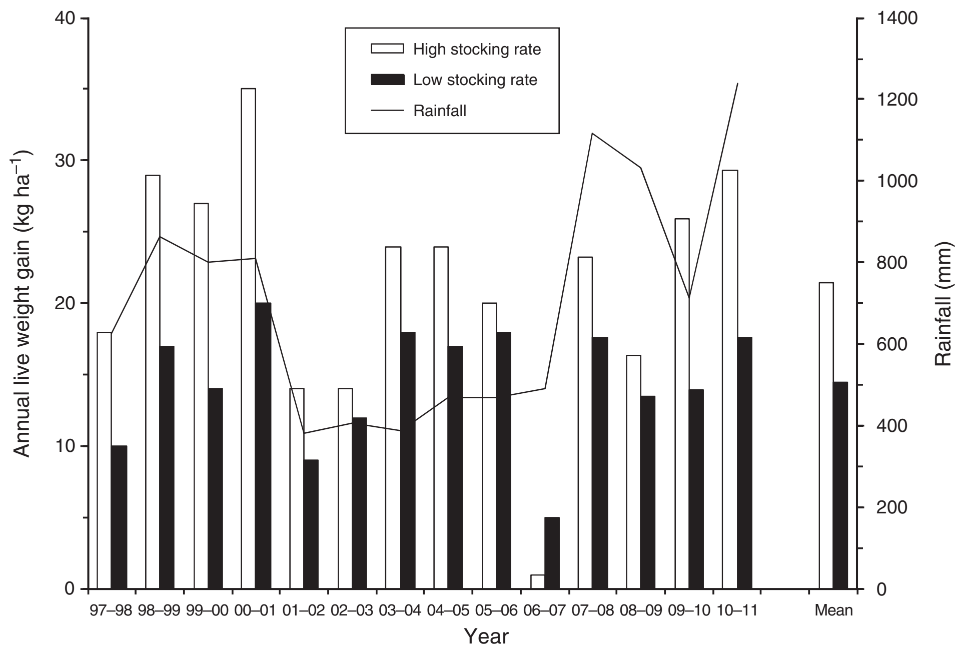

Fig. 2. Annual liveweight gain per hectare for the high and low stocking rate treatments in relation to rainfall during the Wambiana study (1997–2011) (data courtesy of P. J. O'Reagain).

was much greater at higher stocking rates in wet years but the differences were smaller during dry years (Fig. 2). Over all years, production was greatest at the higher stocking rate but costly drought feeding was required to achieve these levels, resulting in a financial loss in dry years.

Our first grazing management principle is thus: manage stocking rates to maintain land condition and economic returns (Principle 1; see Table 3 for grazing management principles and guidelines). Stocking rates that regularly and persistently exceed the carrying capacity of the land, result in a decline in land condition, including the loss of perennial grasses, an increase in bare ground and soil loss, with subsequent loss in pasture and livestock productivity and financial returns. Operating near the long-term carrying capacity of the land helps maintain land in good condition, which is crucial to maintaining the long-term productivity and sustainability of a grazing enterprise (Guideline 1.1).

Managing stocking rates for seasonal variation

Rainfall is highly variable in northern Australia, with the coefficient of variation of annual rainfall ranging between 25 and 41% across the region (greater in the east; Ash *et al*. 1997). This rainfall variability leads to considerable temporal variation in herbage growth (Ash and McIvor 2005) so that short-term herbage availability varies among seasons and years.

Seasonal variation in herbage availability complicates the task of setting stocking rates. While the simplest approach is to use a constant stocking rate at or below the long-term carrying capacity, greater livestock production may be possible in above-average years by increasing stocking rates to take advantage of the extra forage available, but this has associated risks.

The Wambiana study in north-east Qld (O'Reagain *et al*. 2008) specifically addressed the issue of managing for seasonal variation. Based on field measurements and subsequent modelling, O'Reagain and Scanlan (2013) concluded: (1) the most profitable and least risky strategy is constant stocking around the long-term carrying capacity; (2) varying stock numbers around the long-term carrying capacity may help to avoid overgrazing in very dry years and allow higher cattle production in wetter years when forage production is greater; (3) variable stocking can generate good financial returns but has increased ecological and economic risk compared with constant stocking at the long-term carrying capacity; (4) the greatest risk arises in the transition from good to poor years when rapid action is required to reduce stocking rates to avoid pasture damage since high pasture utilisation during poor seasonal conditions can reduce perennial grass basal area and future pasture production (see also Ash *et al*. 2011). Consequently, O'Reagain and Scanlan (2013) recommended a 'constrained flexible stocking rate strategy' (stocking at the long-term carrying capacity with modest increases in good years and substantial reductions in poor years) as a way of exploiting above-average years but minimising the risk associated with poor years. They also recommended forage budgeting in conjunction with seasonal climate forecasts as a basis for adjusting stocking rates in response to changing conditions.

A strategy of variable stocking rates may be a better option in highly variable environments with low average pasture productivity, since continuous conservative stocking rates may not generate sufficient livestock production to be profitable (MacLeod and McIntyre 1997). However, the logistics and increased costs associated with transporting livestock on and off a property, and increased ecological and financial risks, may make a

Table 3. Principles and guidelines for grazing management

Principle 1. Manage stocking rates to maintain land condition and economic returns
Guideline 1.1. Set stocking rates to match long-term carrying capacity. Plan for the average paddock stocking rate to match its estimated long-term carrying capacity, as operating at or around the long-term carrying capacity will help maintain land in good condition. The extent to which stocking rates can exceed the long-term carrying capacity without reducing economic returns and/or reducing land condition is unclear
Guideline 1.2. Regularly assess the need to adjust stocking rates in response to current and anticipated forage supply and quality. Some variation in stocking rates over time is required to manage periods of below-average herbage growth. Capacity to vary numbers over time also provides opportunities to take advantage of periods of above-average herbage growth. The degree of variation that is most beneficial, and achievable, for different production systems is not clear
Guideline 1.3. Management factors and issues other than forage supply also determine the need to vary livestock numbers. The adjustment of stocking rates over time should also consider land condition trend, ground cover, grazing pressure from other herbivores, and economic risk
Principle 2. Rest pastures to maintain them in good condition or to restore them from poor condition to increase pasture productivity
Guideline 2.1. Rest pastures during the growing (wet) season. As a rule of thumb commence the rest period after 38–50 mm of rain or sufficient to initiate herbage growth at the beginning of the growing season. If access to paddocks is difficult after rain then resting should commence before the wet season starts
Guideline 2.2. Rest pastures for the whole growing season. Resting pastures for the whole growing season is likely to provide the most reliable benefit but most of this benefit appears to accrue from rest during the first half of the growing season
Guideline 2.3. Pastures need two growing season rests to improve by one ABCD condition class. Pastures in B condition need rest for one or two growing seasons to improve to A condition. Pastures in C condition will need longer so plan on taking four good growing seasons to recover to A condition. Where growing conditions are poor, more rest periods will be required. Feral and native herbivores should also be managed to maximise the benefit of resting, although this can be hard to achieve in some circumstances
Principle 3. Devise and apply fire regimes that enhance grazing land condition and livestock productivity while minimising undesirable impacts
Guideline 3.1. Use fire to manage woody species. It may not be necessary to kill target species – topkill can be sufficient to alter the structure of woody populations. Mid-to-late dry-season fires of moderate to high intensity are most likely to be effective in reducing the density and biomass of woody plants. Fuel loads are a critical issue – to reduce populations/mass of woody species, a minimum fuel load of 2000 kg ha^{-1} is suggested
Guideline 3.2. Use fire to change the composition of the herbaceous layer in certain pasture types (e.g. Mitchell grasslands and black speargrass pastures) by killing less desirable plants such as wiregrass (*Aristida* spp.), influencing recruitment or altering grazing preferences
Guideline 3.3. Use fire to change grazing patterns by temporarily increasing the attractiveness of previously ungrazed areas and providing rest to previously grazed areas
Principle 4. Use fencing and water points to manipulate grazing distribution
Guideline 4.1. Smaller paddocks and additional water points can achieve more effective use of pastures i.e. reduce the proportion of the paddock that experiences little grazing. In the more extensive grazing areas of northern Australia producers should aim for: paddocks of 30–40 km^2 with two water points, and a maximum distance to water of ~3–4 km to strike a balance between the evenness of grazing distribution and the cost of development. For the more intensive regions in the eastern part of northern Australia, it is likely that paddocks of 20 km^2 with two water points are sufficient from the perspective of optimising grazing distribution. Smaller paddocks may still benefit from sub-division where cattle show a strong preference for land types within a paddock. To minimise the development of large sacrifice areas around water points, the number of head per water point should be limited to no more than 300 head per water point. To protect biodiversity and grazing-sensitive pasture species during drought ~10% of key land types should be kept remote, i.e. 8–10 km, from water
Guideline 4.2. Smaller paddocks and additional water points do not overcome uneven utilisation by cattle within paddocks at the plant community or patch scales. Other methods, e.g. fire, careful selection of water point locations, are needed to increase the evenness of utilisation at these scales
Guideline 4.3. Property development can generate significant increases in livestock production only where it results in more effective use of the pasture (increasing carrying capacity) as substantial improvements in individual livestock production are unlikely. If an undeveloped paddock is already operating at its long-term carrying capacity, paddock development may improve the sustainability of grazing through more even grazing distribution
Guideline 4.4. Fencing and water points can be used to help protect preferred land types and sensitive areas from overgrazing. Fencing to separate markedly different land types is an important strategy for controlling grazing pressure on preferred land types, and to get more effective use of all pasture resources on a property. It can be a practical option in some situations and should be considered where property development is planned

variable approach a less attractive option, especially in more remote regions.

These findings lead to the next guideline: seasonal variability makes it crucial to regularly assess and adjust stocking rates in response to current and anticipated forage supply and quality (Guideline 1.2). Even where the usual practice is to stock at the long-term carrying capacity some variation in stocking rates is required to manage periods of below-average herbage growth (e.g. during an El-Niño sequence of below-average rainfall years). While varying numbers over time provides opportunities to take advantage of periods of above-average pasture growth, the degree of variation that is most beneficial, and achievable, for different production systems is not clear.

Other factors influencing choice of stocking rate

While forage supply is the primary consideration in the choice of stocking rate, other factors should be considered in setting or adjusting stocking rates (Guideline 1.3). For example, stocking rates may need to be lowered to facilitate the accumulation of fuel for prescribed fire, to maintain adequate ground cover, to arrest a decline in land condition or to improve land condition. Total grazing pressure should also be considered so that allowance is made for forage consumption by feral or native herbivores.

Pastoralists who are risk-averse may also elect to operate at lower average stocking rates to avoid the need for crisis management and limit the risk of financial loss and land degradation. Aspects of livestock husbandry, such as the welfare of livestock (ensuring they are receiving adequate nutrition), class of cattle (e.g. breeders or young growing animals versus dry animals) and the management of pests and diseases, may also warrant reductions in stocking rates.

Pasture resting

Background

In this section we discuss the evidence in support of the use of pasture resting, which provides the basis for our second principle and associated guidelines. Pasture resting (or spelling) occurs when livestock are removed from the pasture for a period of time (usually less than 1 year) and there is no livestock grazing. Pasture resting can be used to maintain or improve land condition and to accumulate herbage mass (for various purposes as discussed below). Stimulating 3P grass abundance is the main objective of resting.

Several studies have shown that tropical and sub-tropical 3P grasses are more sensitive to defoliation during the early growing season than at other times of the year (Tainton *et al*. 1977; Mott 1987; Ash and McIvor 1998). This has been attributed to synchrony in tiller growth, with the majority of tillers initiating growth at this time (Mott *et al*. 1992). In addition, the growing season is the time of seedling establishment and seed set, and resting from grazing at these times could be expected to benefit the pasture (Tainton 1981).

Studies of pasture resting in northern Australia

Ash *et al*. (2011) reported that pastures near Charters Towers could be maintained in good condition, or improved if in poor condition, by either light utilisation (use of 25% of annual forage growth) or moderate utilisation (50%) combined with a wet-season rest every year for 8 weeks after the first significant rainfall event of the wet season (>50 mm over 2 days from November onwards). In comparison, high utilisation (75%) both with and without resting led to pasture degradation of land in good condition, and high utilisation without resting prevented the recovery of land in poor condition (there was no treatment with high utilisation and resting on poor condition land). In a subsequent commercial-scale study in paddocks initially in poor condition but then managed with moderate utilisation and two or three periods of wet-season rest over 6 years, there were substantial improvements in pasture condition (total yield, 3P grass yields and ground cover) (Post *et al*. 2006). However, this study did not include any continuously grazed treatments to compare with the experimental paddocks that received wet-season rest, making it difficult to separate seasonal and treatment responses, and recovery in the experimental paddocks was spatially and temporally patchy.

In some studies the effect of resting has been equivocal. For example, Orr and O'Reagain (2011) found that at Wambiana there was no benefit from resting in terms of the survival, recruitment or basal area of perennial grasses. A study in an improved pasture of Siratro (*Macroptilium atropurpureum*) and buffel grass (*Cenchrus ciliaris*) at Narayen found that annual pasture yields were greater on rested pastures but overall animal performance fell because of the higher stocking rates in the paddocks containing the animals from the rested pastures during the summer (Tothill *et al*. 2009).

In several other studies the effects of resting were confounded with those of fire, rainfall amount or other factors, and in some cases control treatments were not included so that it is difficult to determine the effects of resting (e.g. O'Reagain *et al*. 2008; Hunt *et al*. 2013). Interactions between resting and fire and/or poor seasonal conditions highlight the difficulty of practical implementation of a spelling regime in regions with variable environmental conditions. In some studies, the effects of stocking rate or rainfall were more important than resting in determining vegetation change.

Exclosure studies can also provide some understanding of the responses of pastures to periods without grazing. McIvor and Gardener (1990) and McIvor (2001) used exclosures to study the recovery of native pastures from a range of initial land condition states in north-east Qld. Under the good growing conditions experienced in those studies, fair condition land needed 1–2 years of rest, and poor condition land needed 2–3 years of rest, to recover to good condition. In a similar study at Galloway Plains, it was found that protection from grazing for ~4 years was required for land condition to improve from poor to fair or fair to good condition (S. Bray, G. Fraser and G. Stone, pers. comm.). Rainfall was below average for the first year of this study but greater in subsequent years.

We conclude that pasture resting can have a major influence on land condition. Resting pastures helps maintain them in good condition or can help to restore them from poor condition to improve pasture productivity (Principle 2). Above-average seasonal (growing) conditions may be necessary for a pasture response (Orr and Evenson 1991; Orr *et al*. 2006; Orr and Phelps 2013), and in arid areas the recovery of condition can be slow and is dependent on infrequent seasons of above-average rainfall even with protection from grazing (Silcock and Beale 1986).

Factors determining the success of pasture resting

Aside from the effect of prevailing growing conditions, three factors determine the effectiveness of pasture resting in improving land condition – the season (or timing) of resting, the duration of resting and the number of rest periods (or frequency of resting). In the following sections we summarise the experimental evidence related to these factors, and present associated guidelines.

Season of rest

Several experimental studies suggest that resting during the wet season (particularly the early wet season) will be especially important for maintaining pasture productivity. In a multi-site experiment in Qld, the only substantial improvement in pasture condition (including increases in the annual yield and basal area of desirable perennial grasses) occurred with rest during the wet (growing) season in years when favourable growing conditions prevailed (Orr *et al*. 2006). There was little or no improvement with rest at other times. Several experiments in south-east Qld showed improvements in pasture composition (increases in the annual yield and relative density of speargrass and decreases in wiregrass [*Aristida* spp.]) and basal area of speargrass with wet-season rest (and burning) (Paton and Rickert 1989; Orr *et al*. 1991; Orr and Paton 1997; Paton 2004), although this effect was not observed in all studies (e.g. Orr 2004; Silcock *et al*. 2005).

While resting during the growing season has the greatest benefit, resting during the non-growing or dry season may have some benefits for pasture condition (O'Reagain *et al*. 2008). For example, it can: (1) prevent repeated grazing of regrowing shoots if there are small falls of rain or sub-soil moisture sufficient to initiate some growth; (2) retain greater ground cover during the late dry season and so provide better protection of the soil surface; and (3) prevent the removal of aerial buds that are common in some species (e.g. buffel grass and desert blue grass [*Bothriochloa ewartiana*]) resulting in more growing points being available for growth at the start of the following growing season. Nevertheless, a comparison of wet-season versus dry-season resting in the Kimberley found little difference in pasture composition (Hacker and Tunbridge 1991).

To conclude, resting during the growing season and particularly during the early growing season when grasses are most susceptible to heavy defoliation will be most effective in increasing the vigour and/or improving the composition of a pasture (Guideline 2.1). As a rule of thumb, the rest period should commence after rainfall sufficient to initiate herbage growth (i.e. 38–50 mm) at the beginning of the growing season. If access to paddocks is difficult after rain then resting should commence before the wet season starts. Effective control of any feral and native herbivores present is required to ensure these species do not congregate on rested paddocks, although this can be problematic where they can invade from neighbouring properties or where there are legal impediments to their control.

Duration of rest

The duration of the rest period involves a balance between the benefit to the pasture and the loss of grazing and lower nutritive value of the herbage accumulated over the rest period. A limited amount of experimental evidence suggests longer rest periods appear to be more effective than shorter rests. Orr and Paton (1997) reported that the annual yield of speargrass was higher with 4 or 6 months than with 0 or 2 months rest each year, although Ash *et al*. (2001, 2011) found that 2 months of rest in the early growing season each year was sufficient to maintain tropical tallgrass pastures in good condition and improve pastures in poor condition.

Some studies (e.g. Post *et al*. 2006; O'Reagain *et al*. 2008) have recommended resting for the entire wet season, although O'Reagain *et al*. (2008) suggested that shorter periods of rest (6–8 weeks) may be sufficient for recovery in seasons of very high rainfall. The advantages with whole-season rest include: (1) it is more likely that some favourable growing conditions will occur during resting; (2) perennial grasses are protected during the early growing season when they are particularly susceptible to grazing, and also later when setting seed and accumulating reserves; (3) new seedlings can establish, grow and set seed, and existing plants can expand; (4) the root reserves of grasses get a chance to increase (mostly in the late wet season); (5) livestock will not need to be moved during the wet season; and (6) the re-grazing of preferred patches is avoided (Post *et al*. 2006; Corfield and Nelson 2008).

The duration of rest required in a rotational grazing system (c.f. resting to improve condition) depends on the plant growth rate, which determines the time needed for a grass to restore root growth and reserves. A similar situation is likely with resting to improve condition; the higher the plant growth rate, the shorter the period of rest needed, with long rest periods required when the growth rate is low.

In summary, resting pastures for the whole growing season is recommended (Guideline 2.2). Resting pastures for the whole growing season is likely to provide the most reliable benefit but most of this benefit appears to accrue from rest during the first half of the growing season.

Number of rest periods

No experiments in northern Australia have explicitly compared the frequency of rest periods but several recommendations on the frequency of resting have been derived from general observations. A recommendation from South Africa is that 1 year of rest in 4 may be sufficient for range in good condition (Pratt and Gwynne 1977; Tainton 1981) but more frequent rests may be needed where land has been mismanaged (Tainton 1981). In north-east Qld, Post *et al*. (2006) concluded that consecutive wet-season spells accelerate the recovery process compared with biennial resting. Rest in consecutive years is also required to recover land in poor condition under drought conditions whereas biennial rest is sufficient for land in good condition (J. Corfield, pers. comm.). Drought-weakened perennial pastures in the Maranoa region were considered to need two consecutive summers of favourable rainfall to fully rejuvenate (Silcock and Hall 1996); this allows the perennial grasses to set seed and establish new seedlings in the first year, and for these seedlings to grow into robust crowns in the second year (Silcock *et al*. 2005).

The preceding discussion suggests that the required frequency of resting or number of rest periods to achieve a certain goal will be determined by both initial land condition and growing conditions during the rest period. Pasture maintenance and recovery are boosted by favourable growing conditions, and the number and duration of rest periods need to be greater under poor growing conditions. We suggest that pastures need two growing season rests to improve by one ABCD condition class. Pastures in good (B) condition need rest for one or two growing seasons to improve to excellent (A) condition. Pastures in fair (C) condition will need longer, requiring perhaps four good growing seasons to recover to A condition. Where growing conditions are poor, more rest periods will be required (Guideline 2.3). The nature of grazing between rests, e.g. pasture utilisation rate, may have a marked effect on the pasture as well (e.g. Kirkman 2002).

Resting pastures for reasons other than pasture condition

Accumulating herbage to allow for prescribed fire, especially where fuel is needed for intense fires to kill woody seedlings, is facilitated by resting, and resting is also required to allow pasture recovery after a fire. Resting can be used to conserve forage as a drought or fodder reserve, or for special purposes (e.g. weaning). Pastures may be rested when they are beginning to regrow in order to accumulate sufficient herbage to ensure adequate intake by cattle during subsequent grazing. Finally, increases in ground cover and the input of organic material to improve the soil may also be achieved by resting.

Using prescribed fire to manage vegetation

Background

Fire has long been an important ecological factor in many northern Australian ecosystems, influencing the structure and composition of the vegetation. The large bulk of understorey vegetation (predominantly grasses) that grows during the wet season becomes increasingly available as fuel during the ensuing dry season as its moisture content falls (Dyer *et al*. 2001). Fire was used extensively by Aboriginal people for thousands of years for hunting, to encourage food plants and to facilitate travel across the landscape (Pyne 1998). Lightning is also a significant cause of fire, especially during the build up to the wet season.

Fire has remained an important factor since European pastoral settlement (see Fig. 3 for recent fire history), and many northern Australian pastoralists use fire for various purposes (Dyer *et al*. 2001). In this review our focus is on the use of fire to manage vegetation on pastoral lands and to help manage grazing distribution.

Fire and pastoralism in northern Australia

Fire is used to manage the vegetation on pastoral lands in various ways, including: controlling woody vegetation to reduce competition with grasses and other herbage and so maintain a productive understorey; improving access for efficient management such as effective mustering (e.g. Crowley and Garnett 2000; Back 2005; Grice 2008); controlling herbaceous weeds (Orr *et al*. 1997); removing 'moribund' grass material to facilitate access by cattle to more nutritious components of the herbage (Ash *et al*. 1982; Craig 1999); promoting 'green pick' via the growth of nutritious new shoots (Ash *et al*. 1982; Craig 1999; Crowley and Garnett 2000); manipulating pasture composition (e.g. the ratio of grasses to legumes [McIvor *et al*. 1996]); and reducing the risk of destructive wildfires (Crowley and Garnett 2000). By removing moribund pasture and promoting green pick, fire may be used to manage the distribution of cattle at fine or coarse scales (Andrew 1986).

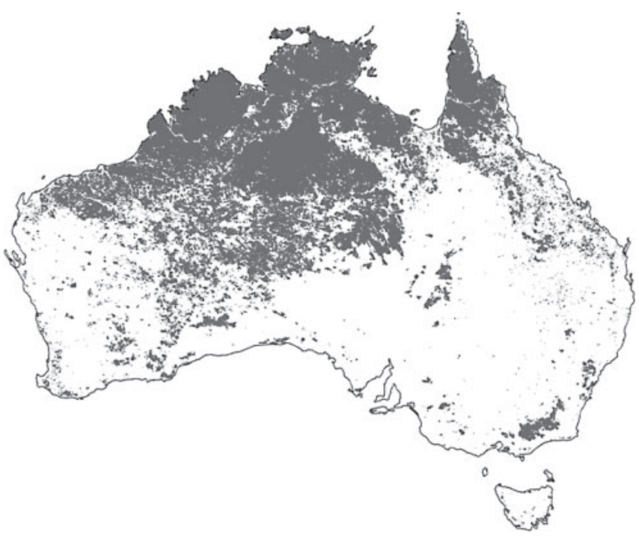

Fig. 3. The area of Australia burnt (shaded) between 2000 and 2012 (map courtesy of A. Edwards).

Research on the use of fire in savanna systems in northern Australia demonstrates that fire has value as a management tool for pastoral systems. Individual fires and fire regimes must be tailored to particular purposes to optimise outcomes. It is important to devise and apply fire regimes that enhance grazing land condition and the productivity of livestock while minimising undesirable impacts (Principle 3). In the following sections, we first discuss some of the factors affecting the use of prescribed fire, and then discuss the use of fire to manage woody species, herbaceous species and grazing patterns.

Factors affecting the use of prescribed fire

Fire characteristics

The nature of individual fires and the fire regime has a strong influence on the effect of fire on the structure and composition of the vegetation. The nature of an individual fire is dictated largely by the fuel available (amount and moisture content) and weather conditions (atmospheric temperature and humidity, and wind speed) at the time of the fire. As the moisture content of the grass falls, the likelihood of it burning and the intensity of any fires increase (Dyer *et al*. 2001). Thus, in the tropical north fires in the early dry season tend to be smaller, patchier and cooler than those in the late dry season. The fire regime, i.e. the timing, frequency and intensity of fires at the landscape and broad temporal scales (Grice and Slatter 1996), experienced in an area is a function of climatic factors, the occurrence of ignition events and land use. For example, heavy grazing may reduce the prospect of fire and its intensity. In general, hotter and/or more frequent fires have greater effects on the vegetation.

Plant responses to fire

Plant responses to fire influence how a fire regime affects the vegetation. Many plant species in Australia are generally fire tolerant due to the long evolutionary history of fire in Australia. While annual plants are likely to die if they are burned, many annual species have a persistent soil seed-bank, insulated from the effects of fire.

Individuals of most species of perennial grass generally survive fire since their growing points are close to or below ground level and sufficiently protected from fires. Individuals of some perennial grasses, e.g. certain species of spinifex, are killed by fire and the populations recover through recruitment from seed.

Shrubs and trees are generally either 'obligate seeders' or 'resprouters'. Most individual plants of obligate seeders are killed by fire and the population must recover from seed. These species may store their seed on the plant inside protective fruits (e.g. woody capsules), or in the soil. In 'resprouter' species, individuals generally survive fire and regrow from growing points that are protected by thick or corky bark or by the soil. Rates of mortality vary with plant size (Fig. 4; Williams *et al*. 1999), and differences in the size classes present for any given species can affect the proportion of the population that survives fire.

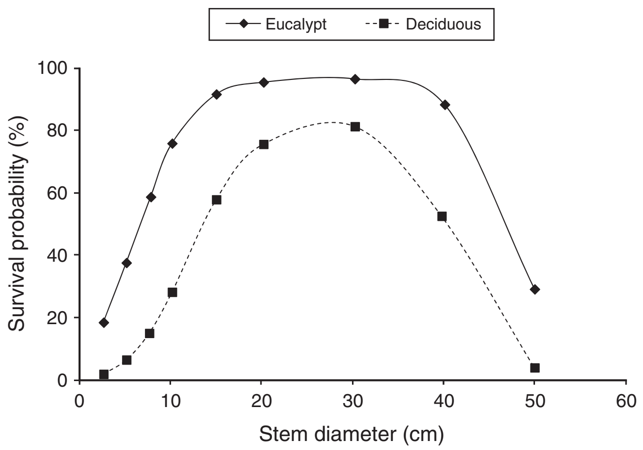

Fig. 4. The relationship between stem diameter and the probability of surviving fire for various tree species of northern Australian savannas (from Williams *et al*. 1999).

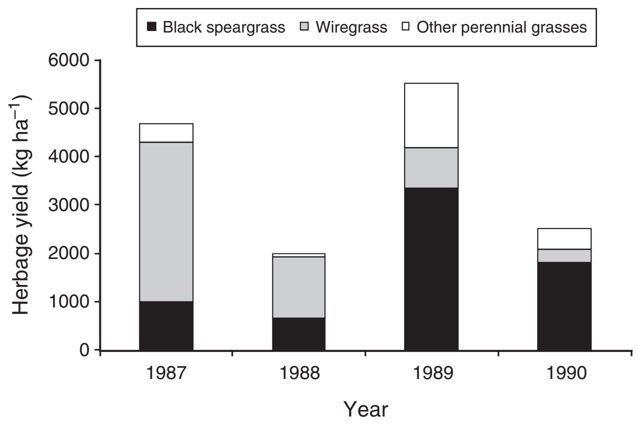

Fig. 5. The proportion of black speargrass (*Heteropogon contortus*) and wiregrass (*Aristida* spp.) in the pasture in successive years under a regime of annual burning and protection from grazing (from Orr *et al*. 1991). Total yield varies with seasonal rainfall.

Using fire to manage woody species

The management of woody plants is the main reason for using prescribed fire in pastoral land management as herbage production declines with increasing basal area of trees (Scanlan 2002). Because of inter-specific variation in the responses of trees and shrubs to fire, it can be used to manipulate the composition of the vegetation. For example, in the savannas of the Northern Gulf, experimental fires caused substantial mortality and/or shifts in the population structure of breadfruit (*Gardenia vilhelmii*) and gutta percha (*Excoecaria parviflora*), which had increased to densities that were problematic for pastoralism (Grice 2008). Mid-to-late dry-season fires can kill significant proportions of individuals of the exotic weeds rubber vine (*Cryptostegia grandiflora*) and parkinsonia (*Parkinsonia aculeata*) (Grice 1997*a*), although multiple fires are necessary to achieve effective control of these species (Grice 1997*b*).

As a general rule, mid-to-late dry-season fires of moderate to high intensity are most effective in regulating the density and mass of woody plants (e.g. Dyer *et al*. 2003). However, a risk with late dry-season fires is that large areas of country may be burnt if the fire gets out of control, and species that are not the intended control target are damaged.

Adequate fuel (usually herbage mass of grasses but also varying amounts of tree and shrub litter) must be available and have spatial continuity to be able to use prescribed fire to manage woody species. For individual fires aimed at reducing woody species, the literature suggests that a minimum fuel load for an effective fire is ~2000–2500 kg ha^{-1} (Grice and Slatter 1996; Dyer *et al*. 2003). However, where tree basal area is high, herbage mass of grasses is usually greatly suppressed. The effectiveness of fires based on marginal fuel loads can be increased by carefully selecting the times at which prescribed burning is undertaken, both seasonally and diurnally. More intense fires can be achieved by burning when the weather is warmer, relative humidity is lower and wind speed is greater.

Repeated burning will usually be necessary to manage populations of trees and shrubs for two reasons. First, fire can promote the germination of woody species that maintain soil seed-banks (e.g. many *Acacia* spp.) and large populations of seedlings can emerge following a fire because the heat of the fire breaks seed dormancy. Species with these characteristics tend to be relatively susceptible to fire, which means that a second fire before these plants reach reproductive size should greatly reduce their populations. One risk with this strategy is that the accumulation of herbage mass of grasses after an initial fire may be inadequate to fuel a second fire before the trees and shrubs reach a fire-resistant size class and/or are able to reproduce (Williams *et al*. 1999).

Second, many woody species in northern Australia are relatively resilient to fire, so a large proportion of individuals survive being burnt. In these situations, relatively frequent burning may be needed to reduce densities but striking a suitable trade-off between fire frequency, fire intensity and short-term cattle production is also necessary. A regime of a fire every 3–5 years may be appropriate, depending on the woody species and the circumstances. An adaptive management approach based on local knowledge is advisable, particularly for those systems whose fire ecology has not been the subject of research. It may not be necessary for target species to be killed by fire since topkill (where only the aboveground components are killed) can be effective in altering the structure of shrub populations in some circumstances.

In conclusion, fire can be used to manage woody species where an increase in their abundance due to a lack of fire causes problems for pastoral land use. Mid-to-late dry-season fires of moderate to high intensity are most likely to be effective in reducing the density and mass of woody plants. To reduce populations and/or mass of woody species, a minimum fuel load of 2000 kg ha^{-1} is suggested. It may not be necessary to kill target species (Guideline 3.1).

Using fire to manage herbaceous species

Fire can be used to manipulate the composition of herbaceous species by killing plants, influencing recruitment or altering grazing preferences (Guideline 3.2) although few examples exist. In one example, Orr *et al*. (1991) recommended combining late dry-season fires in successive years with a rest from grazing over summer to reduce wiregrass and encourage black speargrass (see Fig. 5), since burning can promote the recruitment of seedlings of black speargrass but is detrimental to wiregrass. This is partially because black speargrass has buried seeds protected from fire whereas wiregrass seeds remain on the soil surface and are killed by fire (Campbell 1995). However, in another study with different species of wiregrass, Orr (2004) noted that spring burning and reduced grazing pressure had no marked effect on the density of black speargrass or wiregrasses, highlighting the importance of understanding how different species respond to fire. Differences in the timing of burning and seasonal conditions following burning may also contribute to variation in the effectiveness of fires in changing species composition (Orr 2004).

Early wet-season fires can be used to reduce the abundance of annual sorghum (*Sorghum* spp.) in tallgrass pastures. This is successful because these species lack a persistent seed-bank (Andrew and Mott 1983) and burning in the early wet season after the seed has germinated kills the seedlings. In spinifex country in the Kimberley region, a regime of late dry-season burning every 3–6 years is recommended to increase the abundance of preferred forage species (Craig 1999). Fire has been used to control increasing Seca stylo (*Stylosanthes scabra*) dominance in central Qld although uncertainty exists over when and how often to burn (McIvor *et al*. 1996; D. Orr, pers. comm.). Fire has also been used in an attempt to manage giant rat's tail grass (*Sporobolus pyramidalis*), but results tend to be variable (Bray 2004).

Using fire to manage grazing patterns

As discussed in more detail later, grazing pressure is often concentrated on only a proportion of a paddock. On some land types, this can result in a positive feedback such that livestock (or native herbivores) preferentially graze areas where previous grazing and trampling have occurred because of the nutritious regrowth produced by perennial grasses following grazing. This produces a pattern of patch grazing where areas of over-utilisation occur within a matrix of old poorer quality forage that builds up in areas of low utilisation (Mott 1987). This contributes to reduced productivity and localised overgrazing.

While pasture resting and the appropriate use of fencing and water points are important in managing this issue (see later), fire can also be used to help manage grazing patterns. Fire can be used to change grazing patterns by temporarily increasing the attractiveness of previously ungrazed areas and providing rest to grazed areas (Guideline 3.3). Burning under-utilised areas can encourage grazing animals to use these areas by removing low-quality forage and stimulating more nutritious regrowth (Andrew 1986; Dyer *et al*. 2003; Letnic 2004). Examples where this technique has been used on commercial properties are limited but Andrew (1986) demonstrated the strategy under experimental conditions in the monsoon tallgrass region in the NT.

Fire intensity to remove ungrazed patches need not be high although the fire must carry across grazed patches where these occur in a mosaic of taller, ungrazed patches. Resting to allow fuel accumulation on grazed patches may help. One potential problem with burning only small areas is that the concentration of grazing on these areas may have a negative effect on land and pasture condition, especially if the following season has low rainfall.

Using paddocks and water points to manage grazing distribution

Nature of grazing distribution and its implications

Livestock do not graze the landscape uniformly because of the irregular distribution of resources that they require to survive, grow and reproduce (Coughenour 1991). Where paddocks are large and water points sparse, cattle rarely use areas far from water but can overgraze areas near water, leading to declining land condition (Hunt *et al*. 2007). Distributing grazing pressure relatively evenly across a paddock is crucial to optimising pasture use, maximising livestock production and minimising land degradation (Stoddart *et al*. 1975; Ash *et al*. 1997; Holechek *et al*. 2004). Sub-division fencing (i.e. smaller paddocks) and water points (i.e. the number and location) can be used to manipulate grazing distribution (Principle 4) and be effective in making more of the forage accessible to cattle.

Managing grazing distribution at the paddock and landscape scale

Water points are usually the strongest influence on the distribution of cattle grazing in large paddocks in northern Australia because of the general scarcity of water sources for much of the year and the need for cattle to drink frequently (usually daily). While cattle can range large distances from water, e.g. 10–11 km on the Barkly Tableland (Schmidt 1969; Fisher 2001) and up to 24 km in central Australia (Low *et al*. 1978), cattle activity declines markedly beyond 3–4 km (Fisher 2001; Hunt *et al*. 2013). A study in the Victoria River District of the NT showed that, in large paddocks with sparse water points, ~80–90% of activity is usually within 5 km of water (Fig. 6; Hunt *et al*. 2013). This study concluded that a grazing radius of 2.5–3 km, i.e. ~5–6 km between water points, provided a compromise between achieving moderate forage utilisation across the landscape and limiting the area near water points that suffer extreme defoliation, as long as the number of head per water point is not excessive – see below.

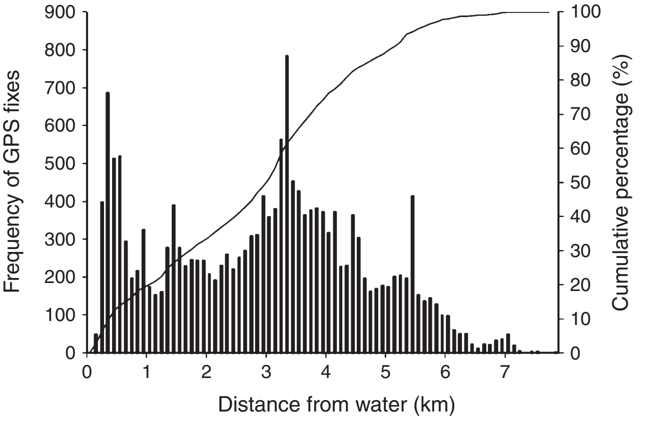

Fig. 6. The distribution of cattle activity at various distances from water (bars) and cumulative percentage of activity (line) in a large (149 km^2) paddock with three water points in the Victoria River District, NT, determined by GPS collars fitted to cattle (from Hunt *et al*. 2013).

Table 4. Combined home range of cattle for three developed paddocks at Pigeon Hole station and an undeveloped commercial paddock at Mt Sanford in the Victoria River District, NT, Australia

The data are from cattle fitted with GPS collars over periods of 6 months. The 'Multiple water point' paddock contained five water points

Paddock	Paddock area (km^2)	Mean combined home range (km^2)	Area of paddock receiving little grazing use[A] (km^2)
Developed paddocks			
One water point	8.9	8.4	0.5
Two water points	34.3	27.6	6.7
Multiple water points	56.9	43.3	13.6
'Typical' undeveloped commercial paddock (three water points)	148.6	113.7	34.9

[A]The area not encompassed by the combined home range.

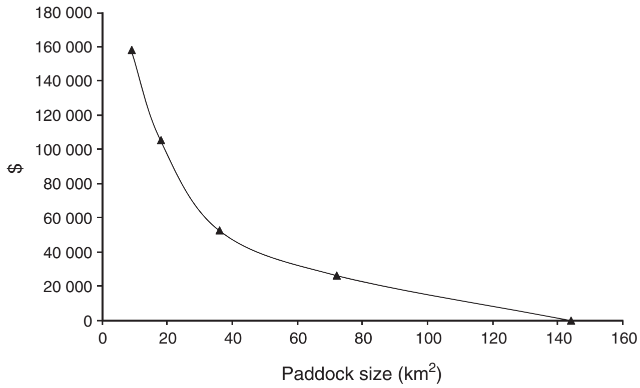

Fig. 7. The cost of sub-dividing a large (144 km^2) paddock into smaller paddocks of varying size in the Victoria River District (based on costs in 2007) (from Hunt *et al*. 2013).

Paddock size is also a strong determinant of how much of the landscape cattle use. As paddock size decreases cattle generally tend to use a greater proportion of the paddock, which reduces the proportion of the landscape that experiences little grazing, although the effect is confounded with the number and distribution of water points within larger paddocks. In the Victoria River District more than 20% of a poorly developed large (149 km^2) paddock was not used by cattle compared with 6% in a small paddock, despite the larger paddock having more water points (see Table 4). However, the cost of fencing to create smaller paddocks increases markedly for paddock sizes below ~30 km^2 (Fig. 7).

The research thus indicates that smaller paddocks and more water points can improve the distribution of grazing across the landscape, resulting in more effective use of pastures and reducing the proportion of the paddock that experiences little grazing (Guideline 4.1). In the more extensive grazing areas of northern Australia, producers should aim for paddocks of 30–40 km^2 with two water points, and a maximum distance to water of ~3–4 km. To minimise the development of large sacrifice areas around water points, stock numbers should be limited to no more than 300 head per water point. For the more intensive regions in the eastern part of northern Australia, paddocks of 20 km^2 with two water points are suggested as being adequate to optimise grazing distribution. It is unlikely there will be any additional benefit from more intensive development in terms of improved grazing distribution and greater livestock carrying capacity, although paddocks may benefit from subdivision where cattle show a strong preference for land types within a paddock. More intensive development may also be justified for other management reasons, e.g. the segregation of animal classes, and to facilitate resting and the use of fire.

Effect of paddock development on patchiness of grazing and livestock production

Although reducing paddock size and installing additional water points provides more control over where cattle graze, uneven grazing distribution will continue to occur within paddocks as cattle will still select certain locations (e.g. preferred plant communities, land condition or land types). Thus, smaller paddocks and additional water points do not overcome uneven utilisation within paddocks at the plant community or patch scales (Guideline 4.2). Other methods (e.g. fire, careful selection of water point and supplement locations) are needed to increase the evenness of utilisation at these scales. Fencing along land-type boundaries can help to control the availability of different land units and pasture resources so that cattle are less able to concentrate in preferred areas (Hodder and Low 1978; Low *et al*. 1981).

Infrastructure development is not expected to lead to a substantial improvement in individual cattle production due in part to its ineffectiveness in improving within-paddock distribution. On large, poorly developed properties, there may be potential to sustainably increase stocking rates if grazing pressure can be spread more uniformly over the landscape (Hunt *et al*. 2013). Thus, an increase in total cattle production may be possible where pre-development stocking rates are below the long-term carrying capacity and infrastructure development results in more effective use of the pasture, thus increasing carrying capacity (Guideline 4.3). If an undeveloped paddock is already operating at its long-term carrying capacity, paddock development may improve the sustainability of grazing through more even grazing distribution.

Protecting sensitive areas

Protecting ecologically significant areas that may be sensitive to grazing, e.g. riparian areas, wetlands, biodiversity refuges and threatened plant species or communities, from excessive livestock grazing is an important aspect of grazing land use (Stafford Smith and McAllister 2008). Because such areas may be associated with water, more fertile soils, a diversity of plant species or shade, they are often preferred by livestock. Separating sensitive land types with fencing is an effective option, but it is often difficult because of the cost and impracticality of separating minor land types (Veira 2007). Cattle grazing may be attracted away from these areas by moving the location of water (Ganskopp 2001; Bailey 2005). Off-stream water points can be used to draw cattle away from riparian areas (Bailey 2005; Veira 2007). In central Qld, Bishop-Hurley *et al*. (2008) found that providing off-stream water reduced the time cattle spent within 10 m of a stream by 80%.

Guideline 4.4 addresses these issues with the following recommendations. Fencing and water points can be used to help protect preferred land types and sensitive areas from overgrazing. Fencing to separate markedly different land types is an important strategy for controlling grazing pressure on preferred land types, and to get more effective use of all pasture resources on a property. It can be a practical option in some situations and should be considered when property development is planned.

Other considerations

The need to protect biodiversity should also be considered when developing paddocks and water points. About a third of native species of fauna and flora are sensitive to grazing and generally survive only in areas remote from watering points (James *et al*. 1999; Fisher 2001). Recommendations are to keep ~10% of key land types remote (i.e. 8–10 km) from water points (Biograze 2000) or to establish exclosures that exclude livestock grazing. Such exclosures or ungrazed areas should be reasonably large (individually at least 100 ha) and ideally scattered throughout the intensified area (A. Fisher, pers. comm.).

The cost of installing new fences and water points can be substantial for large paddocks. Although a cheaper option is to establish more water points without sub-dividing into smaller paddocks, this is a less effective way of improving grazing distribution since there is less control over the grazing pressure exerted on the areas cattle prefer.

On well developed, fully stocked properties there is a risk that a large proportion of a property may be degraded in the event of management error, such as delaying destocking for too long into a drought. Additionally, there may be few spare paddocks in which to move cattle as seasonal conditions and forage availability decline, reducing management options. Managers of properties with a high level of development will, therefore, need to be especially vigilant and respond rapidly where areas are at risk of being overused. The extra paddocks available on a developed property should also allow a spelling regime to be implemented.

Conclusions

The four management principles and associated guidelines identified in this paper are critical to managing extensive grazing in Australia's northern rangelands and can be used to address major management issues. However, implementation of these principles and guidelines on properties is not always straightforward, with uncertainty about what action to take and when, and the likelihood and nature of the outcome that might be expected. The information from which the principles and guidelines have been derived is the basis of considerable efforts by government, industry and private sector advisers to improve grazing management in the pastoral industry, and it is hoped that formalising this information into these principles and guidelines assists in this process. While a range of extension approaches is appropriate, case studies of properties already using these principles and guidelines and demonstration sites in highly visible locations should provide commercially relevant information that should maximise the adoption of the principles and guidelines.

These principles and guidelines were developed specifically for tropical and sub-tropical rangelands of northern Australia where perennial grasses have a critical role in the functioning of the ecosystem and provide the basis for a sustainable livestock industry. Nevertheless, the broad principles have wider relevance to other rangeland systems in Australia and elsewhere. The need to manage stocking rates according to the long-term carrying capacity and to manage grazing distribution is universal in rangeland systems. Similarly, pasture resting will be important in many other systems where perennial grasses and/or shrubs form the basis of livestock diets, particularly where forage plants are not well adapted to grazing. Resting may also be required where climatic fluctuations result in large variations in forage availability. For many systems, fire can be a useful tool in managing woody species, pasture composition and grazing distribution, although the use of fire must be based on an understanding of the sensitivity of the local vegetation to fire. Thus, while these principles and guidelines have broad relevance, some adaptation to specific circumstances will be required.

Acknowledgements

The grazing principles and guidelines presented in this paper are the culmination of a considerable history of grazing experiments, ecological studies, observations by graziers and case studies by many individuals and organisations across northern Australia. We thank Drs M. Quirk and R. Dyer for their support, advice and guidance. The input and feedback from numerous colleagues in state agencies and cattle producers through regional workshops is also greatly appreciated. The funding support of Meat and Livestock Australia and the federal Department of Agriculture, Fisheries and Forestry is gratefully acknowledged. Andrew Ash, Cam McDonald and Peter Johnston provided helpful comments on an earlier version of the manuscript. Andrew Edwards kindly prepared the fire map.

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