final report

Project code: **B.NBP.0579**

Prepared by: **John McIvor**

CSIRO Sustainable Ecosystems

Date published: **July 2010**

ISBN: 9781 7419 1 5648

PUBLISHED BY
Meat & Livestock Australia Limited
Locked Bag 991
NORTH SYDNEY NSW 2059

Enhancing adoption of improved grazing and fire management practices in northern Australia: Synthesis of research and identification of best bet management guidelines

Meat & Livestock Australia acknowledges the matching funds provided by the Australian Government to support the research and development detailed in this publication.

Abstract

This project is part of the Northern Grazing Systems project which aims to increase adoption of innovative best-practice grazing management by beef producers throughout Queensland, the Northern Territory and the Kimberley and Pilbara regions of Western Australia. Published research results relating to four management factors [infrastructure development (fences and water points), stocking rate management, pasture resting and prescribed burning] and other relevant literature were collated and reviewed. This information was used to develop a set of scientifically-based principles and guidelines for managing grazing lands in northern Australia. The principles and guidelines were applied to four widespread management issues - matching feed supply and animal demand, managing C condition land, woody plant problems, and utilising ungrazed areas in large paddocks. In the short term, the combination of this information with results of bio-economic modelling and regionally specific information from Project B.NBP.0578 will provide a solid foundation for future research and extension activities. In the longer term, we can anticipate that grazing land management will be more appropriate for northern Australian conditions and there will be financial benefits to producers, land will be in better condition, and the northern beef industry will be more sustainable.

Executive summary

This synthesis project and an associated project (B.NBP.0578 Enhancing adoption of improved grazing and fire management practices in northern Australia: Bio-economic analysis and regional assessment of management options) form the Northern Grazing Systems project which aims to increase adoption of innovative best-practice grazing management by beef producers throughout Queensland, the Northern Territory and the Kimberley and Pilbara regions of Western Australia.

The objectives of B.NBP.0579 were as follows.

By 1 July 2010 the Research Organisation will have:

1. Completed a synthesis and analysis of research and publications to review and/or develop key principles, response curves and best-bet guidelines for grazing land management particularly relating to infrastructure development, managing stocking rate, pasture spelling and prescribed burning. This work will apply across a climate and soil fertility continuum and for a range of enterprise scales and resource conditions throughout Northern Australia.
2. Contributed draft best bet guidelines to the bio-economic modelling studies in B.NBP.0578 to quantify the impacts and trade-offs associated with different grazing land management strategies (infrastructure development, managing stocking rate, pasture spelling and prescribed burning) on measures of animal production, enterprise profit, land condition, water quality, and risk in five study regions:
    - Savannas of the Victoria River District (NT) and east-Kimberly (WA)
    - Woodlands of the Burdekin and Fitzroy catchments (north-east and central Qld)
    - Mitchell grasslands of western Queensland
    - Mitchell grasslands of the Barkly Tablelands (NT)
    - Woodlands of the Maranoa-Balonne region (southern Qld)
3. Using outputs from Objectives 1 and 2 and B.NBP.0578, developed a revised set of best-bet guidelines for infrastructure development, managing stocking rate, pasture spelling and prescribed burning for each of the five study regions.
4. From the guidelines and value propositions developed in Objectives 2 & 3, selected a sub-set of best-bet guidelines for each of five study regions to be extended via regional producer demonstration sites.
5. Identified priority grazing land management research questions, and their justification, for each study region.

The major activity of the synthesis team was the collation and review of published information from experiments and trials conducted in northern Australia. This information was supplemented with relevant results from other areas (both in Australia and overseas), information from regional workshops, and input from technical experts (including their attendance at a scientific workshop).

The project team produced a report “Grazing management guidelines for northern Australia: Scientific rationale and justification” attached as Appendix 1. The report contains nine chapters. After an introductory chapter, the scientific background that underpins grazing management is presented (Chapter 2) followed by detailed individual reports on each of the four management factors including a principle and three or four guidelines to guide the application of each factor (Chapters 3-6). This is followed by a section where the information is used to devise management responses to common pasture issues in northern Australia (Chapter 7). The report concludes with recommendations for future extension and research activities (Chapters 8 and 9).

The collation, analysis and synthesis of past results has provided a solid foundation for future extension programs and also identified knowledge and information gaps that are suitable topics for future research. When combined with the results for the bio-economic modelling and information and experience from the regional groups, these will provide guidelines for grazing land management that are scientifically sound and practically relevant, and for which the long-term biological implications and financial costs and benefits have been described. In the short-term this will ensure that the guidelines are the best that can be developed with current knowledge and provide a solid foundation for the extension activities in Phase 2. In the longer term, if Phase 2 is successful, we can anticipate that grazing land management will be more appropriate for northern Australian conditions and there will be financial benefits to producers, land will be in better condition, and the northern beef industry will be more sustainable.

Contents

1 Background

Grazing management has been an important research topic for many years in northern Australia and there is over a century of practical experience of the problems and issues that face a grazing land manager. Despite the information from both research and experience, adoption of improved management is limited by inability to predict how variations in practices and combinations of practices affect production and resource condition, and also to determine the economic and practical implications of implementing practices.

The Northern Grazing Systems (NGS) project aims to overcome these limitations by integrating, enhancing and extending key findings and knowledge from past research. NGS is being conducted in two phases. This project is part of Phase 1 which aims to develop grazing land management guidelines; these will then be adopted and implemented in Phase 2. Phase 1 has three components - Bio-economic modelling and Regional assessment (which together form Project B.NBP.0578), and Synthesis (Project B.NBP.0579). The role of synthesis is to review, analyse and synthesise data and outputs from completed research studies.

2 Project objectives

By 1 July 2010 the Research Organisation will have:

1. Completed a synthesis and analysis of research and publications to review and/or develop key principles, response curves and best-bet guidelines for grazing land management particularly relating to infrastructure development, managing stocking rate, pasture spelling and prescribed burning. This work will apply across a climate and soil fertility continuum and for a range of enterprise scales and resource conditions throughout Northern Australia.
2. Contributed draft best bet guidelines to the bio-economic modelling studies in B.NBP.0578 to quantify the impacts and trade-offs associated with different grazing land management strategies (infrastructure development, managing stocking rate, pasture spelling and prescribed burning) on measures of animal production, enterprise profit, land condition, water quality, and risk in five study regions:
   - Savannas of the Victoria River District (NT) and east-Kimberly (WA)
   - Woodlands of the Burdekin and Fitzroy catchments (north-east and central Qld)
   - Mitchell grasslands of western Queensland
   - Mitchell grasslands of the Barkly Tablelands (NT)
   - Woodlands of the Maranoa-Balonne region (southern Qld)
3. Using outputs from Objectives 1 and 2 and B.NBP.0578, developed a revised set of best-bet guidelines for infrastructure development, managing stocking rate, pasture spelling and prescribed burning for each of the five study regions.
4. From the guidelines and value propositions developed in Objectives 2 & 3, selected a sub-set of best-bet guidelines for each of five study regions to be extended via regional producer demonstration sites.
5. Identified priority grazing land management research questions, and their justification, for each study region.

3 Methodology

3.1 Background

Grazing land management covers a wide range of activities but for this project it was limited to four management factors - infrastructure development (fences and water points), stocking rate management, pasture resting and prescribed burning.

Six target regions were identified for NGS:

- Victoria River District-east Kimberley
- Burdekin woodlands
- Fitzroy woodlands
- Mitchell grasslands–western Queensland
- Mitchell grasslands–Barkly Tablelands
- Maranoa-Balonne woodlands.

The synthesis team consisted of John McIvor, Tony Grice, Leigh Hunt (all from CSIRO Sustainable Ecosystems) and Steven Bray (Queensland Department of Employment, Economic Development and Innovation).

3.2 Activities

The major activity of the synthesis team was the collation and review of published information from experiments and trials conducted in northern Australia. This information was supplemented with relevant results from other areas (both in Australia and overseas), information from regional workshops, and input from technical experts (including their attendance at a scientific workshop).

4 Results and discussion

The synthesis team produced a report “Grazing management guidelines for northern Australia: Scientific rationale and justification” attached as Appendix 1.

The report contains nine chapters. After an introductory chapter, the scientific background that underpins grazing management is presented (Chapter 2) followed by detailed individual reports on each of the four management factors including principles and guidelines to guide their application (Chapters 3-6). This is followed by a section where the information is used to devise management responses to common pasture issues in northern Australia (Chapter 7). The report concludes with recommendations for future extension and research activities (Chapters 8 and 9).

5 Success in achieving objectives

5.1 Objective 1

Completed a synthesis and analysis of research and publications to review and/or develop key principles, response curves and best-bet guidelines for grazing land management particularly relating to infrastructure development, managing stocking rate, pasture spelling and prescribed burning. This work will apply across a climate and soil fertility continuum and for a range of enterprise scales and resource conditions throughout Northern Australia.

This objective was achieved and the report is attached as Appendix 1. The report contains chapters for each of the four management options [infrastructure development (fences and water points), stocking rate management, pasture spelling and prescribed burning] which detail the research that has been conducted in northern Australia plus other relevant information, and use this to develop principles and guidelines for grazing land management. These principles and guidelines are then applied to four common management issues in northern Australia (matching feed supply and animal demand, managing C condition land, woody plant problems, utilising ungrazed areas in large paddocks).

5.2 Objective 2

Contributed draft best bet guidelines to the bio-economic modelling studies in B.NBP.0578 to quantify the impacts and trade-offs associated with different grazing land management strategies (infrastructure development, managing stocking rate, pasture spelling and prescribed burning) on *measures of animal production, enterprise profit, land condition, water quality, and risk in five study regions:*

- *Savannas of the Victoria River District (NT) and east-Kimberly (WA)*
- *Woodlands of the Burdekin and Fitzroy catchments (north-east and central Qld)*
- *Mitchell grasslands of western Queensland*
- *Mitchell grasslands of the Barkly Tablelands (NT)*
- *Woodlands of the Maranoa-Balonne region (southern Qld)*

This objective was modified during the project. Rather than the synthesis team producing draft best-bet guidelines for each region, the team produced an overall set of guidelines for northern Australia. These were then used by the individual regional teams to produce guidelines for their regions. The synthesis and bio-economic modelling teams interacted closely throughout the project to identify suitable scenarios for bio-economic analysis.

5.3 Objective 3

Using outputs from Objectives 1 and 2 and B.NBP.0578, developed a revised set of best-bet guidelines for infrastructure development, managing stocking rate, pasture spelling and prescribed burning for each of the five study regions.

This objective was modified during the project. The synthesis team provided input into the individual regional guidelines but the final set of guidelines were produced by the regional groups.

5.4 Objective 4

From the guidelines and value propositions developed in Objectives 2 & 3, selected a sub-set of best-bet guidelines for each of five study regions to be extended via regional producer demonstration sites.

This objective was modified during the project. The synthesis team selected a number of issues that were of general relevance to northern Australia and suitable for extension. These formed part of the selection processes used by the individual regional teams to identify suitable extension activities for their regions.

5.5 Objective 5

Identified priority grazing land management research questions, and their justification, for each study region.

This objective was modified during the project. The synthesis team identified a number of topics that are of general relevance to northern Australia and for which sufficient information is lacking and further research is needed. These formed part of the selection processes used by the individual regional teams to identify research needs in their regions.

6 Impact on meat and livestock industry – Now and in five years time

The collation, analysis and synthesis of past results has provided a solid foundation for future extension programs and also identified knowledge and information gaps that are suitable topics for future research. When combined with the results from the bio-economic modelling and information and experience from the regional groups, these will provide guidelines for grazing land management that are scientifically sound and practically relevant, and for which the long-term biological implications and financial costs and benefits have been described. In the short-term this will ensure that the guidelines are the best that can be developed with current knowledge and provide a solid foundation for the extension activities in Phase 2. In the longer term, if Phase 2 is successful, we can anticipate that grazing land management will be more appropriate for northern Australian conditions and there will be financial benefits to producers, land will be in better condition, and the northern beef industry will be more sustainable.

7 Conclusions and recommendations

This report serves as a statement of our current knowledge and will be a sound technical basis for the extension activities in Phase 2. However, as new information is gathered from research trials this should be incorporated in future revisions so this technical base is kept up to date. If this is done and combined with new learnings, practical experience, and results from further bio-economic modelling, there will be a continuing solid foundation for grazing land management in northern Australia.

8 Appendices

8.1 Appendix 1 Grazing management guidelines for northern Australia: Scientific rationale and justification

Grazing management guidelines for northern Australia: Scientific rationale and justification

John McIvor[1], Steven Bray[2], Tony Grice[1] and Leigh Hunt[1]

[1]CSIRO Sustainable Ecosystems
[2]Queensland Department of Employment, Economic Development and Innovation

1. Introduction

The Northern Grazing Systems (NGS) project aims to increase adoption of innovative best-practice grazing management by beef producers throughout Queensland, the Northern Territory and the Kimberley and Pilbara regions of Western Australia.

Grazing management has been an important research topic for many years in northern Australia and there is over a century of practical experience of the problems and issues that face a grazing land manager. Despite the information from both research and experience, adoption of improved management is limited by inability to predict how variations in practices and combinations of practices affect production and resource condition, and also to determine the economic and practical implications of implementing practices.

The NGS project will integrate, enhance and extend key findings and knowledge from past research to address these limitations. In Phase 1 (to be completed by July 2010) a suite of best-bet management guidelines and strategies for different environments and scales of operation will be developed. (These will be adopted and implemented in the following Phase 2.)

There are three activities in six target regions in Phase 1:

(a) Synthesis – review, analysis and synthesis of data and outputs from completed research studies.
(b) Regional assessment – source, collate and report region specific information and facilitate the input of producers and regional specialists in identifying and assessing best-bet management guidelines.
(c) Bio-economic modelling – modify, link and apply existing simulation models to evaluate best-bet guidelines and strategies in terms of their impacts on production, economic performance, risk profile and resource condition.

For the NGS project, grazing management includes four management factors - infrastructure development (fences and water points), stocking rate management, pasture spelling and prescribed burning.

The six target regions are:

- the Victoria River District-east Kimberley
- Burdekin woodlands
- Fitzroy woodlands
- Mitchell grasslands–western Queensland
- Mitchell grasslands–Barkly Tablelands
- Maranoa-Balonne woodlands.

The location of these regions is shown in Figure 1.1 and typical values for some characteristics of the regions are given in Table 1.1. Annual rainfall varies widely over these regions from 250 mm in the drier parts of the Mitchell grass lands in western Queensland to over 800 mm in parts of the Burdekin woodlands. Rainfall is summer dominant in all regions but rainfall seasonality is greatest in the north-west where >90% of the annual rainfall occurs in summer, and seasonality declines to the east and south so that in parts of the Maranoa-Balonne the proportion falling in summer is <70%. Frosts are common in the Maranoa-Balonne and the southern parts of the Burdekin and Fitzroy woodlands and Mitchell grass-western Queensland. Clay soils are particularly important in the two Mitchell grass regions and also occur in the other regions where they are mixed with a variety of other soils. Property size varies widely with largest properties on the Barkly Tablelands and smallest properties in the Fitzroy and Maranoa-Balonne regions. Cattle breeding and production of animals for live export or sale as stores are important in all regions with backgrounding and fattening also important in the east and south of Queensland.

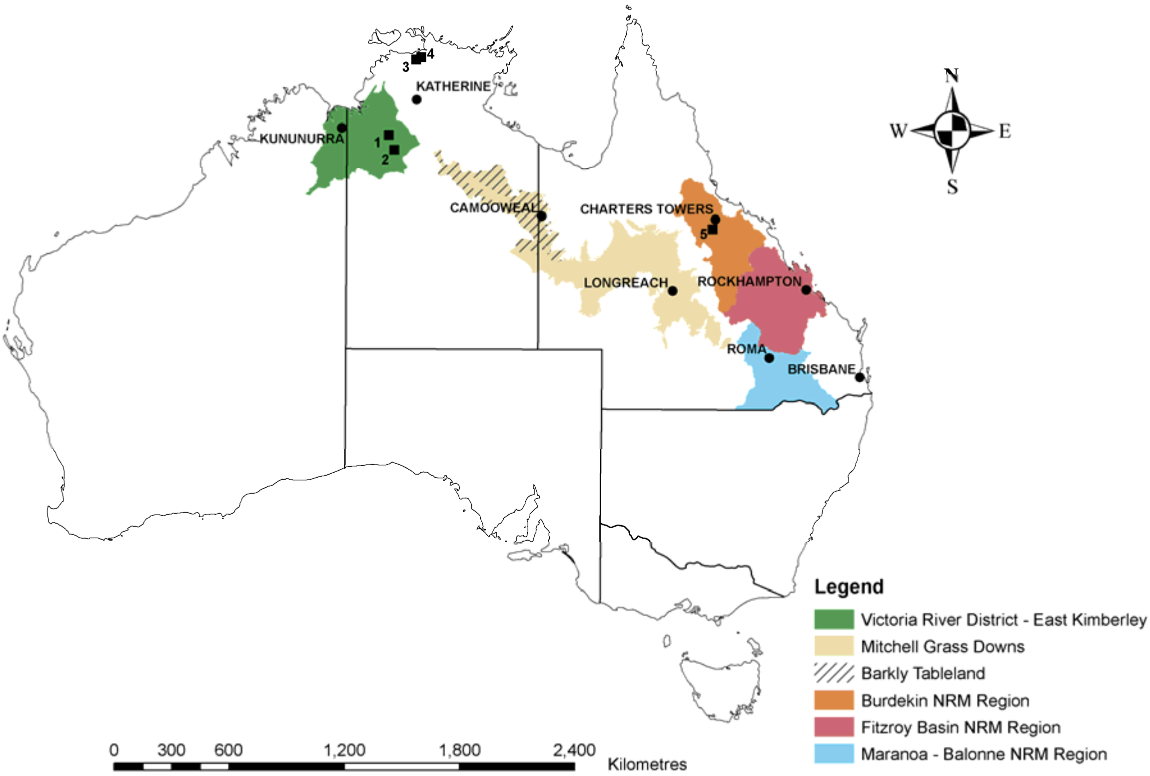

Figure 1.1. The six regions targeted by this review and some locations referenced in the report. The regions are delineated as follows. The Victoria River District - east Kimberley is an amalgamation of the Victoria and Ord River catchments, Victoria-Bonaparte Interim Biogeographic Regionalisation of Australia (IBRA) Region and the Ord-Victoria IBRA sub-region of the Ord-Victoria Plain Region. The Burdekin Woodlands, Fitzroy Woodlands and Maranoa-Balonne Woodlands align with the North Queensland Dry Tropics Natural Resource Management (NRM), the Fitzroy Basin Association NRM and the Border Rivers - Maranoa - Balonne NRM Regions respectively. The Mitchell Grasslands - Barkly Tablelands is delineated as the Northern Territory portion of the Barkly Tablelands sub-region of the Mitchell Grass Downs IBRA Region. The Mitchell Grasslands - Western Queensland is defined as the Queensland portion of the Mitchell grass Downs IBRA region. Numbered locations [1. Kidman Springs; 2. Pigeon Hole; 3. Kapalga (Kakadu National Park); 4. Munmarlary (Kakadu National Park); 5. Wambiana] are referred to in the text.

This document reports the outcome of the "Synthesis" project. The scientific background that underpins grazing management is presented (Chapter 2) followed by detailed individual reports on each of the four management factors including principles and guidelines to guide their application (Chapters 3-6). This is followed by a section where the information is used to devise management responses to common pasture issues in northern Australia (Chapter 7). The report concludes with recommendations for future extension and research activities (Chapters 8 and 9).

Table 1.1. Some characteristics of the six regions.

	Victoria River District-east Kimberley	**Burdekin woodlands**	**Fitzroy woodlands**	**Mitchell grass-western Queensland**	**Mitchell grass-Barkly Tablelands**	**Maranoa-Balonne woodlands**
Annual rainfall (mm)	400-800	500-800	500-800	250-500	350-500	400-650
Rainfall seasonality[1]	90-95	75-85	70-75	70-80	88-92	60-70
Major pasture communities (Tothill and Gillies 1992)	Open downs (*Astrebla*) Perennial tallgrass (*Chrysopogon*) Short grass grassland Spinifex	Black speargrass Aristida-Bothriochloa Brigalow forest/scrub Spinifex	Black speargrass Aristida-Bothriochloa Brigalow forest/scrub Open downs (*Dichanthium*)	Open downs (*Astrebla*) Perennial shortgrass Gidgee woodland Spinifex	Open downs (*Astrebla*) Aristida-Bothriochloa (eucalypt woodland)	Aristida-Bothriochloa Brigalow forest/scrub
Woodland types	Terminalia-Bauhinia Eucalyptus-Corymbia	Ironbark–box woodlands Blackwood Brigalow Gidgee	Ironbark–box woodlands Brigalow	Acacia nilotica Gidgee	Open treeless plains	Poplar box Brigalow Cypress pine Bendee/mulga on ridges
Property size (km^2)	2500-3500	250-350	100-150	200-400	5000-8000	100-250

[1]Percentage of annual rainfall during summer (October-March)

2. Scientific background

The grazing animal is the major means of economic exploitation of rangelands but can also be the means of their degradation. Grazing management aims to balance the antagonistic relationships between efficiency of energy capture, harvest efficiency and livestock conversion efficiency to maximise overall efficiency as it is not possible to maximise all simultaneously (Heitschmidt and Taylor 1991). It is the job of management to integrate the conflicting needs of plants and animals, to effect use without misuse, while achieving the highest level of animal production commensurate with maintaining or improving range condition (Pratt and Gwynne 1977).

Grazing animals convert solar energy captured by grasslands into products useful to humans (Figure 2.1). The vegetation (grasses, forbs, shrubs, trees) captures solar energy and uses it to produce forage which is eaten by animals and used by them to produce animal products that are sold and provide the main income for grazing properties.

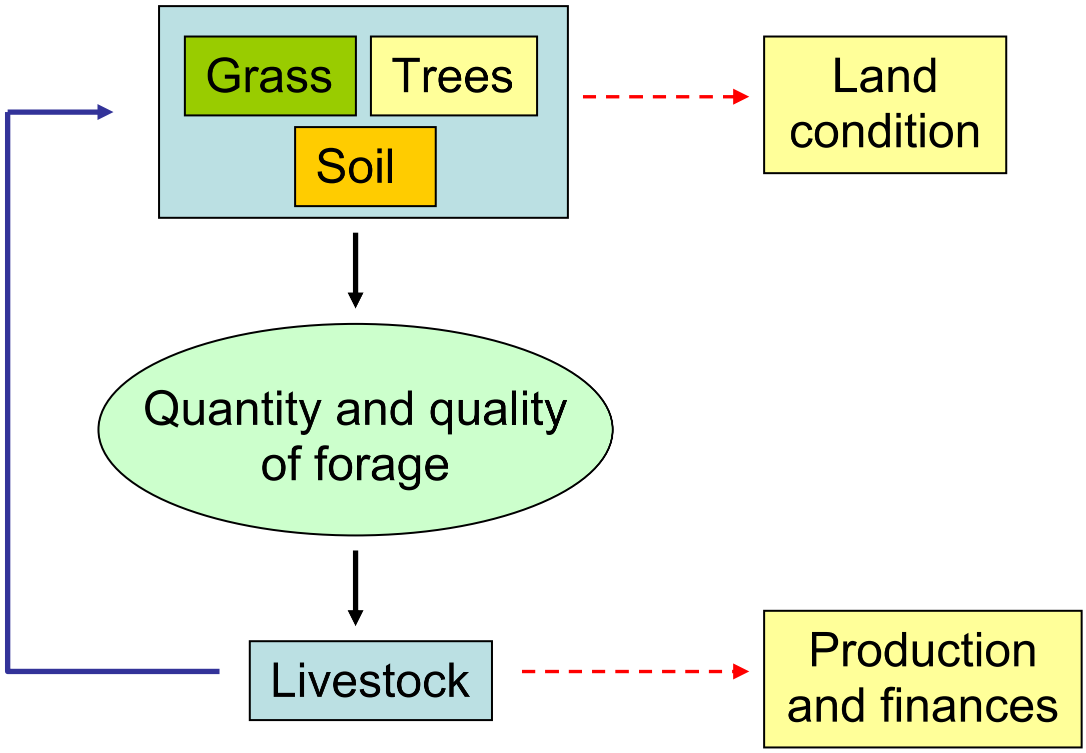

Figure 2.1. Simple model of beef production from pastures.

The four management factors (infrastructure development, stocking rate management, pasture spelling and prescribed burning) directly impact on the vegetation or the livestock and indirectly on the quantity and quality of forage available to the animals. The state of the trees and pastures (and soil) determines land condition while the amount (and quality) of animal product determines production and economic performance. Diet selection and consumption by livestock has a direct feedback on the state of the pasture and land condition.

In most pastures in northern Australia perennial tussock grasses provide most of the feed for livestock and they are also a major source of soil cover and provide habitat for animals and microorganisms. The health and productivity of these pastures is largely determined by what happens to these perennial tussock grasses.

2.1. Impacts of defoliation on individual plants

Frequent and/or severe defoliation adversely affects plant growth and persistence.

- Reduces leaf area and ability to intercept light
- Reduces photosynthesis and carbon capture
- Reduces root growth
- Reduces seed production
- Leads to increased mortality

The ability of pasture plants to replace tissues lost to herbivores is of critical importance for plant survival, growth and reproduction. A number of reviews have concluded that more frequent and more severe defoliation results in a reduction of herbage dry matter yield for both temperate and tropical pastures in a range of environments (Jameson 1963; Alcock 1964; Harris 1978). The influence of defoliation on growth is illustrated in Figure 2.2 which shows the yield of tops and roots of plants of *Andropogon pumilus* cut to three heights (5, 10 or 15 cm) at three intervals (15, 30 or 45 days) over a 90 day period (Singh and Hall 1976).

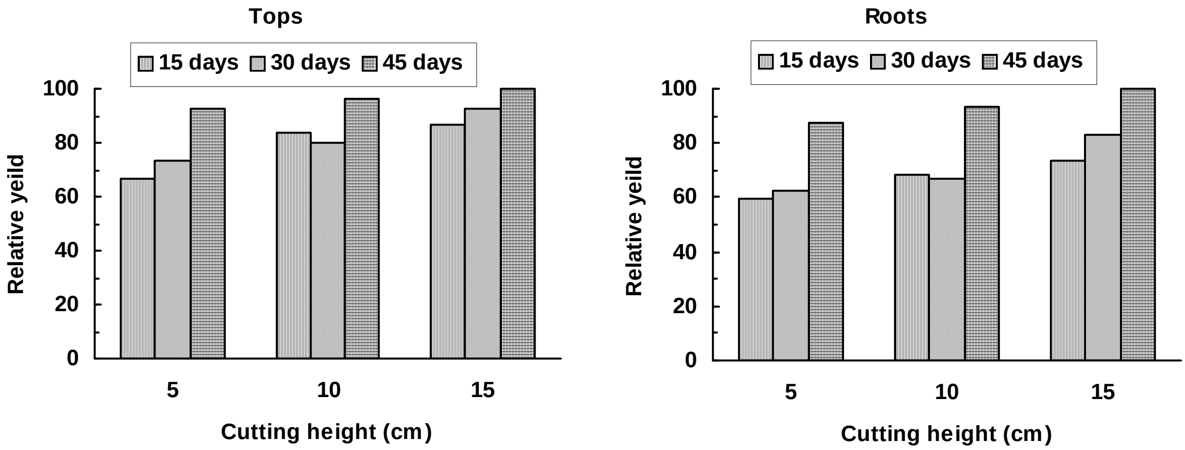

Figure 2.2. The influence of cutting height and cutting frequency on the relative yield of tops (accumulated over all harvests) and roots (at final harvest) of plants of *Andropogon pumilus* (from Singh and Hall 1976).

The impact of defoliation on root growth is illustrated in the following figure.

Figure 2.3. Comparison of the effect of frequent clipping (right) and light clipping (left) on spear grass plants (from Ash *et al.* 2001).

After a discrete defoliation event of moderate to severe intensity, plants immediately enter a transient phase of rapidly changing carbon and nutrient availability and allocation patterns. Photosynthesis is severely reduced by defoliation and the effect of this propagates rapidly through fast-growing plants reducing root growth, respiration and nutrient uptake dramatically within 24 hours after defoliation. Continued availability of photosynthate/labile carbohydrate is important for the maintenance of root growth and function in rapidly growing plants so root growth and maintenance are extremely sensitive to shoot defoliation. Fine roots may also die and begin to decompose soon after defoliation. With the exception of effects on nitrogen fixation, these immediate effects are the result of declining carbohydrate availability in roots and remaining shoot tissues. Substantial carbohydrate depletion occurs before much regrowth is produced.

2.2. Plant growth after defoliation

The following description is largely drawn from Richards (1993).

The immediate transient effects of defoliation are followed by a sequence of recovery processes. The initiation of recovery is most rapid, and may begin within hours after defoliation, when increased relative allocation of both carbon and nitrogen resources to new leaves is driven by active shoot meristems remaining on the plant after defoliation. Rapid activation of quiescent meristems is an alternative that is essential for defoliation tolerance when active shoot meristems are removed by defoliation.

The initial source of carbohydrate preferentially allocated to shoots is the reserves present at the time of defoliation. In grasses the most important location of these reserves is usually in stem bases or stubble and high levels can contribute to more rapid regrowth. The quantitative contribution of carbohydrate reserves to the carbon required for regrowth outweighs that of current photosynthesis for only a few days. After this short period, current photosynthate is the more important carbon source and continues to be preferentially allocated to the regrowing shoot sinks until the demands of these sinks are satisfied. Only then is allocation to roots increased.

A positive carbon balance is required to restore plant growth, maintenance and storage to normal levels. Reduced rates of respiration contribute to this by reducing demand but are inadequate alone to return a plant to positive carbon balance; increases in whole plant carbon gain are necessary. Two processes affect the recovery of carbon gain capacity after defoliation:

(a) re-establishment of the photosynthetic canopy by leaf and shoot growth.

Defoliation-tolerant plants have the capacity for rapid refoliation. The most important characteristic for this is the presence of active meristems remaining after defoliation – these allow leaf expansion from already formed cells rather than requiring new cell production. Differences in defoliation tolerance between rhizomatous/stoloniferous and tussock grasses are largely a function of active meristem availability. In tussock grasses with synchronous tiller development, recovery from defoliation is poor when most meristems are removed; with asynchronous tiller development recovery potential is higher because some active meristems remain.

The influence of bud numbers on plant growth after defoliation was examined by Mott *et al.* (1992). In previously droughted and dormant *Themeda triandra* plants virtually all tiller buds (95%) grew simultaneously at the start of the growing season. Many of the parental tillers were killed by defoliation in the first few weeks and with no further daughter tillers available for replacement, many plants died.

In grasses, high levels of stored carbohydrates cannot make up for absence of active meristems because much of the stored carbohydrate is used by other respiring sinks during the time taken to activate quiescent meristems. However, when active meristems are present high carbohydrate availability can increase rate of refoliation. Refoliation is also influenced by environmental factors such as water stress, nutrient availability and temperature.

(b) increases in photosynthetic capacity of remaining and regrowing foliage.

Photosynthetic rates of foliage on defoliated plants are often (but not always) higher than those of foliage of the same age on undefoliated plants. This response (compensatory photosynthesis) occurs in both mature and expanding leaves remaining after defoliation, and in new leaves produced during regrowth. Compensatory photosynthesis reflects rejuvenation of leaves or an inhibition of the normal decline in photosynthetic capacity as leaves age and senesce. Compensatory photosynthesis can be induced by either changes in the light environment or by changes in endogenous factors (source/sink interactions, root/shoot ratios) that are affected by defoliation or by a combination of these.

The rapid establishment of a photosynthetic canopy, initiated by immediate increases in shoot resource allocation, depends on continued preferential allocation of carbon and nitrogen resources to the shoot system. This preferential allocation refers equally to stored and currently acquired resources. The relative importance of reserves persists longer for nitrogen than for carbon in nutrient-sufficient plants. Increased photosynthetic capacity and high leaf production rates have a multiplicative effect in restoring the plant's carbon balance and contribute to high relative growth rates after defoliation.

These responses to defoliation are illustrated by the different responses of *Cenchrus ciliaris* and *Themeda triandra*. *Cenchrus ciliaris* is better adapted to defoliation than *Themeda triandra* because it is able to retain a much greater amount of leaf area after defoliation which combined with the maintenance of moderate levels of light utilising efficiency generates higher leaf area and shoot weight throughout the regrowth period (Hodgkinson *et al.* 1989).

The age and type of tissues removed strongly influence how quickly a plant recovers. Loss of old leaves usually has much less effect than loss of the same amount of young leaves. Loss of meristematic tissues usually has a much greater effect than the proportional loss of biomass, leaf area or plant resource (e.g. carbon, nitrogen).

Recovery from defoliation depends on the plant's abiotic and biotic environment. Abiotic conditions (light, water, nutrients) that limit resource availability before and after defoliation can have decisive effects on a plant's ability to recover from defoliation. Also plants with undefoliated or more herbivory-tolerant neighbours may not effectively recover from defoliation even though they would recover completely from a similar defoliation in isolation (Richards 1993).

The above conclusions refer to fast growing, vegetative plants growing without competition or major abiotic constraints, and recovering from discrete moderate to severe defoliation events. In slow growing plants under nutrient limited conditions, root growth, respiration and nutrient absorption are reduced less or even increased after defoliation compared with the great decreases in rapidly growing plants. Even after defoliation these plants may be more nutrient than carbon limited. The sequential re-establishment of shoot then root activity described above may be reversed in nutrient-stressed plants.

2.3. Pasture growth after defoliation

As a sward begins to regrow from low leaf area index (LAI), leaf appearance and expansion result in increases in LAI, light interception and gross photosynthesis (Lemaire and Chapman 1996). In the early stages of regrowth, there is little or no death of leaf material, so that gross and net herbage accumulation are similar (Figure 2.4). Leaf death rate initially lags behind the rate of new tissue production; net herbage accumulation rate is maximal during this lag period, but decreases until the rate of tissue death exactly balances the rate of new tissue production and a ceiling yield of live tissue is reached.

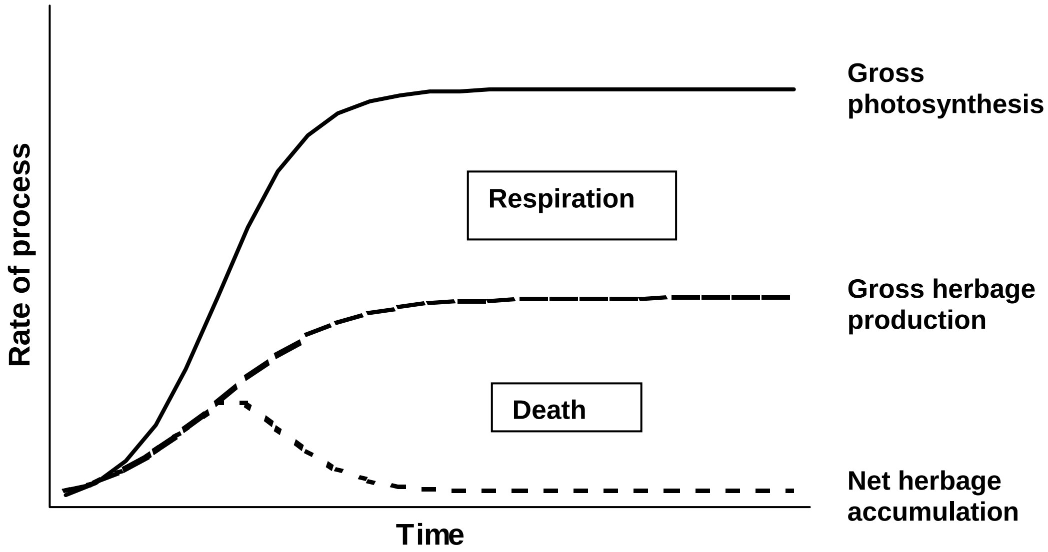

Figure 2.4. The relationship between rates of gross photosynthesis, respiration, gross herbage production, net herbage accumulation and death in a sward during regrowth (from Lemaire and Chapman 1996).

Following severe defoliation, the increase in pasture yield is sigmoidal (Parsons and Penning 1988) (Figure 2.5). Four phases can be recognised.

Phase 1 Early vegetative During this phase the pasture is short and leafy but yield is low; pasture growth rate is slow to moderate due to low leaf area and light interception; the pasture has a high sensitivity to grazing pressure; and pasture quality is very high (low quantity, high quality pasture).

Phase 2 Late vegetative During this phase the leaf area increases and growth rates reach their maximum; pasture yield increases rapidly; the pasture has a moderate sensitivity to grazing pressure; and pasture quality remains high (high quantity, high quality pasture).

Phase 3 Reproductive During this phase stems and seedheads develop; growth rate drops to nil; pasture yield reaches a high level but ceases increasing; the pasture has low to moderate sensitivity to grazing pressure; and pasture quality declines to moderate or low levels (high quantity, low quality pasture).

Phase 4 Mature or dormant Little or no growth; low sensitivity to grazing pressure; low to very low forage quality, (high quantity, low quality pasture)

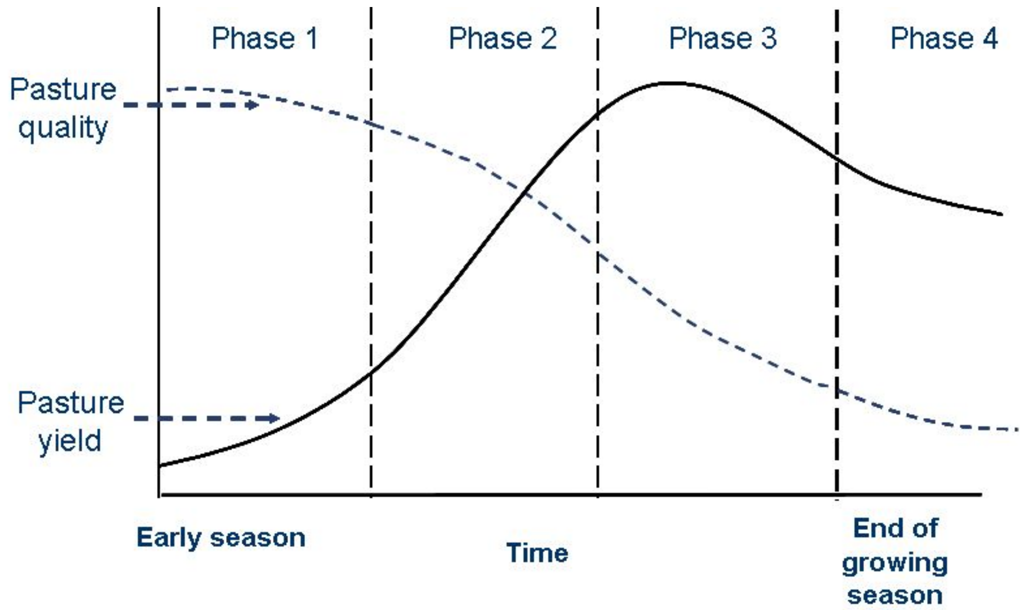

Figure 2.5. Phases of growth in a regrowing pasture.

During regrowth, instantaneous growth rate increases to a maximum during Phase 2 and then declines while average growth rate continues to increase for a longer period (Figure 2.6). To optimise harvested yield in intermittently defoliated systems, swards should be harvested at the time of maximum average growth rate i.e. when instantaneous and average growth rates are equal (Lemaire and Chapman 1996). The net rate of herbage production depends on the balance between gross tissue production and senescence and these processes are out of phase. Growth rates are greater when the sward is increasing in leaf area than when it is maintained at that LAI (Parsons *et al.* 1988).

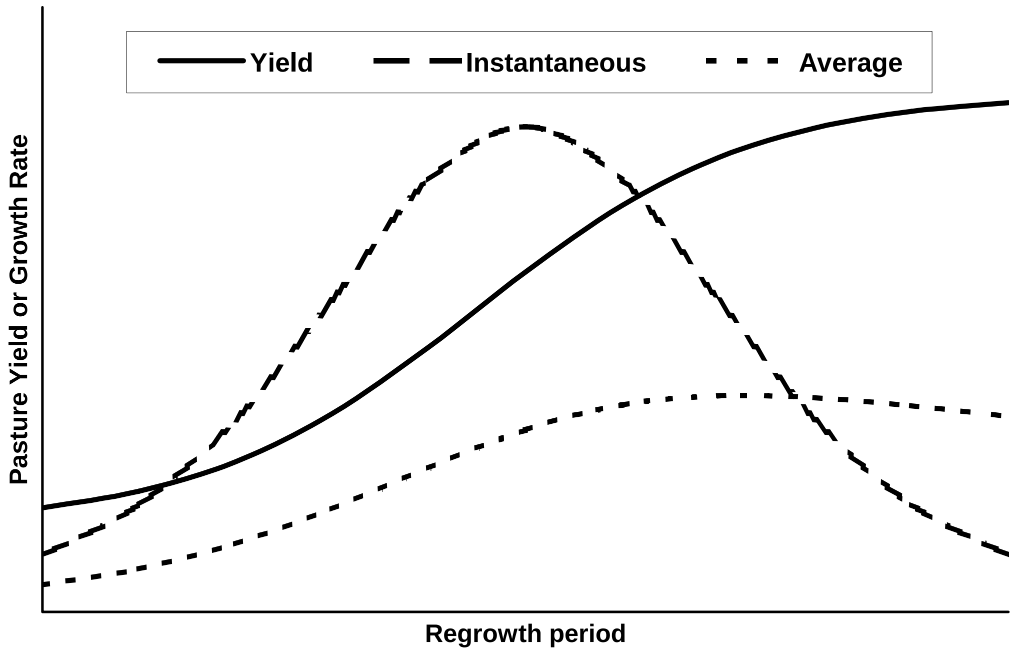

Figure 2.6. The effect of duration of regrowth on pasture yield, and instantaneous and average growth rates (from Parsons and Penning 1988).

Pasture growth rates are often reduced at high stocking rates due to low leaf area and light interception, and at low stocking rates due to increased senescence, but between these extremes pasture growth rates are not greatly affected by stocking rate (White 1987). Hodgson and Wade (1978) concluded that in general, variation in stocking rate had relatively small effects upon herbage production, and these effects were probably insufficient to influence the amount of herbage harvested. In a patchy pasture it is possible to have low growth rates due to low leaf area and light interception in heavily grazed patches, and low growth rates due to increased senescence in nearby ungrazed areas.

2.4. Impacts of heavy grazing on pastures

In addition to the immediate impacts on pasture growth, heavy grazing can change land condition (including botanical composition of the pasture) and the structure/patchiness of pastures. The effects of grazing and the critical levels of factors such as pasture utilisation and ground cover will vary amongst rangeland types, depending on pasture species, soil type, rainfall and other environmental factors.

2.4.1. Land condition

The general changes in land condition with heavy grazing are described in the changes from A (good) to D (poor) in the ABCD land condition framework (Quirk and McIvor 2003). Land in A condition has the following features:

- good coverage of perennial grasses [dominated by the perennial, palatable and productive (3P) grasses]
- little bare ground
- few weeds and no significant infestations
- good soil condition, no erosion, good surface condition
- no sign, or early signs, of woodland thickening

Changes from A condition typically involve a decline in the proportion of 3P grasses (or decreaser species) and an increase in less palatable and/or prostrate grasses, annual grasses and forbs (McIvor and Orr 1991), a decrease in ground cover (more bare ground), a decline in soil condition, an increase in soil erosion and, in some cases, an increase in the density of woody plants.

2.4.1.1. Effects on plants and pastures

Clipping and grazing studies have demonstrated the detrimental effects of heavy or frequent defoliation during the growing season on plant survival and productivity (e.g. Roe and Allen 1945; Mott *et al*. 1992). In a study in the Mitchell grasslands using sheep, Roe and Allen (1945) found that heavy summer grazing (~1 sheep per hectare) almost halved the proportion (by weight) of Mitchell grass (*Astrebla* spp.) in the pasture compared with pastures grazed at the same stocking rate in winter but rested in summer. High levels of pasture utilisation (in excess of 50%) during the growing season have also been shown to cause marked declines in the tussock basal cover of various tropical perennial grass species (e.g. actual percentage basal cover reduced by 3–5%), especially in growing seasons with below average rainfall (McKeon *et al*. 1990). There is an increased likelihood of plant death and reduced productive potential following large declines in basal area.

When perennial plants are heavily and repeatedly defoliated various plant physiological processes can be disrupted (see Section 2.1). These changes can lead to alterations in the rates of plant life-cycle (or demographic) processes. Flowering and seed production are usually the first demographic processes to be disrupted by defoliation (Crawley 1983; Hodgkinson 1991; Hunt 2001), with increasing stocking rates reducing seed production by key perennial savanna grasses such as *Themeda triandra* (O'Connor and Pickett 1992; McIvor *et al*. 1996). These changes occur because plants direct photosynthates to the recovery of leaf area rather than reproduction, and through the consumption of inflorescences by livestock or the death of meristems. In the short term this might not be a concern if there are subsequent opportunities for seed production to occur. However, it is a feature of many palatable perennial savanna grasses that they have only small short-lived seed banks (O'Connor 1991), and recruitment in *Astrebla* spp. and *Themeda triandra*, for example, is generally limited by a lack of seed (Orr 1991; O'Connor 1996). O'Connor (1991) identified the potential for palatable perennial savanna grasses to become locally extinct under heavy grazing as a result of the combination of low seed availability and increased mortality of established plants under sustained heavy defoliation.

Numerous studies have reported the adverse effects of consistently high stocking rates in reducing perennial grass abundance (e.g. Winter *et al*. 1989). Historically, high stocking rates during drought have resulted in declines in perennial grasses in northern Australia (Tothill and Gilles 1992). In South Africa O'Connor (1994) found that short periods of heavy grazing combined with drought markedly reduced the abundance of *Heteropogon contortus* and *Themeda triandra* in the pasture. Similarly O'Reagain *et al*. (2007) reported that the frequency of palatable, perennial and productive (3P) grasses and pasture yield all declined with increasing utilisation rate in the Wambiana study in north-eastern Queensland. The density of 3P tussocks and contribution of 3Ps to total yield and basal cover was greater in the light stocking treatment (8-10 ha per animal equivalents ≡ 20-25% annual pasture utilisation) than the heavily stocked treatment (approximately 5 ha per animal equivalents ≡ 40-50% annual pasture utilisation). Pasture condition was maintained under light stocking despite years with below average rainfall, but not under heavy stocking. Importantly, Ash and McIvor (1998) demonstrated that medium to high pasture utilisation (30–45%) during the growing season can suppress plant growth in subsequent seasons.

Studies of the mortality of perennial grass plants at Lake Mere in the mulga country of north-western NSW showed that the co-occurrence of drought and heavy grazing predisposed grasses to higher mortality than if plants were not grazed. Rainfall and rainfall/evaporation during the preceding 3 months was a good predictor of plant death (Hodgkinson and Muller 2005a) with mortality increasing as the height of plants (reflecting degree of grazing) decreased (Hodgkinson and Muller 2005b; Hacker *et al.* 2006).

2.4.1.2. Effects on soils and ground cover

High stocking rates reduce ground cover (Scanlan and McIvor 1993; McIvor 2002; Silcock *et al.* 2005; O'Reagain *et al*. 2007;) increasing run-off and soil loss. For example, McIvor *et al*. (1995) reported nearly a three-fold increase in soil loss with an increase in stocking rate from 1 AE (an Adult Equivalent is a 450 kg dry steer)/15 ha to 1 AE/3 ha. Given that many of the nutrients required for plant growth are concentrated in the top few centimetres of surface soil, the removal of soil can reduce pasture productivity and limit the recruitment of perennial grasses. Maintaining high levels of ground cover is essential to promoting water infiltration into the soil, minimising soil and nutrient loss, thus protecting the productive potential of the land and maintaining river water quality (O'Reagain *et al*. 2007 ; Post *et al*. 2006). The critical levels of ground cover vary between rangeland types and depend on factors such as soil type, slope, infiltration rates and pasture vegetation type. For the Indian couch grass (*Bothriochloa* *pertusa*) dominated pastures in north-east Queensland minimum ground cover levels of 60% are recommended (Post *et al*. 2006), while 50% cover is the recommended minimum in the Mitchell grasslands of the Barkly Tableland (D. Phelps, pers. comm.).

Type of vegetation (or ground cover) may be important in determining infiltration rates. Observations at Wambiana (north-east Queensland) indicate that infiltration rates appear to be greatest in currant bush (*Carissa lanceolata*) patches, followed by perennial grass patches and then in bare ground. Rates of infiltration are dramatically reduced in bare patches. These trends are likely to be due to changes in soil macroporosity, at least in the upper soil layer, which have been observed to follow a similar pattern of decline from currant bush to bare patches (T. Dawes, pers. comm.).

2.4.1.3. Effects on soil biology

Grazing pressure affects the composition and activity of soil organisms. In studies at Hillgrove and Cardigan (both in north-east Queensland), high grazing pressure reduced soil microbial biomass carbon levels (Holt 1997), peptidase and amidase activity potentially lowering nitrogen availability (Holt 1997), termite species diversity (from six species [mainly grass feeders] to one species [a wood feeder]) at Hillgrove), termite activity (Holt *et al*. 1996a) at both sites, and Acari (mites) populations at Hillgrove although not at Cardigan (Holt *et al*. 1996a). In another comparison at these sites, poor condition pastures had lower total carbon and microbial biomass carbon than good condition pastures presumably reflecting higher grazing pressure (Holt 1997). At Wambiana, the abundance and diversity of soil dwelling mites were greater in perennial grass sites than bare ground sites (Gibb *et al.* 2008). At Manbulloo near Katherine in the Northern Territory, termite composition changed from domination by detritus feeders to domination by dung feeders as grazing pressure increased (Birkill 1985). Populations of mound-building termites were significantly reduced after 14 years in pastures of Sabi grass (*Urochloa mosambicensis*) compared to native semi-arid tropical woodland (Holt and Coventry 1988). These changes in composition have been attributed to changes in available fodder resources (grass, litter, dung, wood).

Similarly, significant decreases in microbial biomass have been observed in bare patches (lowest) when compared to annual (intermediate) and perennial grass patches (highest) at three Ecograze sites near Charters Towers (Holt *et al.* 1996b). In a more detailed study at Cardigan along 60 cm transects near perennial grass tussocks or in bare patches, Northup *et al.* (1999) found highest soil microbial biomass at tussock centres with successively lower levels from tussock centres outwards. The lowest soil microbial biomass levels were in bare patches.

Roth (2004) has pointed out the significance of earthworm activity for soil hydrological function – plots with the highest infiltration rates had high to very high earthworm activity and cattle were excluded from all these plots, contrasting with the lower infiltration rates on grazed plots.

2.4.2. Patchiness

Pastures grow more rapidly than they can be consumed by animals from soon after the onset of growth. In continuously grazed pastures, cattle graze patchily generating heavily defoliated patches by concentrating their grazing on some areas and continuing to graze them until the end of the season while other areas are left ungrazed and become rank and senescent (Mott 1987). Due to the rapid maturation of tropical grasses, differences in quality are rapidly established between grazed and ungrazed areas so stock continually return to the more palatable, higher quality pastures on areas already grazed (Norman 1960; Smith 1960; Teague *et al.* 2004). Andrew (1986a) described the seasonal pattern of grazing at Katherine. Where animals were grazing a pasture burnt in the dry season, the cattle grazed most plants when growth was new and in short supply (late dry season and early wet season) but as grass growth became more abundant, the cattle grazed a smaller and smaller total area until growth ceased. After that cattle began grazing new areas and extending the old patches.

The heavy defoliation of the patches leads to one or more of the following

- Changed vegetation structure to short swards e.g. a maximum height of 5 cm or less (Mott 1987; McIvor *et al.* 2005) compared to 1 m in ungrazed patches (Mott 1987). McNaughton (1984) described these areas as grazing lawns.
- Changes in species composition as perennial tussock grasses are lost and replaced by forbs, stoloniferous and /or defoliation tolerant grasses (Mott 1987; McIvor *et al.* 2005)
- Increases in the amount of bare ground with some deleterious changes to the soil surface (Mott *et al.* 1979; Fuls 1992; Scanlan *et al.* 1996b; Teague *et al.* 2004).

2.5. Timing of defoliation is critical

Most physiological harm occurs when over-utilisation takes place during active growing and flowering/seeding periods (Bosch and Tainton 1988) and plants are most sensitive when regrowing in the early wet season (Phase 1).

Mott (1987) clipped *Themeda triandra* dominant pastures at Katherine that had been burnt during the previous dry season to 5 cm at weekly intervals for 4 weeks at different times during the growing season, and then measured pasture yield at the end of the following growing season to estimate the regrowth potential of the clipped plants. In plots defoliated in December and January the regrowth in the following year was less than 60% of that from plants clipped late in the season (Figure 2.7a). Andrew (1986a) estimated early wet season grazing reduced yields at the end of the wet season by 60% in similar pastures.

Tainton *et al.* (1977) cut previously burnt pasture to 1 cm above ground level. Individual plots were cut on one occasion at various times during the growing season and a final harvest was made after the end of the growing season. Defoliation reduced production during the year (sum of the first cut during the growing season plus the harvest after the growing season). The impact was greatest (estimated to be approximately 60% reduction) when the cut was in the early wet season and declined with later cuts (Figure 2.7b).

In a study by Ash and McIvor (1998), pastures at Katherine dominated by *Themeda triandra* and *Chrysopogon fallax* were grazed for 8 week periods in either the early wet, late wet or dry seasons to achieve three rates of pasture utilisation (low, medium and high). The pastures then remained ungrazed for the remainder of the year. In the following year after these differential utilisations, pastures with medium (22%) and high (42%) utilisation in the early wet season had only 80% and 60% of the yields of those treatments that were grazed at low levels of utilisation (13%) at this time or were grazed during the dry season. Effects of grazing on species composition were also greatest when the grazing was early in the wet season; high rates of utilisation reduced the proportion of *Themeda* and increased the proportion of forbs.

Norman (1965) found only 30 grazing days/acre/yr (approximately 70/ha) in the early wet season (December-February) was sufficient to almost eliminate the perennial grasses at Katherine. After two years of such grazing, pastures that were grazed during the growing season produced only 290 kg/ha of perennial grass compared to 3100 kg/ha for pastures that had not been grazed during the wet season but then grazed during the dry season for the same number of grazing days.

Table 2.1. Impact of grazing (low, medium or high utilisation rate) at different times of the year (early wet, late wet, dry season) on growth (relative yield where low utilisation = 100, and proportion of *Themeda triandra*) during the subsequent growing season at Katherine, NT (from Ash and McIvor 1998).

Season	Utilisation	Relative yield	*Themeda triandra* (%)
Early wet	Low	100	70
	Medium	82	64
	High	61	63
Late wet	Low	100	50
	Medium	91	48
	High	68	34
Dry	Low	100	73
	Medium	107	73
	High	105	67

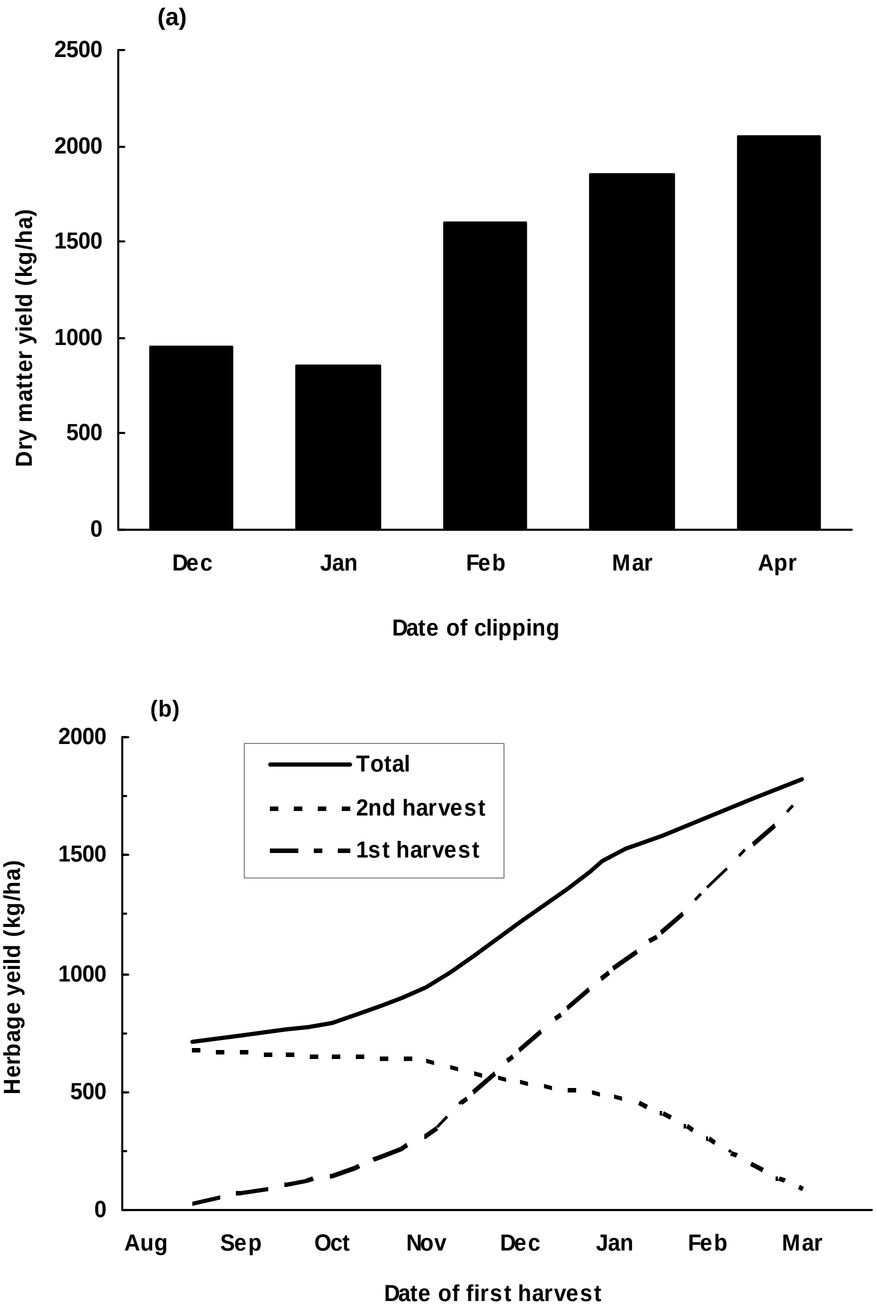

Figure 2.7. Impacts of severe defoliation during the growing season on pasture yields (a) Yield the following growing season after severe defoliation for 4 weeks at different times during the growing season (adapted from Mott 1987); (b) Yields from a first cut at different times during the growing season and a second cut after the end of the growing season for a pasture burnt in August (adapted from Tainton *et al.* 1977).

2.6. Selective grazing

Because animals are selective grazers, grazing distribution problems often occur especially in rangelands. Three principal categories can be recognised:

- Spatially selective grazing related to
  - different land types (vegetation, soil, topography, etc.),
  - varying distances from water

- patches with different levels of attraction to animals.
- Species-selective grazing related to individual animal preferences for plants.
- Selection for specific plants, tillers, leaves and other plant parts.

Grazing is always selective and livestock prefer to use parts of the landscape, some of the patches, some of the species, and some of the plant parts. Due to this selectivity the grazing regime experienced by plants is not necessarily predictable from the numbers of animals and duration of their stay in pastures (Coughenour 1991). Diet selection is extremely complex and a whole range of factors interact to determine diet composition on a particular day.

2.6.1. Spatially selective grazing (patch to paddock scale)

Free-ranging cattle do not use paddocks evenly so that some areas are grazed more heavily than others (Mott 1987; Bailey *et al*. 1998). Such uneven use is a major problem on extensive grazing properties (Mott 1987), having several undesirable consequences for the grazing enterprise including:

- Poor use of forage resources, because the forage in some areas of large paddocks is not used by cattle
- Excessive use of the pasture in other locations due to repeated grazing of plants and trampling, which leads to degradation of the pasture and soils in the medium to long term (including loss of palatable, perennial and productive pasture species, soil erosion and weed invasion)
- Lower levels of livestock production due to the ineffective use of the available pasture and declines in land condition and productive potential.

Spatially selective grazing occurs at scales ranging from the plant to patch to landscape scales, depending on the scale at which the various factors that affect grazing distribution operate. This section focuses on grazing at the patch (i.e. square metres to hectares) to landscape (i.e. hectares to square kilometres) scale, although it is important to recognise that grazing patterns at these scales are also influenced by selective grazing processes operating at smaller scales. It is also important to recognise that widespread degradation often is the result of the process of small overgrazed patches expanding and coalescing over a period of years.

2.6.1.1. Causes of spatially selective grazing

A number of factors, acting singly or in combination, can contribute to uneven grazing distribution in rangelands. These include:

- the location of water points
- the location of preferred (or conversely non-preferred) plant species or communities
- the tendency for livestock to revisit previously grazed patches to consume nutritious regrowth (patch grazing)
- land condition
- soil texture
- soil fertility
- landscape features (riparian zones, hills, roads, creeks)
- weather/climatic conditions
- the location of feed supplements
- fire (especially when patchy)
- behavioural characteristics of different animals

In northern Australia, research studies and land manager experience have provided evidence for the important influence of the location of water, plant community type, soil type (fertility and texture) and land condition (as related to patch grazing or grazing history) on grazing distribution (Schmidt 1969; Hunt *et al*. 2007; Tomkins *et al*. 2009), although the importance of these factors can vary between geographical regions and rangeland types. There is currently less evidence to demonstrate the importance of the remaining factors (i.e. landscape features, weather, feed supplements and animal behaviour) in influencing grazing distribution in cattle herds in northern Australia.

2.6.1.2. Location of water points

The need for cattle in the hot climate of northern Australia to drink frequently means that the location of water is a dominant influence on grazing distribution. Cattle generally drink daily throughout most of the year (Schmidt 1969; Hunt *et al*. unpublished) so that grazing is confined to areas within daily walking distance of water. This pattern of grazing pressure results in the development of piospheres, which are zones centred on water points in which the effect of grazing on land and pasture resources declines with increasing distance from water (Lange 1969). Piospheres can extend several kilometres from water points, depending on the age of the water point and the number of stock using the water point. Piospheres are generally larger around older water points and those that have more stock watering on them. But if water points are well separated (e.g. 10 kilometres or more apart), many square kilometres of land between the waters can remain virtually ungrazed.

In some regions of northern Australia (especially more intensive areas in Queensland) only small piospheres develop around water points. While this might be related to the age of the water points and number of head, other factors including the productivity and resilience of the vegetation to grazing, average distance to water, water quality, climate (especially average maximum temperatures and the effect on the frequency of drinking), and the type and class of cattle might all contribute to a weaker piosphere effect.

2.6.1.3. Pasture species and communities

Cattle show preferences for certain plant species (see Section 2.6.2.), so they will often show a propensity to graze in plant communities containing such species. Thus, in northern Australia plant communities containing perennial grasses that are considered of higher palatability (such as *Astrebla* spp., *Dichanthium sericeum* and *Themeda triandra*) generally experience higher grazing pressure than communities dominated by unpalatable species such as annual sorghum (*Sarga* spp.) and spinifex (*Triodia* spp.). Communities containing the latter species are usually strongly avoided. Tomkins *et al*. (2009) also reported that in north-eastern Queensland cattle avoided areas dominated by *Aristida* spp.

However, reports relating to the selection of plant communities and species are variable since palatability and preference is relative (Ash and Corfield 1998), depending on the range and biomass of species available in a particular location or paddock (Bailey *et al*. 1996). Casual observations suggest that during periods of feed shortage cattle will spend more time in less preferred plant communities seeking out the more palatable minor species present. In a given paddock, cattle will also graze in less-preferred plant communities depending on the location of other resources such as water and the influence of factors such as topography and soil type (Hunt *et al*. 2007; Tomkins *et al*., 2009). It is also apparent that cattle often select areas where the plant community is dominated by annual forbs and grasses, since at times these plants can be of higher nutritive quality (protein and digestibility) than perennial grasses (see Section 2.6.1.5).

2.6.1.4. Patch grazing

Perennial grasses generally produce some regrowth within a few weeks following defoliation, and this young regrowth is highly sought after by cattle as it is of higher nutritive value than older growth which is dominated by stemmy material of lower nutritive value (Ganskopp and Bohnert 2006). Livestock thus have a strong tendency to revisit grazed patches of perennial grass to consume the regrowth (Ash *et al.* 2001; Ganskopp and Bohnert 2006). If not properly managed this patch grazing can result in an ongoing cycle of regrowth and grazing which over time can lead to the development of heavily grazed patches where there is a change in the structure and composition of the pasture (in particular a decline in perennial grass density) (Mott 1987; McIvor *et al*. 2005; Section 2.4.2.). Patch grazing is a particular issue with perennial grasses since they have the ability to regrow throughout much of the year because their well-developed root system means they are able to obtain moisture from deep in the soil. Patch grazing occurs at the scale of square metres to many hectares and patches appear to expand and coalesce over time without appropriate management intervention.

2.6.1.5. Land condition

While it is generally assumed that cattle would elect to graze in areas that support healthy stands of palatable perennial grasses (i.e. A and B condition land), there is increasing evidence to suggest that this is not always so. A number of studies in the Charters Towers district have shown cattle prefer to graze patches in poorer land condition. In the Ecograze project, animals concentrated much of their grazing on the short annual grass patches, leaving ungrazed many of the vigorous but rank perennial grass patches (Ash *et al.* 2001). In studies on a range of soils (Post *et al.* 2006), paddocks with low to moderate long term stocking histories in overall good (A) to fair (B) condition had a wide diversity of patch condition types and there was a strong preference for C and D condition patches. For paddocks on both granodiorite (goldfields) and sedimentary country, C and D condition patches were twice as likely to be heavily grazed (>50% defoliated) as B condition patches, and five times more likely than A condition patches within the same land type. By contrast, paddocks with a history of long term high stocking rates in poorer overall condition had less diversity in patch condition and most patch types were grazed in proportion to their abundance due to overall high grazing pressure and shortage of available forage. Studies at Virginia Park (Post *et al.* 2006; Corfield *et al.* 2006; Bartley *et al.* 2007) where *Bothriochloa pertusa* was a common species confirmed these findings and also showed that preference for C and D condition patches was higher when they were on preferred land types (riparian sodic soils) exposing these patches to the risk of accelerated degradation.

Hunt *et al*. (2007) reported similar findings from Pigeon Hole (Victoria River District or VRD) and also reported that cattle show a preference for areas with lower pasture biomass. This phenomenon appears to be related to the change in structure of the vegetation as much as the species composition. Short-lived forbs and grasses are often of high nutritive value (Ash *et al*. 1995) and usually contain a lower proportion of old stemmy material than ungrazed perennial grass communities. Although the biomass of perennial grass communities would usually be substantially higher than in the annual communities and cattle intake may be reduced in the latter, the cattle may trade-off pasture quantity for pasture quality, presumably to maximise their intake of digestible energy (Wallis de Vries and Daleboudt 1994). This may be an unconscious response of the animals rather than being evidence of nutritional wisdom.

2.6.1.6. Soil texture and soil fertility

Soils that are difficult for cattle to walk on can deter grazing use, although there are no data to support this conclusion. Observations in the field however do consistently suggest that livestock try to avoid boggy, sandy or rocky soils. For example, cracking clay soils may become very boggy following heavy rain and are avoided. In the VRD, this appears to result in heavier use of the firmer red soils and paradoxically riparian zones, where soils usually contain a greater proportion of coarser material including gravel.

Areas with more fertile soils are known to attract herbivores since forage growing on these soils can be more nutritious, more abundant and remain greener for longer (Augustine *et al*. 2003; Ganskopp and Bohnert 2009). Forage on soils with greater nitrogen concentrations may also contain lower concentrations of unpalatable compounds and toxins, at least in temperate systems (Wright *et al*. 2010), or the higher nutritive value can help livestock to detoxify such compounds in other plants (Provenza *et al*. 2003).

Different soil types can also support different types of plants, and a preference for particular plants may also contribute to grazing being concentrated on certain soils. For example, cattle have shown a slight preference during the dry season for areas of red kandosol soils that occur as minor areas within the broader matrix of black clays (vertisols) in the VRD (L. Hunt, unpublished data), presumably because these areas support palatable grasses such as *Enneapogon* spp. and a diversity of nutritious forbs.

2.6.1.7. Landscape features

Landscape and topographical features can affect the extent of grazing use because they have properties that are attractive, or conversely unattractive to cattle, or they may restrict access (Stuth 1991). Cattle generally do not like to negotiate steep slopes so grazing use of hills can often be low or zero while riparian areas are heavily used (Bailey *et al*. 2004). Riparian areas are well-known to be favoured by cattle because water is often available in the creeks, pastures remain greener and more nutritious for longer in the dry season because of increased availability of soil moisture, and because of the increased shade from trees usually associated with riparian areas. This phenomenon is widely recognised to occur across the cattle growing areas of northern Australia. Heavy grazing can extend several hundred metres out from riparian zones. However, there is little information available to quantify the relative use of different landscape features.

2.6.1.8. Weather and seasons

Weather conditions can determine patterns of grazing use by livestock in rangelands (Stafford Smith 1988). During hot weather cattle spend much of the day loitering near water points and in shade (L. Hunt, unpublished data). Over time this can result in such areas being subject to high grazing pressure and as a consequence becoming degraded.

Whether cattle graze further from permanent water points during the wet season remains unclear. Early in the study at Pigeon Hole the cattle appeared to remain closer to permanent water points during the wet season than during the dry, as judged by the size of cattle home ranges (L. Hunt, unpublished data). This presumably reflected the increased abundance of fresh pasture near the water during the wet, and the need to graze out further during the dry season as pasture biomass was depleted closer to water. However, later in the study the reverse was true. Cattle ventured further from water during the wet season presumably because the availability of water in creeks and waterholes across the landscape meant the animals were not compelled to return to permanent water points to get a drink. The reasons for this switch in behaviour are not clear but did not appear to be related to the type of wet season.

2.6.1.9. Feed supplements

The provision of feed supplements such as urea and phosphorus is common practice in the northern beef industry. These supplements are often provided as solid lick blocks that are placed on the ground in paddocks. Cattle are attracted to these blocks, so that they can be a focus of cattle activity. The effect on grazing distribution has not been adequately studied in northern Australia, although initial studies at Springvale Station in the Kimberley indicated that there was a small increase in the percentage of grazed perennial plants (from no grazing to 16% of plants grazed) in the immediate vicinity of the supplement (P. Novelly, unpublished data).

Research in the US has shown that supplement blocks can increase the use of underutilised areas by cattle (Bailey and Welling 2007). However, to save labour the common practice in northern Australia is for blocks to be placed at water points during water runs rather than at under-utilised locations. Providing dietary supplements may also indirectly affect grazing distribution by improving the physiological state of cattle, allowing them to forage further from water or to consume less nutritious plants from a larger area of a paddock.

2.6.1.10. Fire

Fire can be a strong influence on grazing distribution as it removes accumulated rank growth or dead plant material (which is usually of poor quality and not attractive to cattle) and stimulates the production of new, higher quality growth from perennial grasses (Andrew 1986a). This new growth attracts cattle to recently burnt areas to graze. However, care is required in managing grazing pressure in the post-burn period when regrowing perennial grasses are susceptible to heavy grazing (Andrew 1986a).

2.6.1.11. Animal behaviour

Research in the US has shown that cattle can differ markedly in the areas they graze because of behaviours learnt from their mother or peers early in life, or because of physiological or genetic differences (Howery *et al*. 1998). In one study, four different home range groups were found to occur in a herd of 116 cows grazing in a single paddock, resulting in about half the herd predominantly using one valley in the paddock and the remaining animals another valley (there was some overlap between home range groups; Howery *et al*. 1996). Cattle prefer to use areas and plant community types that they are familiar with (often because that is where they were reared), and avoid unfamiliar areas. However, exposing cattle to different land types can increase their use of those land types. Differences also occur among breeds, class and age of cattle (Bailey *et al*. 2004; Walburger *et al*. 2009).

It is likely that animal behaviour is an important influence on grazing distribution in northern Australia but we have a very poor understanding of this. Observations in a 57 km^2 paddock with five water points at Pigeon Hole suggested that two waters (and the surrounding area) were usually each used by about 40% of the herd, while another two waters were normally each used by about 10% of the herd. Studies of the behaviour of a limited number of animals fitted with GPS collars suggested that cattle generally favoured one water point but sometimes used a second water point. Such behaviour can mean that strategies that aim to improve grazing distribution in a paddock by rotating livestock around a series of water points are relatively ineffective without animal training.

Schmidt (1969) also reported marked differences between individual cattle in herds grazing on the Barkly Tableland in how far they would move from water to graze. He found that cattle could be differentiated into two groups: 'walkers' who travelled approximately 6-7 km from water to graze while the rest (non walkers) remained within about three kilometres of water.

2.6.2. Species

The preference status of a particular plant species is largely dependent upon its inherent abundance, its morphological and phenological characteristics, the array of species on offer, and the species of animal (Stuth 1991). Preference constantly changes as abiotic factors (i.e. season and weather conditions) alter the nature of the plant community (Stuth 1991). Factors that have been identified as influencing species selection include morphological features (amount of leaf and stem, leaf table height, vegetative versus flowering tillers), plant moisture contents, tiller and plant heights, chemical composition, crude protein contents, pasture yields, relative species abundance and leaf tensile strength (Gammon and Roberts 1978a and b; Danckwerts *et al.* 1983; O'Reagain and Mentis 1989b; Heitschmidt *et al.* 1990; Horadagoda *et al.* 2009). O'Reagain and Mentis (1989b) found cattle preferred grass species that were leafy and non-stemmy, with a high leaf table and leaves of low tensile strength with high crude protein. They avoided species that were generally stemmy with low crude protein.

Studies of the selection of grasses in northern Australia are limited but they do show there is a range of selectivity for different species but the differences between species are not consistent across different environments. At Springmount near Mareeba, *Themeda triandra* was seldom selected and sometimes rejected (Hendricksen *et al.* 1999), but at Katherine it was actively selected for (Andrew 1986b; Ash and Corfield 1998). *Heteropogon contortus* was selected in autumn at Galloway Plains near Calliope (Orr 2005) and also at Brian Pastures near Gayndah (Henricksen, unpublished data referred to by Orr 2005); however at Springmount, while *Heteropogon contortus* was preferred early in the wet season it was rejected in the late wet and dry seasons (Hendricksen *et al.* 1999). *Chrysopogon fallax* was selected at Galloway Plains (Orr 2005) but avoided at Katherine (Andrew 1986b).

Some South African studies have shown that grass species are selected in the same order on different occasions (O'Reagain and Mentis 1989a; Hatch and Tainton 1993) - cattle always grazed the same species preference group in a set sequence of preferred then intermediate acceptability, with the least acceptable species largely avoided. This research suggests that while increasing intensity of use may force animals to utilise less palatable species, this only occurs when the preferred species are very heavily grazed. Cattle continue to graze selectively even when defoliation is severe (Danckwerts *et al.* 1983) and increasing intensity of use plays little part in altering the sequence of preference of species (Daines 1980; Stoltsz and Danckwerts 1990; Hatch and Tainton 1993).

However, this was not always so and the degree of selection for different species by animals can change during the year. Gammon and Roberts (1978a) found the most selected species were not the same in different seasons; Daines (1980) found species were generally grazed in the same order of selection throughout the year except for *Alloteropsis semialata* which was highly palatable early but rejected when it was mature; Danckwerts *et al.* (1983) found that the preferred species changed with time of year, but the changes were not large and cattle returned to tufts of preferred species before even partial grazing of less preferred species. In mixed grass-legume pastures cattle select strongly for grass early in the growing season (Stobbs 1977; Gardener 1980; Gardener and Ash 1994; Coates 1996; Jones and Hu 2006). In native pastures at Katherine, cattle were least selective between grasses when grazing post-burn growth at the start of wet season and selectivity was greatest at the end of the rainy season (when presentation yields were greatest) and then declined in the dry season (Andrew 1986b). In contrast, in unburnt pastures at Springmount there was no change in selectivity during the wet season although animals were more selective in the wet season than during the dry season (Hendricksen *et al.* 1999). Stoltsz and Danckwerts (1990) found animals grazed more selectively in winter than autumn.

The amount of a preferred species in the sward can affect diet selection. At Springmount, *Sorghum plumosum* was preferred when it comprised less than 5% of the sward but not when it was present in greater amounts. In a study at Katherine (Ash and Corfield 1998), *Themeda triandra* was always preferred to *Chrysopogon fallax* and intensity of selection was greater in pastures with a smaller proportion of *Themeda*. When *Themeda* was common, *Chrysopogon* was selected against, but in pastures with less *Themeda*, there was selection for *Chrysopogon*. Hatch and Tainton (1993) in South Africa also found selection for *Themeda triandra* was negatively related to abundance in the sward; this increased selection on a small but desirable component of the sward may accentuate the rate of further degradation.

2.6.3. Tillers and leaves

It is generally agreed that within a single plant, animals select leaf in preference to stem, and green (young) in preference to dry (old) material (Arnold and Dudzinski 1978). Green leaf is the preferred pasture component (Arnold 1964; Stobbs 1973; Arnold and Dudzinski 1978) with the uppermost fully elongated leaf most frequently defoliated, older leaves less frequently defoliated, and senescing leaves rarely defoliated (Hodgson 1966; Barthram and Grant 1984; Clark *et al.* 1984; Mazzanti and Lemaire 1994; Lemaire and Chapman 1996; Lemaire and Agnusdei 2000).

2.7. Stocking rate

Stocking rate refers to the number of animals per unit land area for a given period. Long-term carrying capacity refers to the average stocking rate that a paddock can be expected to support over a period of years without causing land or pasture degradation. While some pastoralists may elect to use stocking rates close to the long-term carrying capacity, many vary their stocking rates over time to some degree. Stocking rate determines the pasture utilisation rate, which is the proportion of annual pasture growth consumed by livestock.

Stocking rate is the principal factor under the control of management that affects livestock productivity and future condition and productivity of the land (Heitschmidt and Taylor 1991; Ash and Stafford Smith 1996). Stocking rate has such an important influence because it is an important determinant of the amount and quality of forage consumed by livestock (i.e. their intake), the severity of defoliation of pasture plants and effects of livestock on the soil. Matching stocking rates to the feed supply is thus a fundamental part of managing a grazing enterprise (Ash and Stafford Smith 1996). While this is widely recognised, getting this balance right is challenging.

In a sensitivity analysis of the factors affecting the financial returns of northern beef businesses on very large properties in the Victoria River district with low to moderate levels of property development (i.e. paddocks and water points), stocking rate had a stronger effect on short- to medium-term profitability than reducing operating costs, improving branding percentage and liveweight gain, and reducing animal mortality (S. Petty, pers. comm.). This analysis suggests that increasing stocking rate is the most effective way of improving profit for such properties.

Stocking rate largely determines the frequency and intensity of defoliation of plants and can affect land condition by influencing:

- the ability of palatable perennial grasses to survive, grow and reproduce;
- the maintenance of desirable plant species composition in the pasture and resistance to weed encroachment;
- the tree-grass balance (from its effect on the availability of fuel for prescribed fires) which has ongoing implications for forage production; and
- soil condition, soil function (including nutrient cycling and water infiltration) and soil erosion.

The effects of overgrazing on land condition have been discussed in Section 2.4.

Because of seasonal fluctuations in forage availability and the potential for overgrazing to reduce land condition and future productivity, the choice of stocking rate at any given time is a compromise between short- and long-term financial returns. In practice, this is usually best achieved by stocking at around the long-term carrying capacity of the land.

2.8. Summary

This chapter has provided some relevant scientific background. This is built on in the next four chapters which consider the research results from trials examining the four management factors (infrastructure development, stocking rate management, pasture spelling and prescribed burning).

3. Infrastructure (water points and paddocks) development

Livestock graze the landscape unevenly because of the irregular distribution of resources they require to survive, grow and reproduce (Coughenour 1991). The interaction of these factors with animal behaviour (including livestock preferences and the strategies they use to obtain the necessary resources) results in the observed patterns of use. Where there is little management of grazing distribution, livestock overuse some parts of the landscape and under-use other areas, which can result in some areas becoming degraded while the forage in other areas remains unused. The focus in this chapter is on the use of fences and water points to manage grazing distribution.

3.1. Developing paddocks and water points to manage grazing distribution

Distributing grazing pressure as uniformly as possible across a paddock is considered a fundamental aspect of grazing management to optimise pasture use, maximise livestock production and minimise land degradation (Stoddart *et al*. 1975; Holecheck *et al*. 2004; Ash *et al*. 1997). Some managers of very large properties in northern Australia with little infrastructure development (i.e. large paddocks and a limited number of water points) maintain stocking rates at levels below the overall carrying capacity of the land to avoid large concentrations of cattle and limit the extent of land degradation. For example, properties in the Heytesbury Company were known to use stocking rates equivalent to annual utilisation rates of about 10% (S. Petty, pers. comm.), although utilisation rates of about 20% are considered sustainable on black soil pastures (Cowley *et al*. 2007). On such properties there is potential to sustainably increase stocking rates (and thus livestock production) if grazing pressure can be spread more uniformly over the landscape, such as by subdividing large paddocks or installing additional water points. On properties with large paddocks and few water points but where the stocking rates near the long-term carry capacity, infrastructure development that leads to better grazing distribution should improve the sustainability of the enterprise. It is not known whether this will have benefits for the productivity of the herd.

Paddock configuration (which includes paddock size and number and location of water points) is an important factor in managing the distribution of livestock grazing to optimise livestock production and maintain land condition. Such property development not only offers better control over grazing, in particular the distribution of grazing pressure across the landscape, it facilitates the use of animal husbandry practices that require the separation of different classes of animals (such as weaning and controlled mating), and facilitates the resting of paddocks and use of fire.

The rationale for developing paddocks and water points on a property therefore includes:

- Smaller paddocks and more water points can improve the effectiveness of pasture utilisation by making poorly utilised areas available, potentially allowing more stock to be carried and increasing total livestock production;
- Smaller paddocks and more water points may slow the expansion of heavily grazed areas within paddocks that are subject to degradation;
- Fences and water points can help to protect sensitive areas or different land types;
- Increasing the number of smaller paddocks facilitates the use of other management options and in some circumstances may reduce operating costs.

In conclusion, the development of paddocks and water points can improve the distribution of grazing pressure across the landscape, may increase livestock production in some circumstances and can help maintain land condition by improving the control of livestock grazing.

Principle 1. Use fences (paddocks) and water points to manipulate grazing distribution

3.2. Water point distribution and paddock size: research and key issues

Fencing and water points both have a role in managing grazing distribution. Subdividing large paddocks into smaller ones and installing more water points are the two primary infrastructure options for improving grazing distribution. There are numerous considerations associated with implementing these two options, which are considered below.

3.2.1 Cattle activity

Water points are usually the strongest influence on livestock grazing distribution in northern Australia because of the scarcity of other water sources for much of the year and the need for cattle to drink frequently (usually daily). A number of studies over the last 30-40 years have investigated cattle behaviour in relation to water points in northern Australia, and in particular the distance cattle have been observed to walk from water. For example, Schmidt (1969) observed that some cattle on the Barkly Tableland regularly travelled up to 11 km from water during the late dry season, and Fisher (2001) reported cattle activity on the Barkly up to 10 km from water. In central Australia cattle usually went no further than 5-8 km from water, although on occasions when the pasture was scarce some were observed up to 24 km from water (Low *et al*. 1978). However, the effective grazing distance is usually much less than the maximum distance travelled from water. The latter is of little value in determining the number and spacing of water points to make best use of available feed, since the level of grazing use at the outer limits of cattle distribution is generally very low. Most grazing by cattle occurs much closer to water.

When considered in terms of the proportion of total activity in concentric zones around a water point, cattle activity increases to approximately 3 km from water, and declines quite markedly thereafter. This is illustrated for the Barkly Tableland in Figure 3.1, but similar patterns of cattle activity were observed at Pigeon Hole station in the VRD. About 80-90% of activity is usually within 5 km of water, although where waters are well separated this distance can increase. The pattern of activity is a result of the combined effect of the concentration of cattle activity around water points and the increasing area within each concentric kilometre zone around a water point. These results suggest that in extensive areas such as the VRD, Barkly Tableland and central Australia approximately 3-4 km could be considered as the maximum effective grazing distance, and hence the furthest cattle should be required to travel from water in order to maximise grazing use of the landscape within a paddock.

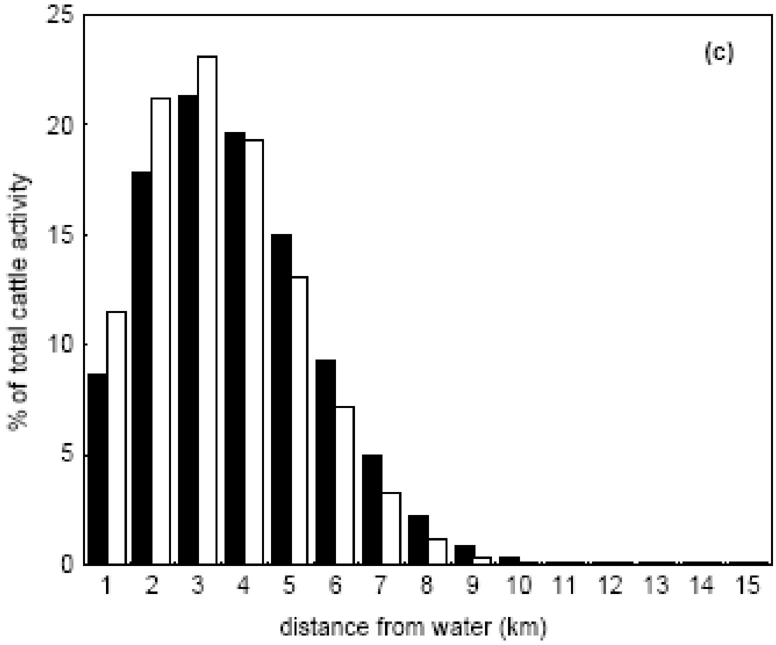

Figure 3.1. The percentage of total cattle activity at various distances from water on two cattle stations (black and white bars) in the Barkly Tableland, NT [from Fisher (2001) and based on hoof print, dung and defoliation data at a number of water points].

Foran (1980) reported that the radius around waters in central Australia within which most grazing impact occurred was about 2 km. Squires (1981) reported that in central Australia cattle grazing is concentrated within 3 km of water when pasture conditions are good.

At Pigeon Hole Station in the extensive grazing lands of the VRD, paddock development (adding waters) resulted in 90% of activity being within 2.7 km of water in a 57 km^2 paddock with five waters (maximum distance recorded 5300 m which was the approximate maximum distance from water possible in the paddock) and 3.3 km in a 34 km^2 paddock with one water (maximum distance recorded 4560 m which was the approximate maximum distance from water possible). A reasonable conclusion from the Pigeon Hole results was that a grazing radius of about 2.5 km (i.e. approximately 5 kilometres between waters) provided a good compromise between getting good forage utilisation across a wide area and limiting the area near water points that suffers extreme defoliation. Positioning waters points approximately 5 km apart would also appear to minimise any overlap in the grazing radii surrounding adjacent water points.

There has been only a small amount of research in northern Australia on how different paddock configurations (including paddock size and the number and location of water points) affect grazing distribution. The recent project at Pigeon Hole is the sole study to explicitly explore these issues. Consequently the following discussion is based on limited experimental results combined with practical experience and a 'first principles' understanding of grazing behaviour.

Paddock size is a strong determinant of how much of the landscape cattle use. As paddock size decreases and the area available becomes restricted, cattle tend to use a greater proportion of the paddock. This was apparent from studies at Pigeon Hole, where the home range of individual cattle and the composite home range (i.e. the amalgamation of individual home ranges within a paddock) more closely matched paddock size as paddock size declined (L. Hunt *et al*. 2010; Table 3.1). This suggests there was more effective paddock use in smaller paddocks. Confining cattle to smaller paddocks appears to have some effect in ‘forcing’ them to use areas they may not use if paddocks were larger (although they still may not use areas that contain few palatable plants). This effect means that having more smaller paddocks results in grazing being distributed more widely across the landscape as a whole, and should improve the effective use of available forage.

Table 3.1. Average home range and the proportion of paddocks used for individual cows and the composite home range for these cows in three paddocks of different size for six-month periods. All paddocks contain one, centrally-located water point. n = number of cows in sample.

Paddock area (km^2)	Mean individual home range (km^2) & sd	Mean percentage of paddock used by individual cows (%)	Mean composite home range (km^2) & n	Mean composite home range as percentage of paddock (%)
8.9	7.7 (1.18)	87	8.4 (16)	94
21.3	13.3 (3.65)	62	19.2 (6)	90
34.5	22.0 (4.88)	64	28.7 (7)	83

Increasing the number of water points in large paddocks can also increase the proportion of a paddock used by cattle. Additional waters have this effect by attracting cattle to under-utilised areas, making previously water-remote areas more accessible to livestock and potentially attracting livestock away from preferred and frequently used areas (e.g. riparian zones) or water points (Bailey 2005; Ganskopp 2001). The design of the Pigeon Hole study did not allow a direct test of this effect (since in most cases paddock size increased with the number of waters). However, the home range of individual cattle in paddocks of the same size was greater in the paddock with two water points (compare the 34 km^2 paddocks in Tables 3.1 and 3.2), although this did not translate into an increase in the overall proportion of the paddock used by the cattle (i.e. composite home range). These results likely reflect the individual land type characteristics of the study paddocks.

Tomkins (2008) reported no significant differences in cattle home ranges between paddocks with one and three water points on the Barkly Tableland. The distance between waters in this study was 6.8 to 9.6 km (compared with approximately 3.5-4 km at Pigeon Hole), which was probably too great a distance to allow the cattle to readily use more than one water.

Table 3.2. Average home range and proportion of paddocks used for individual cows and the composite home range for these cows in four paddocks of different size and number of water points. Home ranges calculated over six, six-month periods (different cows used each time), except for the largest paddock which was for two six-month periods. n = number of cows in sample.

Paddock area (km^2)	Number of water points	Mean individual home range (km^2) & sd	Mean percentage of paddock used by individual cows (%)	Mean composite home range (km^2) & n	Mean composite home range as percentage of paddock (%)
8.9	1	7.7 (1.18)	87	8.4 (16)	94
34.3	2	25.1 (7.78)	73	27.6 (15)	81
56.9	5	31.3 (7.61)	55	43.3 (15)	76
148.6	3	72.7 (31.41)	49	113.7 (4)	77

As paddock size increases or the number of water points decreases (or the spacing between water points increases) it might be expected that cattle will walk further each day as they travel between feeding areas and water, and so more energy will be expended in walking. No studies appear to have investigated the effect of daily distance walked on livestock productivity, but an increase in the daily distance walked might mean that liveweight gain or body condition suffer, depending on the balance between the additional energy presumably gained from foraging at greater distances and that expended in walking to those locations. Reducing the distance between waters might then be expected to reduce energy expenditure and potentially improve livestock productivity.

Surprisingly, the effect of paddock size and the distribution of water points on the daily distance walked by cattle appears to be relatively small. The results from various studies suggest that in broad terms cattle walk a similar distance each day irrespective of paddock size (Table 3.3), although published results are based on varying methods. Consequently, the issue of energy consumed in walking may not be a critical consideration when planning the number and placement of water points. The emphasis in planning paddock configuration should therefore remain on maximising the effective use of pasture resources across the landscape. The distance between water points does seem to have some effect on the distance cattle walk each day, but many studies have not reported this.

Table 3.3. Average daily distance walked by cattle in paddocks differing in size and number of water points.

Location	Paddock size and number of water points	Distance walked per day (km)	Reference
Charters Towers, Qld	105 ha with one water	6-7	Tomkins *et al*. (2009)
Victoria River District, NT	9 km^2 to 57 km^2 and one to five waters	5-6	Hunt *et al*. (2010)
Victoria River District, NT	149 km^2 with 3 waters	7.5	Hunt *et al*. (2010)
Central Australia	170 km^2 with 2 permanent and 3 temporary waters	9.3	Low *et al*. (1981a)
Barkly Tableland, NT	250-280 km^2 and 1-3 waters	8-9	Tomkins (2008)

3.2.2. Grazing impacts (paddock and landscape scales)

3.2.2.1. Water points

The concentration of livestock activity around water points produces a pattern of decreasing pasture defoliation and other effects such as trampling with increasing distance from water that generally conforms to an exponential decay curve (see Figures 3.2 and 3.3). In a recent study in a dune-swale system in the eastern Simpson desert, Fensham *et al.* (2010) reported a similar trend in cattle activity with distance to water (based on dung density) as that reported by Fisher (2001) for the Barkly Tableland (Figure 3.2).

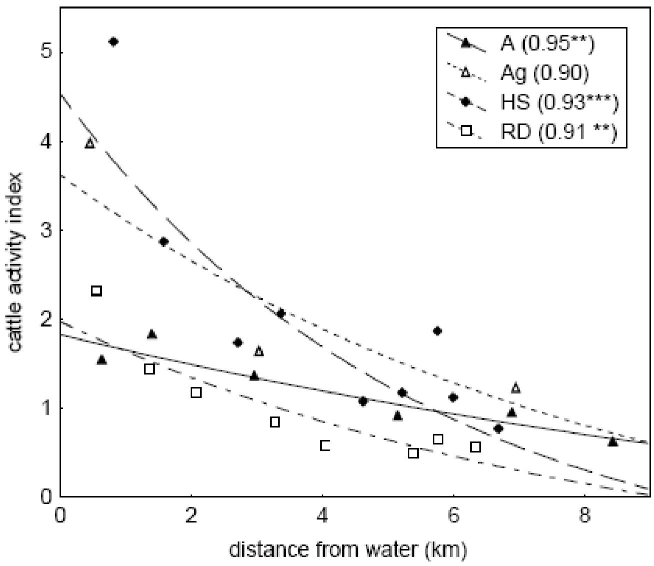

Figure 3.2. The trend in cattle activity with distance to water for four water points on stations on the Barkly Tableland (from Fisher 2001).

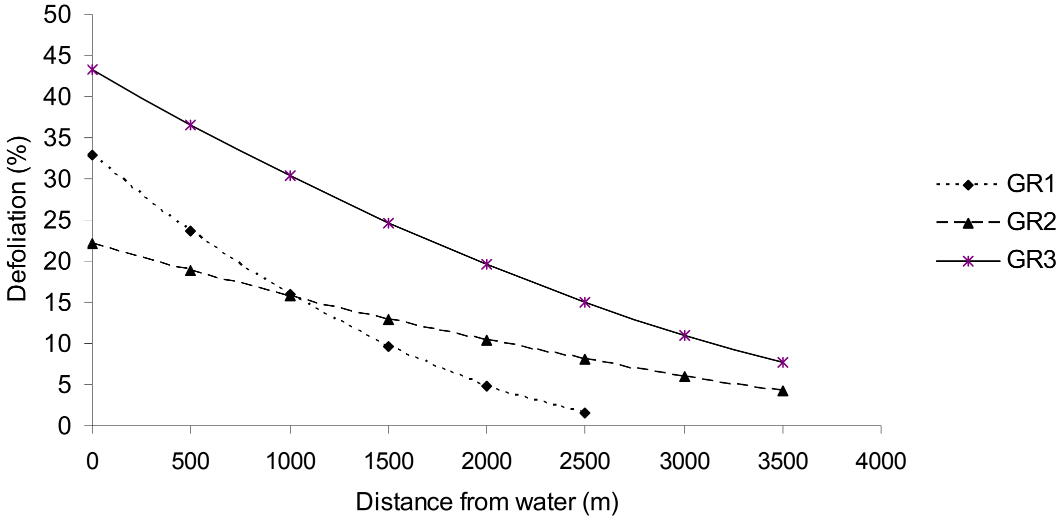

Figure 3.3. Dry season defoliation rates of the pasture in three paddocks of different size at Pigeon Hole. Each paddock has a single central water point. GR1 = 9 km^2, GR2 = 21 km^2, GR3 = 34 km^2. Predicted results from model of observed defoliation rates.

These trends in grazing with distance to water can mean that palatable species can be subject to intense defoliation near water points (Figure 3.4), which eventually results in the loss of these species near water. Figure 3.4 is also notable because it suggests the general nature of the defoliation-distance to water relationship is similar between at least some regions. It might therefore be reasonable to assume that for much of the arid and semi-arid rangelands of northern Australia defoliation declines with distance to water according to an exponential decay curve, and that the majority of grazing impact occurs within 3-4 km of water.

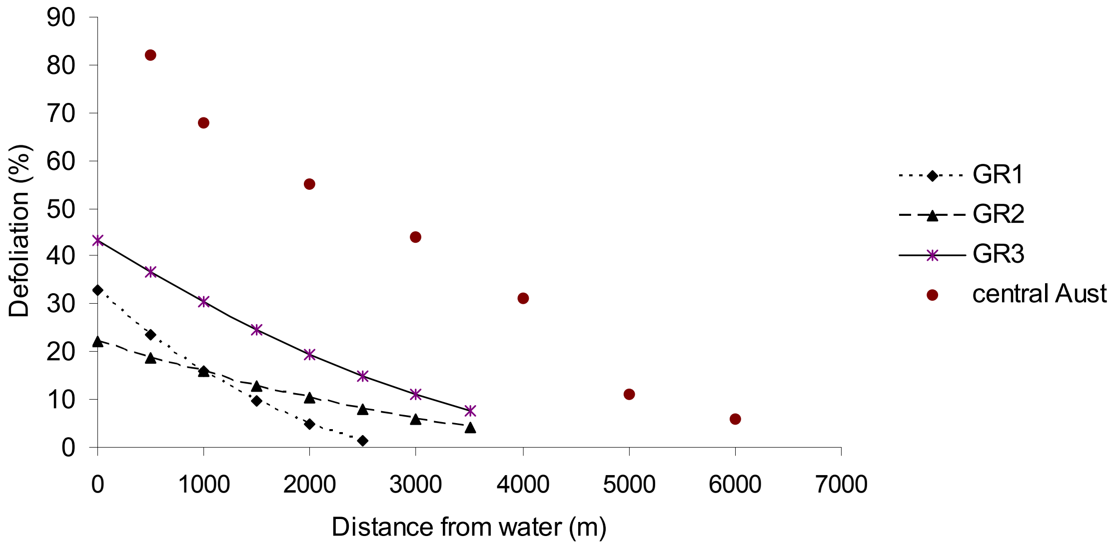

Figure 3.4. Overall pasture defoliation versus distance to water for three paddocks in the VRD (Pigeon Hole station; L. Hunt unpublished) and defoliation of Mitchell grass in central Australia (Leys 1977). Note that the data for Pigeon Hole are from the paddocks presented in Figure 3.3.

The strength of these grazing trends with distance to water depends on the vegetation type, the degree of heterogeneity in the vegetation (especially the location and abundance of unpalatable species) and the presences of other landscape features such as hills, different soil types and creeks, which can mask or dilute the apparent strength of these trends. Poor water quality (particularly high dissolved salts) can also reduce the distance travelled from water and thus steepen the relationship. In their Simpson Desert study where ephemeral plant species dominated, Fensham *et al*. (2010) reported virtually no trend in plant cover, species richness and species diversity with distance to water after approximately 20 years of grazing, although a few species increased in abundance and others decreased with distance from water.

On properties with large paddocks and a limited number of water points areas usually exist that are virtually ungrazed. Because of the strong influence of water on cattle grazing patterns, a good distribution of water points will also allow livestock to disperse more widely across large paddocks and improve the utilisation of available forage.

Increasing the number of water points in large paddocks appears to improve the distribution of grazing (Stafford Smith 1988). Additional water points reduced peak rates of defoliation near water points and generally produced a flatter relationship between distance to water and overall pasture defoliation in the Pigeon Hole study (i.e. grazing is dispersed more uniformly; Figure 3.5). No differences in overall pasture biomass or composition were detected as a result of these paddock configurations, although differences may have emerged over a longer time frame.

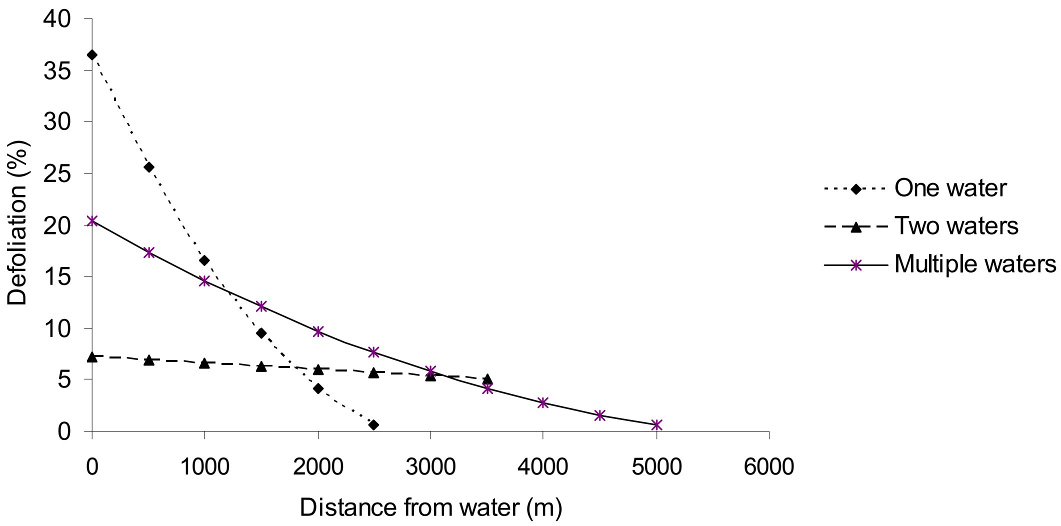

Figure 3.5. Dry season defoliation rates in three paddocks of different size and number of water points at Pigeon Hole. One water = 9 km^2, Two waters = 21 km^2, Multiple (5) waters = 57 km^2. Predicted results from model of observed defoliation rates.

A benefit of installing more waters in a paddock is that it reduces the average number of cattle per water point (assuming the paddock stocking rate remains the same). Reducing the number of cattle using a water point will limit the rate of growth of the 'sacrifice' zone (i.e. the area of heavily use and degradation) around water points (see later).

3.2.2.2. Paddock size

Reducing paddock size reduces the proportion of the landscape that experiences little grazing use. This was demonstrated in the Pigeon Hole study, where the area of paddocks not encompassed within the 'composite home range' of cattle decreased as paddock size decreased (where composite home range is the combined home ranges of individual cattle estimated using GPS collars; see Table 3.4). These data suggest that the available forage would be used more effectively in smaller than larger paddocks. In the examples presented in Table 3.4, the 'ungrazed' area increased with paddock size despite the addition of extra water points in the developed paddocks.

Table 3.4. Composite home range of cattle for three developed paddocks at Pigeon Hole station and an undeveloped commercial paddock at Mt Sanford in the VRD, NT.

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

* the area not encompassed by the composite home range

In some regions small paddocks also appear to reduce the piosphere effect. For example, surveys of paddocks in the Charters Towers region have shown that pasture defoliation is fairly constant with distance to water in the relatively small paddocks (500-2000 ha) typical of the region (Figure 3.6). Elevated levels of cattle activity were confined to within approximately 300 m of water (Post *et al*. 2006).

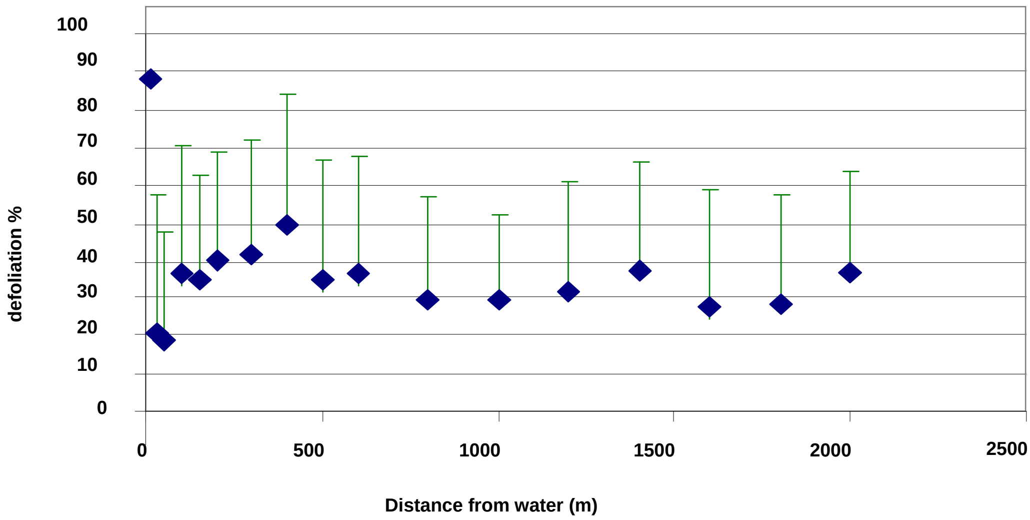

Figure 3.6. Pasture defoliation in relation to distance to water in the Charters Towers region (from Post *et al*. 2006). Declines in defoliation near water may reflect an increased abundance of unpalatable species.

Although there has been only limited formal research on the effects of infrastructure developments on grazing distribution, it seems reasonable to conclude that reducing paddock size or establishing more water points in large paddocks where under-utilised areas exist in areas away from water appear to improve the use of these areas by livestock. These developments may allow additional livestock to be carried (assuming properties are not already operating at the carrying capacity of the land).

3.2.3. Grazing impacts (patch scale)

Some international studies have suggested that grazing is more uniform in smaller paddocks (Teague and Dowhower 2003; Teague *et al*. 2004; Barnes *et al*. 2008). However, evidence from the Pigeon Hole study suggests paddock size and water point distribution primarily influence patterns of grazing at larger (paddock to landscape) spatial scales rather than at patch scales. Reducing paddock size or increasing the number of water points are much less effective at improving the uniformity of grazing at smaller spatial scales (i.e. at the patch scale within paddocks) in northern Australia. The ineffectiveness of fences and water points in improving the overall evenness of grazing use in paddocks is because they fail to alter a number of factors that determine grazing distribution and habitat selection by animals including the heterogeneity in plant and soil resources and patterns of past grazing.

For example, studies with GPS collars at Pigeon Hole suggested that although the proportion of a paddock visited by cattle was greater in smaller paddocks, cattle continued to concentrate on preferred areas in these paddocks, such as areas of red soil, previously grazed patches and around water points (Hunt *et al*. 2007). Some plant communities (e.g. dense stands of annual sorghum) provide little grazing value and tend to be avoided by cattle under most circumstances. Areas where palatable species such as Mitchell grass (*Astrebla* spp.) are tall and stemmy are also often avoided (although in general it is likely that desirable plants are used more uniformly in smaller paddocks than in larger paddocks). On the other hand, a potential risk with reducing paddock size is that if a paddock contains a high proportion of less favoured plant communities it is likely that favoured plant communities will be subject to relatively heavy grazing.

Although water points are usually the dominant influence on grazing distribution in large paddocks, the spatial arrangement of vegetation communities and other features in a paddock, including topography and the effects of past use, also strongly influence the way livestock use paddocks (Stafford Smith 1988), and our ability to alter patterns of use. The location of water points in relation to other landscape elements is therefore an important consideration in attempts to improve the evenness of use of pasture. Thus, while preference for particular plant species or communities can be a strong influence on grazing patterns, what is actually consumed is influenced by accessibility especially in relation to the location of water (Hodder and Low 1978), palatability and quality relative to other plant species or communities on offer. To maximise use of the entire landscape, it is usually recommended that waters be placed away from preferred vegetation communities and other favoured sites so that cattle are attracted to underutilised or less preferred areas. However, there are no data to indicate how effective this is at reducing the selective use of preferred areas, or what effect attracting cattle away from preferred areas has on livestock production.

The location of water within paddocks is an important consideration to maximise their effectiveness in improving the distribution of grazing pressure. Stafford Smith (1990) showed that evenness of use in arid rangelands improved if water points were sited away from fences. This is also likely to apply in tropical savanna rangelands since Roth *et al*. (2003) found that distance from water and fences were two key drivers of grazing distribution in the Burdekin catchment in north-east Queensland. Water points should therefore be centrally located in a paddock whenever possible. Locating waters away from riparian zones, preferred areas and previously grazed areas will likely help to improve grazing distribution.

In conclusion, while reducing paddock size or installing more water points provides more control over where livestock graze, uneven grazing distribution will still occur within paddocks (although the incidence and size of heavily grazed areas may be reduced).

3.2.4. Livestock production

Improving the distribution of cattle grazing across the landscape might be expected to increase individual animal production as a result of better access to forage resources. In the Pigeon Hole study changes in paddock configuration, including smaller paddocks or large paddocks with additional water points, did not demonstrate any difference in individual livestock production. However, with improved distribution of livestock across the landscape as a result of using smaller paddocks and more water points, increases in stocking rates and hence total livestock production should be possible if properties are not already running at the long-term carrying capacity. Where stocking rates currently exceed what is appropriate for the paddock configuration, a small improvement in individual performance with the addition of more infrastructure might be possible, but there is no evidence available to support this suggestion.

It has been suggested that larger paddocks may offer a benefit to livestock production because increased pasture (and hence dietary) diversity associated with more diverse habitats in larger paddocks allows livestock to buffer seasonal declines in pasture quality and productivity. Conversely, smaller paddocks may negate any potential spatial buffering effect. However, in a study in the Dalrymple Shire in Queensland that examined paddock sizes from 600 to 27,000 ha there was no evidence to suggest that paddock size was an important influence on livestock production, although cattle were able to select a more nutritious diet (crude protein content about 2% greater) in paddocks with more diverse vegetation (C. Stokes, pers. comm.). Rittenhouse and Bailey (1996) also reported from the US that as pastures mature and lose quality livestock productivity can be higher in paddocks that contain heterogeneous vegetation.

Placing water points in underutilised or less preferred areas is an effective technique for improving grazing distribution across the landscape. However, it seems plausible that using waters to move cattle away from preferred areas may have a negative effect on livestock production. Currently there has been no research into this issue. The outcome may well depend on the particular circumstances of a situation, and the relative quantity and quality of forage in the new and original location.

3.2.5. Economic aspects

The optimum paddock size for a property or region will also be a function of the trade-off between the cost of infrastructure to reduce paddock size and the improvement in grazing distribution and stocking rates (and hence returns) that are likely to result. The inherent productivity of the land will influence the economically optimum level of development.

In the Pigeon Hole study, livestock production per area (and per animal) did not differ amongst any of the paddock configurations tested, which included paddocks with a grazing radius of approximately 1.5 and 2.5 km. Thus, intensive development that reduces the grazing radius to less than 3 km does not appear to be justified. An analysis of hypothetical development scenarios (using actual costs in 2007) for the VRD also indicated that capital costs for fencing were disproportionate for paddock sizes below approximately 30-40 km^2 (Figure 3.7). Since each paddock will require at least one water point, the cost of providing water must also be factored into overall development costs.

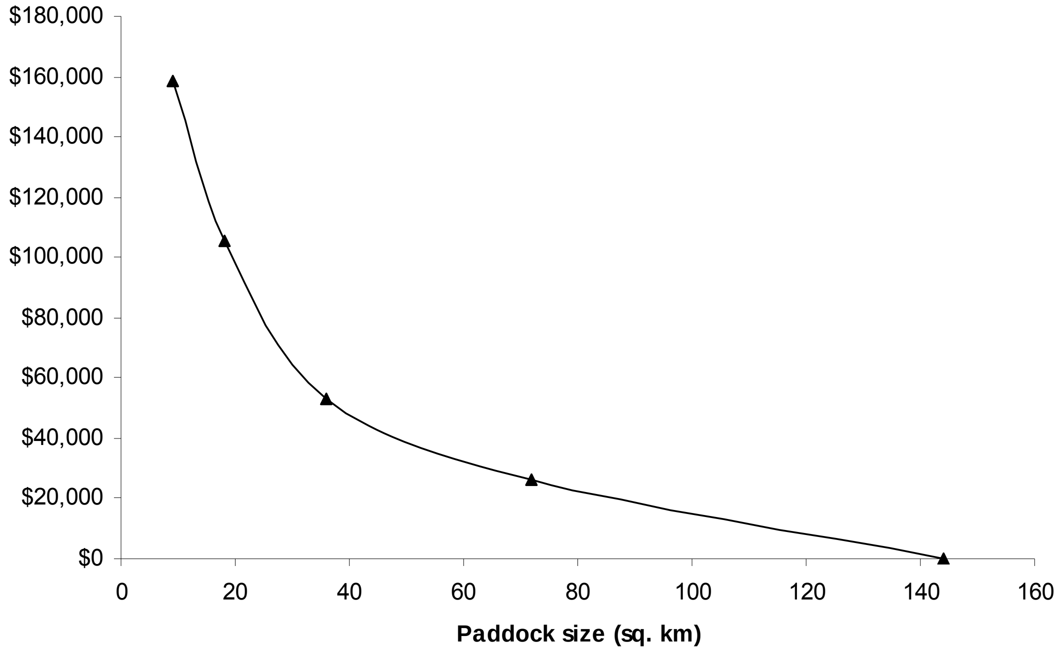

Figure 3.7. The cost for subdividing a large (144 km^2) paddock into smaller paddocks of varying size in the VRD (based on costs in 2007).

Paddock sizes smaller than those that maximise use of the landscape as a whole will generate a lower return on capital invested (unless there are other benefits from closer management such as improved heifer reproductive rates). This is illustrated in Figure 3.8 for the VRD region with three paddocks each using a 20% annual pasture utilisation rate and a single water point in each paddock. In this region a paddock size of around 35 km^2 (roughly equivalent to a grazing radius of 3 km) is expected to maximise overall use of the landscape and hence the effectiveness of forage use. As a result, smaller paddocks will have a smaller return on capital because the additional costs of smaller paddocks are not being offset by higher returns. Adding a second water point to improve grazing distribution in a 35 km^2 paddock reduced the return on capital in this example by only 0.1%.

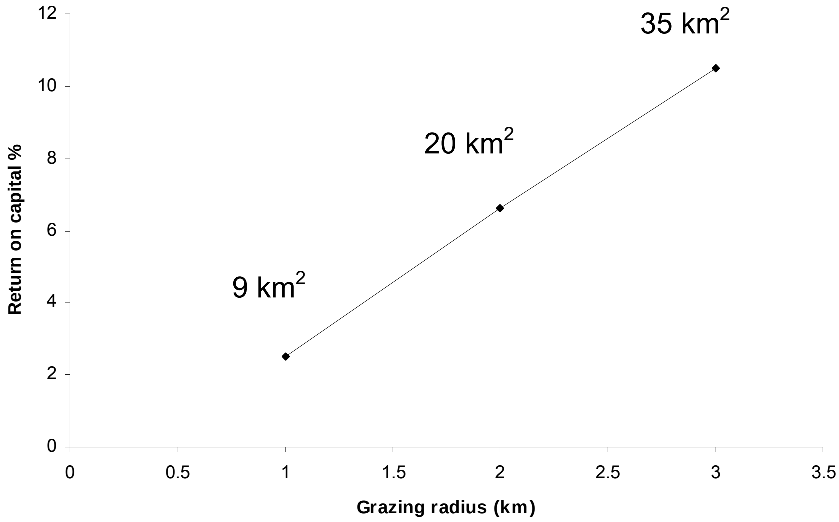

Figure 3.8. Return on capital for a range of paddock sizes in the VRD. In this case, each paddock contains only a single water point.

3.3. Analysis and implications for management

3.3.1. Key findings

3.3.1.1. Grazing distribution (paddock and landscape scale)

Key findings from the research are that smaller paddocks and more water points can improve the distribution of grazing across the landscape. Since the aim is to effectively use most of the landscape, the paddock configuration (i.e. size and number and spacing of water points) that will optimise carrying capacity in a region will be largely determined by the effective distance that cattle graze from water. This is about 3-4 km for most of the extensive grazing areas. A grazing radius of 3 km approximates a paddock size of 36 km^2.

The optimum paddock size will vary between regions. In addition, more intensive development than that required for optimum grazing distribution may be justified for other management reasons. However, in general it is unlikely there will be any additional benefit from more intensive development in terms of improved grazing distribution and greater livestock carrying capacity.

A large number of livestock using a water point will increase the rate at which the sacrifice area around the water point expands. When a large number of livestock use each water point, large, highly-degraded sacrifice zones develop around water points. The experience of pastoralists and studies in sheep rangelands (e.g. Lange *et al*. 1984) indicate the need to limit the number of head per water point. Installing more water points in a paddock will reduce the number of cattle per water point. This is likely to limit the rate of growth of the piosphere and sacrifice zone around water points.

The Pigeon Hole study investigated the issue of the appropriate number of cattle per water point in the VRD by studying three different sized paddocks each with one water point but all run at the same pasture utilisation rate. This meant that the larger the paddock the greater the number of cattle using the water point. Observations suggested that managers should aim to limit the number of head per water point to approximately 300 in this region to restrict the size of sacrifice zones around waters.

For a given situation, the number per water will be determined by the utilisation rate (i.e. stocking rate), the number of waters in a paddock, the effective grazing radius and paddock size. In this way it is possible to estimate the effective stocking rate within a grazing radius around a water point.

Based on the effects in improving grazing distribution and cost, optimum levels of development for the more extensive grazing areas of northern Australia are:

- Paddocks of 30-40 km^2 with two water points;
- A maximum distance to water of about 3-4 km.

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. This recommendation assumes:

- there is no relationship between distance to water and pasture utilisation in paddocks of up to 20 km^2 (or ~2 km radius around water points);
- there is no livestock production benefit from more intensive development;
- that grazing will not be evenly distributed within paddocks, and there will be no improvement in uniformity of grazing use within paddocks with more intensive development (because of the nature of livestock grazing behaviour and the effect of spatial heterogeneity within paddocks).

For more productive areas with higher carrying capacities smaller paddock sizes are likely to be warranted in order to better manage stocking rates and minimise the occurrence of high concentrations of livestock within paddocks.

In regions where the extent of property development is currently low but stocking rates are already high it is unlikely there would be substantial gains in livestock production as a result of reducing paddock size, although long-term sustainability is likely to improve.

Guideline 1.1. 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 about 3-4 km**

to strike a balance between improving 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.

3.3.1.2. Grazing distribution (patch scale)

While reducing paddock size or installing more water points provides more control over where livestock graze, uneven grazing distribution will still occur within paddocks (although the incidence and size of heavily grazed areas may be reduced).

Guideline 1.2. Smaller paddocks and additional water points do not overcome uneven utilisation by cattle at the plant community or patch scales. Other methods (e.g. fire, careful selection of water point locations) are needed to improve evenness of utilisation at these scales.

3.3.1.2. Animal production

Improvement in individual livestock production is not expected following property development due to the ineffectiveness of infrastructure in improving within-paddock distribution. Improvement in total livestock production may be possible where initial stocking rates are below the long-term carrying capacity.

Guideline 1.3. 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 better grazing distribution.

3.3.2. Other considerations

3.3.2.1. The effect of land type and land condition

The effectiveness of infrastructure in improving grazing distribution can be reduced by landscape characteristics such as land type since these factors can override effect of paddock size and water points on evenness of use. For example, Tomkins and O'Reagain (2007) reported that cattle avoided areas of steep, stony country in a study near Charters Towers in Queensland. The topography of a property will also influence how practical and expensive fencing will be, how animals use the paddock and so how effective sub-division will be.

As with land type, land condition can have a strong effect on efforts to improve grazing distribution using infrastructure. A preference for land in C condition over land in A condition (Post *et al*. 2006, Hunt *et al*. 2007) can mean cattle will continue to seek out or concentrate in areas in poorer condition following changes in paddock configuration.

3.3.2.2. Fencing of land types

Because cattle usually show a preference for grazing particular land types within paddocks (for example Box country is preferred in the Charters Towers region), strategies are needed to avoid preferred land types being over-grazed. Subdivision along land type boundaries to separate markedly different land types is often recommended to allow control of the grazing pressure on land units that differ in attractiveness to cattle and sensitivity to grazing. Fencing allows a manager to control the availability of different land units and pasture resources to livestock so they are less able to concentrate in preferred areas (Hodder and Low 1978; Low *et al*. 1981b). This should help in achieving more uniform utilisation and avoid over-use of preferred land types.

Separation of markedly different land types is critical, practical and economically feasible in some circumstances. However, it is often not practical or cost-effective in some circumstances (for example, where preferred land types are only a minor part of a paddock), and is not usually economically feasible where fences are already established. In these cases it is only when fences require replacing that consideration can be given to realigning fences according to land or pasture types. However, separating markedly different land types should be considered where property development is planned. Where the separation of land types is impractical, the use of other techniques for shifting grazing distribution within paddocks such as the strategic location of lick blocks may offer a way for managing the use of minor preferred land types.

There may be disadvantages from fencing off different land types. Many producers argue that there is a benefit in retaining a diversity of land types in a paddock since land types can respond differently to seasonal conditions and can thus provide cattle with improved pasture availability and diet selection for year-round grazing. This is supported by the work by Stokes (mentioned above). In the VRD, for example, many producers like to have a mix of red and black soils in a paddock so the cattle have useful grazing areas during the wet season when the black soils are too boggy (and in this case it is often not practical to separate these land types). However, the red soils can suffer overgrazing in this situation.

3.3.2.3. Protecting sensitive areas

Fencing to protect sensitive areas such as riparian areas, wetlands, biodiversity refuges or threatened plant species or communities is widely recommended in northern Australia. Separating sensitive land types is often a difficult objective to satisfy because of the cost and impracticality of separating minor land types (Veira 2007).

Grazing distribution can also be altered to attract livestock away from sensitive to less preferred or lightly utilised 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; Bishop-Hurley *et al*. 2008). Bishop-Hurley *et al*. (2008) found that providing off-stream water reduced the time cattle spent within 10 m of a stream by 80%. While providing less control over grazing distribution and so being less effective than fencing, this is usually a more practical option.

Guideline 1.4. 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.

3.3.2.4. Providing for biodiversity

The need to provide for the protection of biodiversity values should also be considered in determining the choice of paddock size. Research at numerous sites throughout the rangelands has demonstrated that about a third of native species of fauna and flora are sensitive to grazing and generally survive only in areas remote from stock watering points (Fisher 2001; James *et al*. 1999). In many regions these water-remote areas are crucial to the maintenance of biodiversity so paddock designs should allow for areas of appropriate size remaining remote from water. A number of guidelines have been developed (Biograze 2000). These include fencing off or keeping remote (i.e. 8-10 km) from water about 10% of key land types. Exclosures that protect areas from cattle grazing can also provide refuges for native species. 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.).

3.3.3. Options for large and very large paddocks

When developing paddocks and water points to improve grazing distribution, it is usually the case that subdivision with fencing also requires that more waters be installed. The need for both new fences and water points adds substantially to the cost, particularly for large and very large paddocks in the more extensive grazing areas. **Installing more water points in large paddocks without subdivision into smaller paddocks is a cheaper but less effective way of improving grazing distribution when subdivision is not feasible.** However, without fencing there is less control over what parts of the landscape cattle use and the grazing pressure exerted on preferred parts.

In large and very large paddocks it will be crucial to provide an adequate number and distribution of water points to allow cattle to use most of the landscape. Ideally, the average distance between waters should be about 5 km. The cattle are unlikely to distribute themselves evenly amongst water points. Certain water points will experience higher use than others because they are favoured by the cattle (due to factors such as water quality, availability of shade, topography, proximity to favoured grazing). It can also be expected that certain parts of the landscape will be heavily used. **The use of additional techniques (e.g. the strategic placement of supplements or use of fire) will be required to actively manage grazing distribution in these paddocks.** At this stage, no work has been done to comprehensively test and develop these tools or assess their effectiveness and implications on commercial properties.

Rotating the stock around the various water points in a paddock may be another option to increase the overall use of the paddock over a season or year. A number of producers have attempted to do this, but it may have limited effectiveness and it presents several problems. Firstly, the need to limit the number of head per water point means that if all water points but one are switched off, the overall stocking rate for the paddock will be quite low. An alternative might be to only switch off a minority of the water points. However, depending on the distance separating the waters, cattle might still be able to graze the same areas of the paddock rather than being forced to use new areas so that overall use is not. A final problem is that cattle often return to a water point they have been regularly using after it has been switched off. Cattle are known to continue to loiter near these waters for some days, with the potential for them to perish from lack of water or at least result in a loss of condition.

In large paddocks with multiple waters, it is possible that cattle can be trained to use a specific water point. If that is the case, this could result in more even use rather than many animals congregating on a limited number of water points. However, little is known about the fidelity of animals to individual water points and how this might be encouraged. Anecdotally, it has been noted that many cattle prefer specific water points and will be faithful to these for lengthy periods, and this preference can be encouraged by droving the cattle back to the same water when returning them to the paddock after mustering.

3.3.4. The effects of small paddocks (20-200 ha)

There is little information on the effects of very small paddocks on grazing distribution, pasture condition and livestock production in the context of Australian rangelands, and reports from overseas are contradictory. Some reports from US rangelands indicate that reducing paddock size improves the evenness of use pasture within paddocks (e.g. Hart *et al*. 1993, Teague and Dowhower 2003; Teague *et al*. 2004; Barnes *et al*. 2008) because walking distance to water is reduced and by limiting the area available to cattle. In Hart's study evenness of use was greater in 24 ha paddocks compared with a 207 ha paddock (although this was a long narrow paddock designed to increase the distance to water). Hart *et al*. (1993) also reported that live weight gain per head was greater in 24 ha paddocks than in a 207 ha paddock where cattle had to walk more than a kilometre to water. In comparison, Hacker (1988) working in very small paddocks (1-8 ha) in the western US found that paddock size did not affect the uniformity of pasture utilisation, liveweight gain or overall pasture utilisation. Grazing patterns were influenced by the spatial distribution of forage and by plant size. More productive areas that produced more forage and areas where larger plants occurred were favoured by livestock.

Based on these results and the studies of paddock size at Pigeon Hole, it would appear reasonable to suggest that paddock size does not have a strong effect on individual livestock production, and therefore it is unlikely that very small paddocks would offer any grazing distribution or livestock production benefit to producers in northern Australia. The high cost of developing such infrastructure would be hard to justify on economic grounds, and it is likely that ongoing management costs would be greater with many small paddocks because of the inefficiency of operations such as mustering. As discussed earlier, optimum grazing distribution and maximum livestock production per land area are most likely to be achieved with paddocks that approximate the size of the grazing radius around water points within which most grazing occurs.

The expectation that very small paddocks sizes will allow an increase in utilisation rate has yet to be demonstrated. There is the possibility that reducing paddock size so that cattle use the whole paddock could allow an increase in the utilisation rate. Safe utilisation rates are currently conservative to allow for uneven use, so when grazing distribution is more uniform utilisation rates above current levels may be possible.

3.4. Risks associated with paddock and water point development

A high level of development, with cattle spread over an entire property for most of this time, brings a risk of large areas of land experiencing overuse. This is because of the degradation usually associated with concentrations of livestock (especially around water points), and the possibility that if a management error is made (such as delaying destocking for too long into a drought) much of a property will be affected. In contrast, on properties with poorly developed paddock and water infrastructure, it is likely that large areas will experience only light grazing and thus better cope with drought, helping to retain these areas in good condition. Managers of properties with a high level of development will need to be vigilant and respond rapidly where areas are at risk of being overused.

3.5. Interactions with other management factors

3.5.1. Stocking rates

- Given the recommended limit of approximately 300 head per water point, stocking rates in a paddock will need to be restricted if the paddock does not contain sufficient waters to carry the number of stock at usual stocking rates.
- To minimise the risk of large concentrations of cattle occurring it may be necessary to limit the number of head per paddock (perhaps no more than 600 head), except in very large paddocks where waters are well separated and cattle are not likely to move between water points (for example in central Australia with very large paddocks).

3.5.2. Resting

- Having more smaller paddocks will facilitate the use of spelling by allowing smaller areas to be destocked while providing other paddocks where cattle can be grazed.

3.5.3. Fire

- Smaller paddocks will facilitate the use of fire by allowing smaller areas to be burnt and facilitating the management of livestock by providing other paddocks where cattle can be grazed before, during and following fire.
- Fire can be used to remove grazed patches and redistribute grazing pressure within paddocks (Andrew 1986a), thus enhancing the effect of fences and water points (although the practicalities, required frequency, effectiveness and costs are unknown).

3.6. Strength of evidence and understanding (paddocks and water points)

There is reasonable confidence in the general conclusions relating to the effectiveness of reducing paddock size and establishing additional water points in improving the distribution of grazing across the landscape. However, there is less confidence in the specific details of optimum paddock configurations for different regions, the nature of the relationships that determine the optimum configurations and the benefits for livestock production and land condition. A number of these issues are discussed in the following section.

3.6.1. What don't we understand?

3.6.1.1. Regional variation in pasture utilisation versus distance to water

The pattern of declining use with increasing distance from water (termed piospheres) will have a strong effect on the size of the grazing radius and optimum spacing of water points. It is suggested that these relationships will be stronger in arid regions compared with more mesic regions. This is because in arid regions cattle need to water at least once a day throughout the year, and there are fewer natural water holes scattered across the landscape that would reduce reliance on permanent waters and weaken the concentration of grazing around them. This may result in a more gradual decline in grazing pressure away from water points in mesic areas (Figure 3.9), although no studies are available to support this.

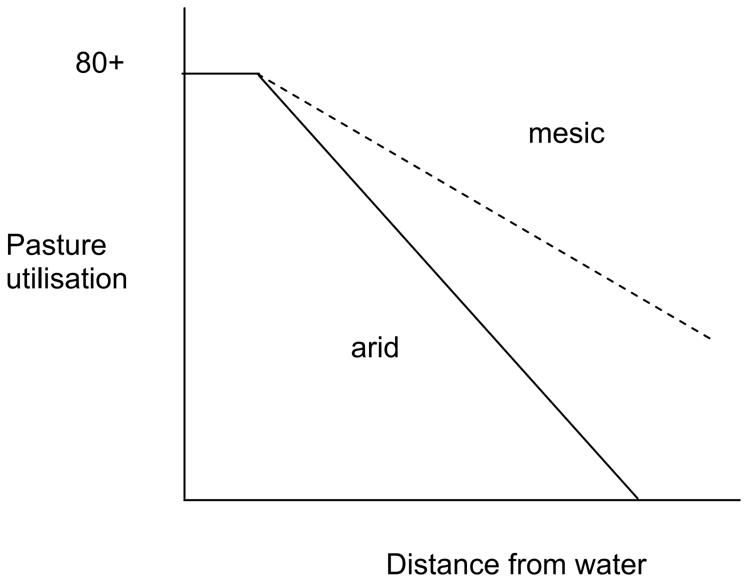

Figure 3.9. Postulated trend in utilisation in relation to distance to water in mesic and arid rangelands.

3.6.1.2. Effect of development on livestock production

We currently have a poor understanding of the effect of paddock size (and grazing radius) on livestock production per land area. In the Pigeon Hole study, livestock production per area was stable with a grazing radius of up to 3 km (single water per paddock) or a paddock size of up to about 60 km^2 with five water points. However, it is not known what effect a larger grazing radius (i.e. fewer water points) or larger paddock would have on livestock production per area, since lower levels of development were not included in this study. It is possible that livestock production will decrease at lower levels of development because of a reduction in the effectiveness of forage use, and because of a decline in land condition within the grazed area of large paddocks if there are too many livestock (Figure 3.10). This relationship assumes similar target annual utilisation rates are used irrespective of the level of property development.

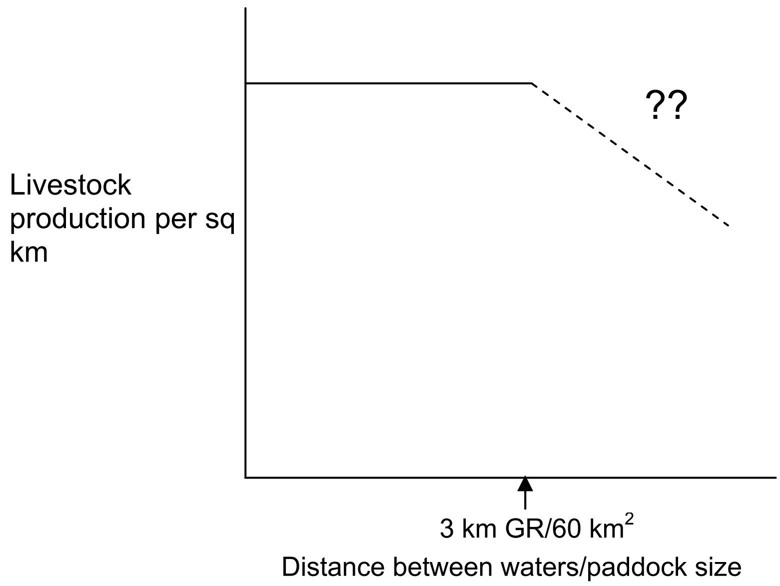

Figure 3.10. Hypothesised relationship between the level of property development (paddock size and number of water points) and livestock production per square kilometre. Research has suggested that livestock production per land area does not improve with a reduction in grazing radius below 3 km or a paddock size less than about 60 km^2 (assuming multiple waters).

The hypothesised relationship presented in Figure 3.10 assumes the country is flat and of the same land type, since topography and preferences will affect the nature of the relationships. On many properties the quality of the land that is currently undeveloped will have significant bearing on the benefit to be gained from more intensive development. In many areas past development has been concentrated on the most productive land, which could mean that the land that is further from water is of poorer quality and the benefits to livestock production of further development are marginal.

The effect of the level of development on livestock production represents a gap in our understanding at present. Determining if there is an effect of the level of development (i.e. paddock size/grazing radius) on total livestock production will better inform the question of the optimal level of development. The data presented above would suggest there is no benefit from the use of very small paddocks, but there remains some uncertainty concerning the effect of such paddocks on foraging behaviour and hence potential livestock production.

3.6.1.3. How much development is enough?

The optimum level of property development will be dependent on the particular circumstances of a given property. Looking solely from the perspective of improving grazing distribution, the financial benefit of development is expected to be maximised at some intermediate level of development where the majority of a property is being effectively used by cattle (Figure 3.11). This response is considered to be a consequence of the capacity to increase the number of livestock carried with some reduction in paddock size or better distribution of water, and the excessive cost of infrastructure with minimal further increases in total livestock production at more intensive levels of development. Ongoing management costs will also contribute to this relationship. It is likely that operating costs per head will increase at high levels of development. For example, increased costs associated with mustering many smaller paddocks and the cost of maintaining more water points are expected at higher levels

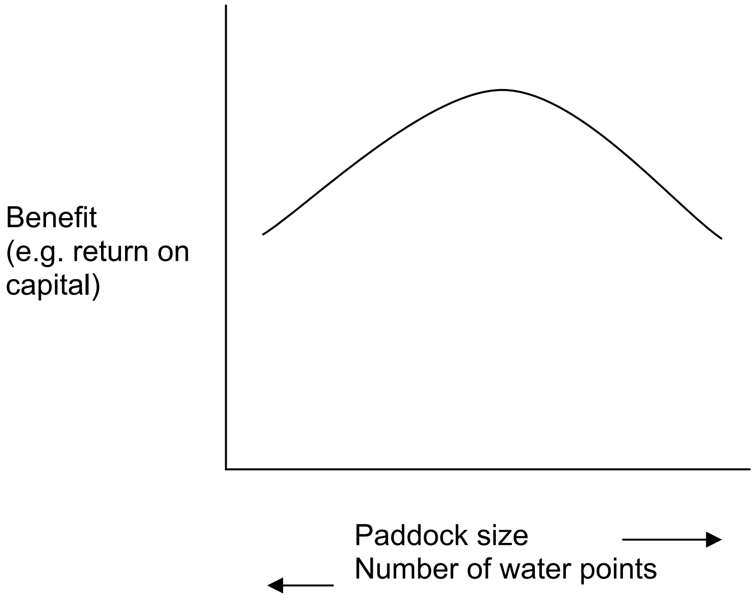

Figure 3.11. Proposed general relationship between the degree of paddock and water point development on extensive grazing properties in northern Australia and the expected financial benefit.

3.6.1.4. Other knowledge gaps

Improving grazing distribution within paddocks

Management options to improve grazing distribution within paddocks to achieve more uniform grazing use are poorly understood. Potential strategies include:

- How to manage grazing distribution with fire
- How to use strategic supplement location to improve grazing distribution.

Research is required on how best to use these options, their effectiveness at improving grazing distribution, the effect on livestock production and land condition and strategies to incorporate their use into whole-property management.

Behavioural aspects related to the use of multiple water points

Given the high cost of fencing, it is likely many producers will take the option of establishing additional waters in large paddocks rather than subdividing them in to smaller paddocks. However, this is much less effective at distribution grazing pressure across the landscape and risks overgrazing due to large concentrations of livestock. Better understanding cattle behaviour in relation to the use of multiple waters may provide options for avoiding potential problems. Important aspects include:

- the fidelity of cattle to a specific water point;
- what causes the use of more than one water point by cattle;
- how to improve the fidelity of use; and,

- how to improve the adoption of alternative water points under a strategy where selective access to water points over time is used to rotate cattle grazing around a paddock. Understanding the potential benefits for land condition and livestock production of this strategy is also required.

Decision aids for options to improve grazing distribution

The challenge for producers that have large paddocks but a limited amount of money available for developing the water point and paddock infrastructure on the property is how to decide what options to adopt. The development of a decision tree based on the key principles for paddock and water development could help producers to determine the most appropriate types and extent of development for individual properties. Linking the decision tree to case study examples should maximise its value to producers.

Exploratory modelling of the effects of paddocks and water point developments on land condition, livestock production and cost:benefit analysis would be another useful development.

3.7. Conclusions

The establishment of additional water points in large paddocks or reducing paddock size can improve the distribution of grazing (across the landscape) and improve access to forage. Where stocking rates are not already at the long-term carrying capacity, such development should allow an increase in the number of livestock carried and thus the level of animal production. However, there is a limit to the extent that infrastructure can provide grazing distribution benefits and this is related to the distance cattle graze from water. Paddocks that are smaller than the usual grazing radius of cattle are unlikely to generate increases in livestock production due to improved grazing distribution, but may provide other management benefits.

In summary:

- Smaller paddocks improve overall landscape use.
- Additional waters improve uniformity of use in paddocks (including in subdivided paddocks).
- Improvement in individual livestock production and land condition is not expected following property development due to the ineffectiveness of infrastructure in improving within-paddock distribution. Improvement in total livestock production may be possible where initial stocking rates are below the long-term carrying capacity.
- There is unlikely to be a distance to water effect on grazing distribution outside of 300 m for paddocks of less than 20 km^2 in eastern and southern Queensland. Piospheres do not appear to be as well-developed in tropical regions compared with more arid regions.
- Elsewhere an exponential decay curve can be used to describe how grazing declines with distance from water.
- The evenness of grazing use in paddocks is improved if water points are sited away from fences.
- Smaller paddocks provide better control over grazing distribution. In large paddocks some waters are favoured by cattle potentially leading to greater overgrazing of nearby areas (although note that the effect of smaller paddocks on land condition have not been demonstrated).
- To protect sensitive areas, frontage/riparian country should be fenced off, off-stream water should be provided to reduce riparian use and water points should

be sited away from preferred areas (although the effects on land condition are uncertain).
- Allowance should be made for protecting biodiversity where grazing-sensitive flora and fauna still exist by not establishing new waters that would make these areas accessible to livestock.

These points form the basis of the principle and guidelines for the development and management of fencing and water points that were listed in earlier sections.

4. Stocking rate management

Stocking rate is the principal factor under the control of management that determines livestock productivity and the future condition and productivity of the land (Heitschmidt and Taylor 1991; Ash and Stafford Smith 1996). Stocking rate has such a profound influence because it is an important determinant of the amount and quality of forage consumed by livestock (i.e. their intake) and their productivity, the severity of defoliation of pasture plants and effects of livestock on the soil. It is widely accepted that high stocking rates result in a decline in land condition (including loss of perennial grasses, increase in bare ground and soil loss, with subsequent loss in productivity).

Here we consider the financial objective for a beef enterprise is to optimise net returns per land area rather than maximising production per land area. This is a function of land condition and pasture growth. Stocking rate can affect these and interacts with these to determine productivity.

The rationale for managing stocking rates includes the following points:

- Stocking rate is a major driver of land condition and livestock production
- Coping with seasonal and annual variability in pasture growth is critical to land condition, financial returns and sustainability
- Stocking rates may be adjusted to:
    - Avoid land degradation in poor years
    - Take advantage of good seasons to increase production
    - Reduce the risk of overgrazing due to uncertainty about seasonal conditions

Matching stocking rates to the capacity of the land to support livestock is therefore one of the most crucial aspects of grazing management, but it involves striking a balance between short- to medium term financial returns and maintaining good land condition, and thus long-term financial returns.

Principle 2. Managing stocking rates is vital to meeting livestock production and land condition goals

4.1. Review of past studies

There have been about a dozen major studies that have investigated the effects of stocking rate on land condition or livestock production (or both). Brief summaries of these studies follow (in approximate chronological order). Table 4.1 summarises the experimental design features of each of the studies and Table 4.2 presents an overview of the climatic and land condition context for the studies.

These tables highlight some of the limitations associated with the studies which make it difficult to draw firm conclusions concerning the management of stocking rates or use of pasture utilisation rates for setting stocking rates. For example, a number of studies did not use the pasture utilisation rate concept, or used it in varying ways. About half the studies did not include replicates as part of the experimental design, meaning that it is difficult to separate the effects of stocking rate treatments from site effects. One study continued for a relatively short time (four years). Also, some studies compared fixed stocking rates, others used variable stocking rates and another group compared fixed with variable stocking rates. While most studies measured livestock production, the majority of the studies used steers (i.e. grower cattle) and not breeders. This meant that liveweight gain was the sole measure of productivity for these studies and measures of reproductive performance were not available.

Other issues that confound interpretation of the studies were that stocking rates were often varied from the nominal stocking rate for the treatments because of drought conditions or supplementary feed was provided to the cattle. Finally, many studies occurred in relatively small experimental paddocks rather than in ones of commercial size, meaning that the effect of spatial variation in grazing pressure across paddocks typical of commercial operations was negated.

Table 4.1. Key features of the experimental designs of the main stocking rate studies in northern Australia.

Study	Type of study*	Used utilisation rates	Livestock production recorded	Study included replicates	Duration (years)
Kangaroo Hills	S	No	Yes	No	10
Aristida-Bothriochloa	V	Yes	Yes	Yes	8
Glenwood	S	No	Yes	Yes	8
Lansdown	S	No	Yes	Yes	5
Galloway Plains	S	Yes/No	Yes	Yes	13
Ecograze	V	Yes	No	Yes	8
Wambiana	C	Yes	Yes	Yes	8
Mt Sanford (NT)	V	Yes	Yes	No	6
Pigeon Hole (NT)	C	Yes	Yes	No	4
Northern stocking rate demo	C	Yes/No?	Yes	No	5

*Type of study: S - set stocking, V - variable, C - comparison of variable versus set stocking rates.
Note: there also sheep stocking rate trials at Augathella, Toorak and Arabella in Queensland that used pasture utilisation to set stocking rates on the basis of consuming a percentage of standing feed at the start of the dry season.

Table 4.2. Summary of climatic and land conditions for key stocking rate studies. Percentages in the final column indicate the proportion of land in each condition.

Study	Climatic conditions	Initial land condition	Ending land condition
Kangaroo Hills (Qld)	Above average	A/B	A/B
Glentulloch (Qld)	Dry to average	B	C
Keilambete (Qld)	Dry to average	A/B	B
Galloway Plains (Qld)	Dry	B+	B (50%), C (50%)
Ecograze (Qld)	Drought/wet	A & C	A/B
Wambiana (Qld)	Early severe drought, then above average	A/B	C (40%)
Mt Sanford (NT)	Wet	B	A (30%), B (50%), C (20%)
Pigeon Hole (NT)	Good	C	C

4.1.1. Kangaroo Hills – Gillard (1979)

This study focussed on the issue of pasture improvement through the over-sowing of Townsville stylo, tree clearing and fertiliser application (superphosphate). The study occurred in the Upper Burdekin west of Ingham where annual rainfall is approximately 650 mm. Two stocking rates were used in the study (0.4 and 0.2 beasts per ha). These were considerably higher than the district average of 0.06 beasts/ha.

The pasture remained dominated by black spear grass (*Heteropogon contortus*) and forest blue grass *Bothriochloa bladhii* at the end of the study (i.e. there was no change in pasture condition). The principal finding was that mean liveweight gain was correlated with the length of the growing season and hence the ability of the animals to select a high quality diet. Greater liveweight losses occurred on heavily stocked treatments during the dry season of drought years. There was no effect of stocking rate on livestock production in years when rainfall was average or above average (i.e. feed quantity was not a limiting factor).

4.1.2. The 'Aristida-Bothriochloa' study

Silcock *et al*. (2005) reported on a grazing study at two sites in the *Aristida-Bothriochloa* pastures in Queensland. One site (Keilambete) was an 'Ironbark' site with a gritty red duplex soil in central Queensland. The pasture was dominated by desert blue grass (*Bothriochloa ewartiana*), black spear grass and ribbon grass (*Chrysopogon fallax*), with desert blue grass generally having the highest yield and basal area. The second site (Glentulloch) was a 'Poplar box' site near Injune in southern Queensland which had a texture contrast soil with a shallow loamy surface soil above a heavy clay subsoil. Pastures at Glentulloch were dominated by *Aristida* spp. and *Bothriochloa* spp. with some ribbon grass and *Enteropogon* spp.

The study included three grazing pressures which were based on livestock consuming a given proportion of the standing autumn pasture biomass over the following 12 months:

- Low - utilise 25% of the standing autumn pasture biomass over the following 12 months (but allowed to vary between 15 and 35% depending on seasonal conditions);
- Medium - utilise 50% of the standing autumn pasture biomass over the following 12 months (but allowed to vary between 40 and 60% depending on seasonal conditions);
- High - utilise 75% of the standing autumn pasture biomass over the following 12 months (but allowed to vary between 65 and 85% depending on seasonal conditions).

Thus, stocking rates varied each year according to the amount of forage available at the end of the growing season. With this form of stocking rate adjustment the actual annual utilisation imposed by can vary substantially each year since the stocking rate reflects the amount of forage grown in the season just passed rather than in the ensuing growing season. Modelled pasture consumption (i.e. of standing autumn biomass) for one of the 75% consumption paddocks varied annually between about 20% and 115%, while for one of the 45% consumption treatments the rate varied between 20 and 110%. These pasture consumption data were available for only a limited number of paddocks.

One of the aims of this study was to examine the effect of timber clearing on productivity. However, only the results from the undeveloped treatments are considered here.

Paddock sizes were from 4-18 ha, with two replicates of each treatment at each site. The study occurred during a very dry period and rainfall in the lead-up to the study was low (decile 3). The study ran for seven years (July 1994 to June 2001).

The authors reported that there is some uncertainty about aspects of the results because of changes in observers between sampling periods and inconsistencies in the way stocking rates were set.

Stocking rate did not affect tree and shrub density or basal area, and low grazing pressure did not reduce the regeneration of woody plants at the poplar box site.

At both sites higher grazing pressure decreased pasture yield, perennial grass basal area, ground cover and plant longevity and resulted in accelerated soil erosion (particularly when ground cover was below 40%), and lowered animal production. The level of recruitment and mortality for both desert blue grass and black spear grass increased at higher stocking rates. Perennial grass basal area tended to increase under low grazing pressure during the study, in association with improving seasonal conditions. Two years elapsed before the effect of high grazing pressure in reducing perennial grass basal area was apparent. Higher grazing pressure did not appear to affect the seed banks of perennial grasses. Rather, seed banks were more affected by rainfall than management, and seed banks generally increased when there was above average rainfall in the previous summer. It was not possible to determine whether enhanced recruitment of desirable perennial grasses at higher grazing pressure was sustainable in the long term. The authors expected that heavy grazing would reduce seed production which would eventually reduce recruitment.

Grazing pressure had no significant effect on the frequency of desert blue grass, ribbon grass or black spear grass at the Ironbark site. It should be noted, however, that frequency is not a particularly sensitive indicator of change in perennial plant communities. Nevertheless, the frequency of kangaroo grass (*Themeda triandra*) was reduced under medium and high grazing pressure in most years of the study.

Ground cover, total pasture yield and individual species yields all increased in the ungrazed plots compared with the grazed plots at the Ironbark site, and the frequency of kangaroo grass was lower in the grazed plots. Perennial grass basal area did not show a response until the last two years of the study when it was higher in the ungrazed plots. The survival of individual perennial grasses was higher on the ungrazed plots. The density of desert blue grass and ribbon grass was unaffected by grazing pressure.

The number of individual plants of the dominant grasses was higher in grazed plots than ungrazed plots at the poplar box site. This was attributed to the greater fragmentation of tussocks under grazing, as well as the possibility that more open space allowed for higher recruitment.

At the Ironbark site grazing pressure had little effect on the contribution of the major perennial grasses and the minor pasture components to total pasture biomass. At the poplar box site the contribution of decreaser species to total pasture yield was reduced by higher grazing pressures.

In the short term, the highest economic returns were achieved by the high stocking rate (3-4 ha per AE) but in the long term returns from the high stocking rate were similar to those generated by the medium stocking rate. The high stocking rate treatment was not considered ecologically sustainable. The low grazing pressure treatment produced lower financial returns.

It was concluded that a safe carrying capacity equated to an average pasture utilisation level of around 25% of standing autumn pasture biomass. At this grazing pressure pasture composition was maintained while under moisture stress and the density of key perennial grasses was maintained. Notably, recruitment of perennial grasses increased with increasing grazing pressure. To minimise runoff and soil loss on the ironbark land type it was recommended that ground cover be maintained at 50-60%.

These results are broadly consistent with the other grazing studies in Queensland.

4.1.3. Glenwood study – MacLeod and McIntyre (1997)

This project studied the effect of three stocking rates on livestock production, economic performance and land condition from 1988-1996 in native pastures over-sown with legumes and fertilised. Yearling steers were used to impose the three stocking rates: low (= 0.3 steers/ha or ~ 0.25 AE/ha), medium (= 0.6 steers/ha or ~ 0.45 AE/ha) and high (= 0.9 steers/ha or ~ 0.68 AE/ha). Steers remained in the study for two years with an annual changeover of the older steer. The study occurred at 'Glenwood' west of Mundubbera. The study period experienced severe drought so stocking rates were halved for slightly more than half of the study period and supplementary feeding was provided in many years. A third very low stocking rate (0.15 steers/ha) was introduced partway through the study by reducing the number of cattle in some paddocks being run at 0.3 steers/ha. Stocking rates were not presented in terms of pasture utilisation rates and it would be difficult to reliably calculate utilisation rates from the data presented. Land condition was assessed in terms of the frequency of occurrence and frequency of dominance of black spear grass.

Liveweight gain per steer declined in all treatments for much of the study due to the worsening drought. In the last two years lower liveweight gain was recorded in the highest stocking rate.

Liveweight gain per hectare was greater in the medium and high stocking rates in the years that full stocking rates were applied. In these years there were significant increases between the very low, low and medium stocking rates with gain increasing with stocking rate, but no difference between the medium and high stocking rates.

Gross margin per hectare was largely a function of liveweight per hectare so that returns increased with stocking rate. However, the high stocking rate did not always generate the largest economic return because of slower growth and weight for age penalties that apply at market and because of the cost associated with the increased need for supplementary feeding. The medium stocking rate generated the highest net profit. The very low stocking rate generated the lowest profit because it produced only limited quantities of saleable beef.

The frequency of dominance of black spear grass declined in all treatments during the study but was significantly different amongst stocking rates in two years, and was favoured by the low stocking rate. The frequency of occurrence of black spear grass declined over the study, with greater declines as stocking rates increased (decline of 9% and 24% at low and high stocking rates respectively) although these differences were not statistically significant. In general the decline in black spear grass was similar in the very low, medium and high stocking rate while its dominance was best maintained at the low stocking rate. The decline in black spear grass in all treatments reflects the poor seasons and the legume oversowing.

The study concluded there are important trade-offs between livestock production, economic returns and land condition. The study found that the relationship between liveweight gain per animal and stocking rate was largely insensitive to stocking rate changes at low to medium stocking rates as has been suggested by others (see Ash and Stafford Smith 1996). However a significant decline occurred particularly in the high stocking rate in the last two years when stocking rates were fully applied. This was considered to be consistent with the ‘break’ in the relationship between liveweight gain per head and stocking rate which is considered to be an indicator of overgrazing.

Increasing marginal costs associated with carrying more stock, the marketing penalties and costs for additional supplementary feed reduced the profitability of the high stocking rate despite the greater production per hectare.

While the medium stocking rate generated the highest economic returns it was not clear if this was ecological sustainable in the longer term since there was some decline in perennial grass populations during drought (although this was not statistically significant).

4.1.4. Lansdown study – Jones (1997)

This study compared pasture production and steer liveweight gain on native pasture at three stocking rates (0.3, 0.6 and 0.9 steers/ha) at Lansdown near Townsville. The steers in each paddock were of mixed age (one weaner, one yearling and one two-year-old). Stocking rates were not presented in terms of annual pasture utilisation rates and insufficient data were presented to allow their subsequent calculation. The soils were duplex soils (solodic-solodised-solonetz). The study period encompassed drought requiring that stocking rates be reduced for much of the study, the high and medium stocking rate treatment be destocked for about 12 months and supplementary feed be provided in the high and medium stocking rate treatments.

There was a linear decline in pasture yield and liveweight gain with increasing stocking rate. At the lowest stocking rate the native pasture was stable over the study period but declined (i.e. there was a loss of palatable perennials such as black spear grass, kangaroo grass and *Bothriochloa decipiens*) in the medium and high stocking rate treatments. Losses were faster at the higher stocking rate. Peak liveweight gain per hectare was obtained at about 0.6 steers/ha (i.e. the medium stocking rate), which is approximately 0.46 AE/ha. Stocking at the high stocking rate was not sustainable, and rates of gain were much slower at this stocking rate. Conservative stocking was recommended to maintain ecological sustainability without sacrificing economic returns.

4.1.5. Galloway Plains - Orr (2005)

This study used stocking rates of 8, 5, 4, 3 and 2 ha/steer on native pasture dominated by black spear grass and forest blue grass. Soils were duplex and grey clay soils of low fertility. There was a eucalypt overstorey (Ironbark and Poplar box at the two soil types), which was cleared in some treatments. The results presented here are from the native pasture treatments rather than those oversown with legumes.

The study continued for 13 years from 1988 and 2001, although the 8 ha/steer treatment was discontinued after eight years. Mean annual rainfall of the area was 854 mm, but the study occurred during the driest period since records were kept (approximately averaging 500 mm per year).

Pasture utilisation rates were calculated (based on simulated pasture growth) for the period that steers were in the paddocks (rather than on an annual basis). The stocking rates of 8, 5, 4, 3 and 2 ha/steer were approximately equivalent to average utilisation rates of 15, 20, 30, 40 and 50%.

The effects of the stocking rates were assessed at both the plant community and plant population level. Some conflicting results emerged from this study, depending on the level of pasture assessment (population versus community) and the response variable of interest.

It was notable that there was a considerable time lag (about five years) before the pastures began to show some effects of the different stocking rates. Black spear grass increased in abundance at light stocking rates and decreased at high stocking rates. These differences were attributed to changes in seedling recruitment (i.e. more recruitment at lower stocking rates) rather than increased mortality at higher stocking rates.

According to the plant community studies, there was no effect of increasing stocking rate on overall perennial grass basal area because there was an increase in the basal area of increaser species at higher stocking rates. There were also few effects of stocking rates on the basal area of individual grasses. However, the more detailed study of black spear grass populations indicated that basal area did decline with increasing stocking rate. However, these differences were due to changes in plant density not due to changes in the basal area of individual plants. Such changes may have serious implications for long-term sustainability.

Soil surface condition assessments (or Landscape Function Analysis - LFA) indicated that the proportion of transect length occupied by perennial grasses, the landscape stability index and nutrient cycling index were all higher at 5 ha/steer, although most of these differences were not statistically significant.

Increasing stocking rate reduced the yield and availability of preferred species (although this was significant only in two years) so other less preferred species were selected. Decreaser species were the major component of the diet but the contribution of increaser species such as *Bothriochloa bladhii* increased with increasing stocking rate. It is important to note, however, that there appeared to be a pre-existing trend in the yield of black spear grass with stocking rate treatment (i.e. higher stocking rate treatments had lower initial yield at the start of the study). The frequency of both dominant species was unaffected by stocking rate.

The most noticeable effects of stocking rate on the pasture were through the population dynamics of black spear grass. The density of black spear grass increased at 5 and 4 ha/steer and decreased at 3 and 2 ha/steer. Differences in density were the result of changes in both seedling recruitment and plant mortality (increased recruitment at lower stocking rates and increased mortality at higher stocking rates). The survival of the original black spear grass plants was greatest at 5 ha/steer and lowest at 2 and 4 ha/steer. In the long term there was little difference in the survival of seedlings with stocking rate. Heavy grazing reduced the production of seed, the abundance of seed in the seed bank and recruitment. This flowed through to lower plant density.

The more fertile duplex site showed fewer effects of higher stocking rates than the infertile clay site.

Liveweight gain per head decreased linearly with increasing stocking rate, but liveweight gain per hectare increased linearly with increasing stocking rate. The reduced LWG per animal with increasing stocking rate was consistent with the lower pasture yields and the reduced contribution of black spear grass to the diet at higher stocking rates.

Variation in amount and timing of rainfall (and management factors) resulted in a large variation in LWG between years at all stocking rates. A regional (state-wide) trend of increasing LWG from the north to south of the black spear grass pastures was attributed to soils being more fertile and there being more green days in the south (the latter because of the more even distribution of rainfall during the season in the south).

Highest financial returns were achieved at the highest stocking rate of 2 ha/steer (~2.7 ha/AE) calculated over a 13-year period (Burrows *et al.* 2010). However, these returns were only slightly higher than those at 3, 4 and 5 ha per steer (approx. 4, 5.3 and 6.7 ha/AE respectively) indicating that stocking rates could be reduced without greatly reducing financial returns. Although heavier stocking rates were profitable in the short term, LFA analysis suggested there were negative effects on the pasture and soil which would indicate that these stocking rates (2 and 3 ha per steer) were not ecologically sustainable.

It was concluded that stocking at 4 ha/steer (which equates to an average pasture utilisation rate of 30%) was sustainable. Stocking rates above this reduced pasture yield, increased the occurrence of undesirable pasture species, and reduced the density of black spear grass. To maintain the density of black spear grass it was recommended that grazing pressure should be reduced in autumn to allow seed production, followed by a spring burn (in years when seasonal forecasts suggest a good wet season is expected).

4.1.6. Ecograze - Ash et al. (2001, 2010)

This study was on three land types (from infertile to fertile) in two conditions (good and deteriorated) in north-eastern Queensland. Perennial grasses present included black spear grass, desert blue grass, kangaroo grass and Queensland blue grass (*Dichanthium sericeum*). Three pasture utilisation rates (25, 50 and 75% utilisation of annual forage grown) were imposed with and without annual spelling for the first eight weeks of the wet season. Treatments were imposed in small experimental paddocks from 1 to 5 ha. The study ran for nine years (1992 to 2001) and encompassed a range of seasonal conditions from extreme drought to good seasons. Stocking rates were adjusted in accordance with variation in annual pasture growth to maintain the target utilisation rates.

The study concluded that continuous stocking at 25% utilisation or at 50% utilisation following annual wet season spelling would maintain land condition, and can improve the condition of deteriorated pastures (i.e. recovering 3P grass biomass) even during drought. However, some 3P grasses were still present in the deteriorated pastures at the beginning of the study. Recovering degraded pastures that had lost 3P grasses would be more difficult. Continuous grazing at 75% utilisation caused a decline in the productivity of 3P grasses. There was good recovery at the fertile site once good seasons returned but at one less fertile site the 3P grasses failed to recover. It is important to note that the recovered pastures were much patchier than pastures in good condition. The recovery was largely a result of existing plants getting larger rather than there being substantial recruitment of new plants (A. Ash, pers. comm.). This suggests that recovery of the plant population had not occurred. It was not until very favourable seasons late in the study that any recruitment in perennial grasses was observed.

Simulations indicated financial returns were similar for good and deteriorated pastures but returns were more variable for the latter (since this was more sensitive to seasonal conditions). Years with negative returns were thus more common on deteriorated pastures. It was suggested that where wet season spelling allows an increase in the pasture utilisation rate (to 35%) financial returns should increase and be more profitable than continuous grazing (at either 25 or 35% utilisation). However, the possibility that individual livestock performance may suffer at higher utilisation rates could mean that livestock take longer to reach market specifications.

4.1.7. Wambiana – O'Reagain et al. (2007)

The primary aim of the Wambiana study was to test different approaches to managing stocking rates in a seasonably variable tropical savanna. The work occurred on a site with a range of infertile soils with an *Aristida-Bothriochloa* pasture community and an open *Eucalypt* and *Acacia* overstorey. The main vegetation-soil associations were Silver-leaf Ironbark (*Eucalyptus melanophloia*) on low fertility kandosol soils, Box (*E. brownii*) on moderate fertility texture contrast soils) and Brigalow (*Acacia harpophylla*) on relatively fertile clay soils. In addition to species of *Aristida* and *Bothriochloa* the understorey included ribbon grass, black spear grass, and Queensland blue grass depending on the soil-vegetation association.

Five stocking strategies were compared over a period of eight years (1998-2006):

1. light stocking at the recommended long-term carrying capacity (8 ha/AE);
2. heavy stocking at twice the long-term carrying capacity (4 ha/AE);
3. variable stocking where the annual stocking rate was adjusted based on the available pasture (actual range used was 4-12 ha/AE);

4. variable stocking where the stocking rate was adjusted based on the Southern Oscillation index and available pasture (actual range used was 4-12 ha/AE),
5. rotational wet season spelling using a moderate stocking rate (6 ha/AE).

These strategies were tested in experimental paddocks that ranged in size from 92 to 115 ha. There were two replicates of each treatment.

The study highlighted the ecological and financial benefits of moderate stocking rates. Stocking which achieved an average annual utilisation rate of about 25% maintained good pasture condition and provided better livestock performance (i.e. average liveweight gain per head), better financial returns and reduced runoff compared to heavier stocking regimes. It was necessary to provide supplementary feed to cattle (or reduce the stocking rate) in the higher stocking rate treatment during drought and feed shortages.

The two variable stocking rate options resulted in financial losses and damage to the pasture resource in the transition from a sequence of good years to poor years. While these approaches provided acceptable levels of livestock production and financial returns overall, they involve greater risk compared to the use of constant light stocking rates. Three recommendations to reduce the risk associated with variable stocking were: 1) to set an upper limit to the stocking rate that can be used; 2) minimising fluctuations in stocking rates and particularly the size of increases; 3) reassessing stocking rates in the early to mid-wet season, and reducing stock numbers if seasonal conditions dictate this. The use of seasonal forecasts to aid stocking rate decisions was also recommended.

O'Reagain *et al*. (2007) concluded that using stocking rates close to the long-term carrying capacity (for the study area this equates to 20-30% annual pasture utilisation) was the most profitable and least risky stocking rate strategy. Although heavy stocking rates (40-50% annual pasture utilisation) initially gave the greatest economic returns, financial losses occurred when there were below average seasonal conditions because cattle lost weight which was not compensated for later.

Other findings:

- Variable stocking performed well economically but suffered in the transition from good to poor years. It therefore had increased risk compared with constant light stocking.
- Individual animal production (liveweight gain/head) was greatest at lighter stocking rates. Total liveweight was maximised at utilisation rates of 20-30%.
- Overgrazing may occur during extended periods of low rainfall despite the use of safe average utilisation rates, so it may be necessary to adjust stocking rates in accordance with rainfall or pasture growth.
- It was recommended that even with light stocking at the long-term carrying capacity, some wet season spelling of pastures and some variation in stock numbers is probably necessary. This variation is intended to allow the recovery of grazed patches, avoid overgrazing in very dry years and to take advantage of wetter years when forage production is greater.

O'Reagain *et al*. (2007 also noted the importance of the timing of pasture utilisation in relation to seasonal conditions. They found that grazing prior to and during drought had a larger effect on pasture condition that at other times. In particular they concluded that the timing of heavy utilisation (in excess of 40-50% for their study site) relative to dry years was as important as the average utilisation rate in terms of the effect on pasture condition.

4.1.8. Mt Sanford

The Mt Sanford project compared six annual pasture utilisation rates (13, 21, 23, 31, 39 and 47%) in native pastures on cracking black clay soils (Wave Hill land system) in the Victoria River District of the Northern Territory. The study ran for six years in small experimental paddocks of about 4-8 km^2. Livestock numbers were adjusted each year to achieve the desired utilisation rate. Treatments were not replicated. The study followed on from a stocking rate study that occurred in the same paddocks during the six years prior to the utilisation rate study. Seasonal conditions were generally favourable, with many years recording above average rainfall.

No marked effects of pasture utilisation rates on pasture production or plant species composition were observed. Daily liveweight gain per animal was significantly lower at higher utilisations but higher utilisation rates did not result in marked reductions in weaning rates. Weight weaned per unit area was positively related to utilisation rate. While aspects of individual performance appeared to suffer at higher utilisation rate, overall performance per unit area improved. Gross margin per hectare increased with increasing utilisation rate.

An annual pasture utilisation rate of 23% was considered to be a sustainable long-term carrying capacity. Since there were no marked declines in performance (either livestock or ecological) above 23% utilisation ground cover, residual biomass and individual animal performance criteria were used to evaluate what is a safe carrying capacity.

These criteria included a minimum pasture biomass of 1500 kg/ha dry weight in October (sufficient to carry a fire) and a minimum of 40% ground cover in October (to protect the soil from erosion in early wet season storms). However, 31% utilisation resulted in a biomass in October of 1000 kg/ha, which is the minimum biomass regarded as necessary to protect the soil from early wet season storms. Increased inter-calving interval and reductions in LWG (weaner weight) were the only observed changes in livestock production attributes at or above 23% utilisation (although there was only a weak and variable effect on LWG and in most years there was no trend with increasing utilisation rate). Thus, in the years tested there was little evidence to indicate the need to stock at less than 30% annual utilisation.

4.1.9. Pigeon Hole

The Pigeon Hole study explored options for intensifying beef production in the VRD region of the Northern Territory, including an experiment that investigated safe pasture utilisation rates. The study was on the same land type as the Mt Sanford study but was in commercial paddocks of approximately 20 km^2 rather than small experimental paddocks. The annual pasture utilisation rates in this study were 13, 17, 19, 24 and 32%. This was an unreplicated study that ran for four years (from October 2003 to October 2007). The actual utilisation rates for each treatment (based on total pasture biomass) and the overall range in utilisation rates were less than the target utilisation rates. For example, the highest target utilisation rate was intended to be 40% but the actual rate for that treatment was 32%. Land condition was predominantly C at the start of the study and the pasture contained a high proportion of unpalatable species. Consequently, palatable perennial grasses within the pasture were sometimes subject to defoliation rates of 20-30% over the wet season and more than 50% by the end of the dry season.

Generally the results were not strongly conclusive since responses were variable among years and utilisation rates, and there were no consistent significant differences in pasture and livestock production with increasing utilisation rate. The yield of palatable pasture in May (i.e. end of the wet) declined with increasing utilisation rate as did ground cover in October (i.e. towards the end of the dry), but there were no significant differences in pasture yields at the end of the wet season in the last two years of the study. In some years pasture yields were lower in higher utilisation rate treatments. Often higher utilisation rates had higher cover but the trend wasn't consistent and often the differences were not significant. Ground cover was greater than 50% for all utilisation rates on most occasions; unplanned fires were usually the cause of marked reductions of ground cover in a given treatment.

There was no consistent effect of utilisation rate on perennial grass basal area during the study (although basal area estimates included both palatable and unpalatable species), so it is possible that any declines in the basal area of desirable 3P grasses that may have occurred could have been masked by increases in the basal area of unpalatable species (particularly feathertop wire grass [*Aristida latifolia*]).

There was considerable variation amongst treatments and years in the availability of palatable pasture and no consistent trend with utilisation rate was apparent. In October of some years the yield of palatable pasture was at or less than 300 kg/ha (the approximate point at which cattle intake declines) at pasture utilisation rates greater than 17%. This suggests that in some years (generally following a poor wet season) at this site cattle intake may be restricted towards the end of the dry season even under low to moderate utilisation rates.

Various measures of the performance of individual livestock (including liveweight gain, breeder weight, branding and weaning rate and inter-calving interval) were independent of utilisation rate. Body condition score was better in lower utilisation rate treatments in poorer years.

Livestock production per unit area (weight weaned per hectare and total production per unit area) increased with pasture utilisation rate. This reflected the higher stocking rate and the lack of effect of higher utilisation rates on the performance of individual animals. As a result economic returns increased with utilisation rate. Earnings per square kilometre before interest and tax at 32% utilisation were more than twice the earnings at 13% utilisation, as was the return on capital.

Despite the equivocal results for pasture and individual livestock production responses, it was concluded that an annual utilisation rate of 19% was optimal at Pigeon Hole. This was based on the following observations:

- species composition and cover trends were stable or improving in the 13-17% utilisation rate treatments;
- the greatest decline in land condition occurred at 32% utilisation. At this rate species composition was showing an adverse trend and there appeared to be a higher risk of ground cover levels reaching minimum acceptable values in October.
- pasture yield and cover targets were not met at or above 24% utilisation in some years.

4.2. Assessment of what has been learnt from previous studies

In this section we discuss the key findings relating to the management of stocking rates from the above studies. These findings are supplemented with insights that have emerged from other studies not described above.

The reviewed stocking rate studies did not produce consistent results in terms of the effect of stocking rates on land condition and livestock production (notwithstanding the variation in regions and stocking rates amongst the studies). There are several possible explanations for this.

1. Some studies continued for only a relatively short period (4-6 years) and hysteresis in the ecological system meant there may have been insufficient time for any potential changes to become apparent during the study period.
2. Some studies experienced above average seasonal conditions and did not encounter a below average season or sequence of below average seasons when marked changes to pastures and livestock production are most likely.
3. Many of the studies that measured livestock production started with the pasture in reasonable condition (B or A) and this would likely have contributed to hysteresis in the system.
4. In most studies pasture dynamics were measured using relatively coarse techniques (e.g. Botanal) that are not sensitive to incipient pasture changes particularly changes in life cycle processes and population dynamics (e.g. reduced seed production, reduced recruitment, increased plant mortality) which are better indicators of likely long-term change in species abundance.
5. Some studies used only a narrow range of stocking rates or utilisation rates and/or the highest rates were comparatively low so the ecological and productivity limits of the system were not tested.
6. The ‘state-and transition’ nature of rangeland dynamics may also have played an important role in determining the outcome of the studies. In many rangeland types substantial change in the vegetation can occur when heavy grazing coincides with drought. However, at other times the vegetation can appear to be strongly resilient to the effects of grazing at similar levels to that which can cause severe damage during drought or after other events such as fire.

The conclusions in the subsequent sections that have been drawn from these studies should be read with the above caveats in mind.

4.2.1. Effect of stocking rate on livestock production

The effect of stocking rate on livestock production is usually interpreted in terms of the Jones-Sandland model (Jones and Sandland 1974), which considers the relationship between stocking rate and livestock production by individual animals and per unit grazed area (Figure 4.1). According to this model, individual animal production is high at low stocking rates but declines at higher stocking rates. Animal production per unit area increases from low levels at low stocking rates to a peak at intermediate stocking rates and then declines as stocking rates increase further. Since costs increase linearly with stocking rate maximum profit occurs at a stocking rate somewhat less than that which provides maximum livestock production per head (see Figure 4.1).

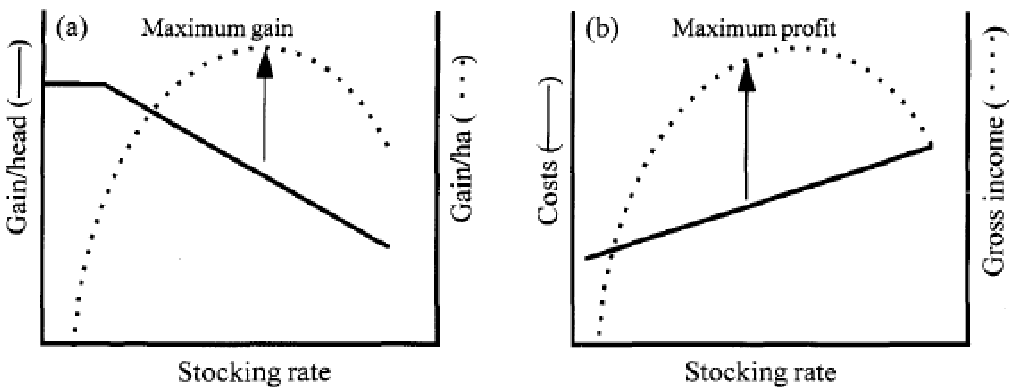

Figure 4.1. (a) The Jones-Sandland model relating livestock performance to stocking rate. (b) The relationship between stocking rate and economic performance based on the Jones-Sandland model (from Ash and Stafford Smith 1996).

Most of the studies reviewed for this report showed that as stocking rate (or utilisation rate) increased, production per animal generally declined but livestock production per land area increased (Table 4.3). Most studies did not show the expected decline in livestock production per land area at higher stocking rates. The absence of this response in many cases may reflect the low to moderate stocking (or pasture utilisation) rates often used, stocking rate reductions or supplementary feeding when poor conditions occurred during the studies, or favourable seasonable conditions. Maximum annual utilisation rates exceeded 50% in two studies only (*Aristida - Bothriochloa* and Ecograze; Table 4.4) but livestock production was not measured in the Ecograze study. In only two studies (one *Aristida-Bothriochloa* site and Lansdown) was a peak in livestock production per land area evident, so that stocking rates lower than the highest studied were most productive.

Table 4.3. Average annual liveweight gain per hectare (kg) in relation to stocking rate for trials in northern Australia. For stocking rate, 1 = lowest stocking rate and 2, 3 , … represent progressively higher stocking rates

Trial	**Years**	**Stocking rate**					
		1	**2**	**3**	**4**	**5**	**6**
Kangaroo Hills	10	24	42				
Aristida-Bothriochloa - Keilambete	8	43	61	53			
Aristida-Bothriochloa - Glentulloch		37	52	59			
Glenwood	2	26	50	90	95		
Lansdown	3	35	49	46			
Galloway Plains	13	18	28	34	37	53	
Wambiana	10	14	21				
Pigeon Hole	3	13	16	19	20	27	
Mt Sanford	6	15	21	21	25	26	43

It is important to consider temporal effects in the relationship between stocking rates and livestock production. For example, while higher stocking rates were more productive overall in the Wambiana study (O'Reagain *et al*. 2007 Figure 4.2) there were marked differences in performance over the life of the study. Higher stocking rates performed better in the short term but they suffered following the onset of severe drought (Figure 4.3). Following drought, higher stocking rates did not result in substantially greater livestock production per unit land area, although notably there was still no evidence of the expected decline in production with increasing stocking rate (Figure 4.3). O'Reagain *et al*. (2007 concluded that high stocking rates reduce land condition, livestock production and financial returns in the medium to long term.

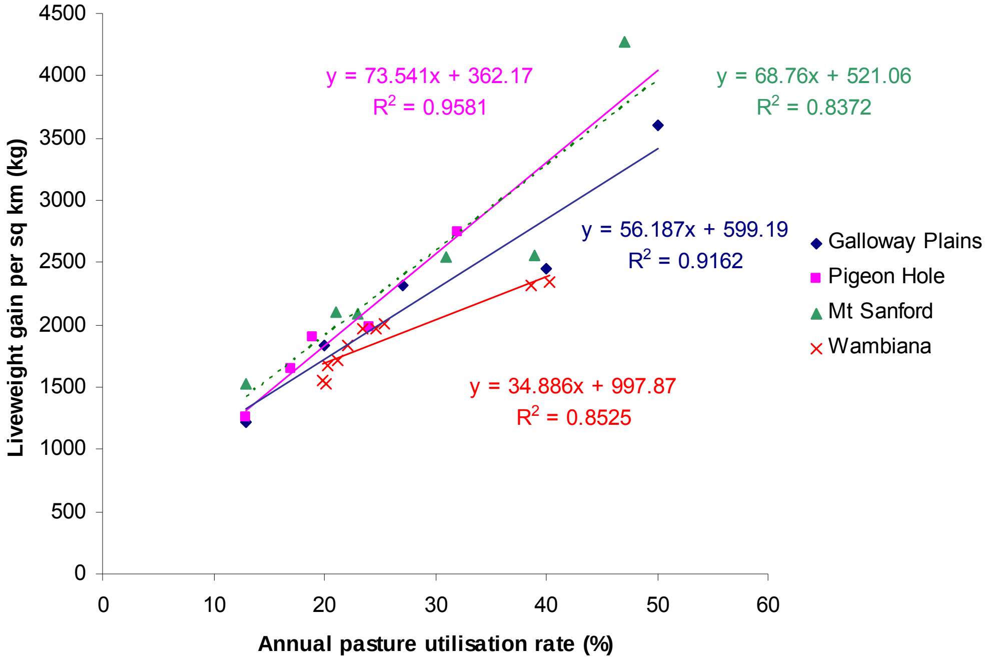

Figure 4.2. Livestock production per land area against pasture utilisation rate for four grazing studies in northern Australia. These data represent results over the entire study period for each study.

Table 4.4. Average maximum annual pasture utilisation rates and stocking rates used in the main grazing studies.

Study	Maximum utilisation rate used (%)	Maximum stocking rate used (AE/km^2)
Aristida-Bothriochloa	115*	
Glenwood	50#	68
Lansdown		69
Galloway Plains	50	37
Ecograze	75	
Wambiana	40	
Mt Sanford (NT)	47	38
Pigeon Hole (NT)	32	21

* calculated using GRASP and based on use of standing autumn forage
# estimated from published data (R. Cowley pers. comm.)

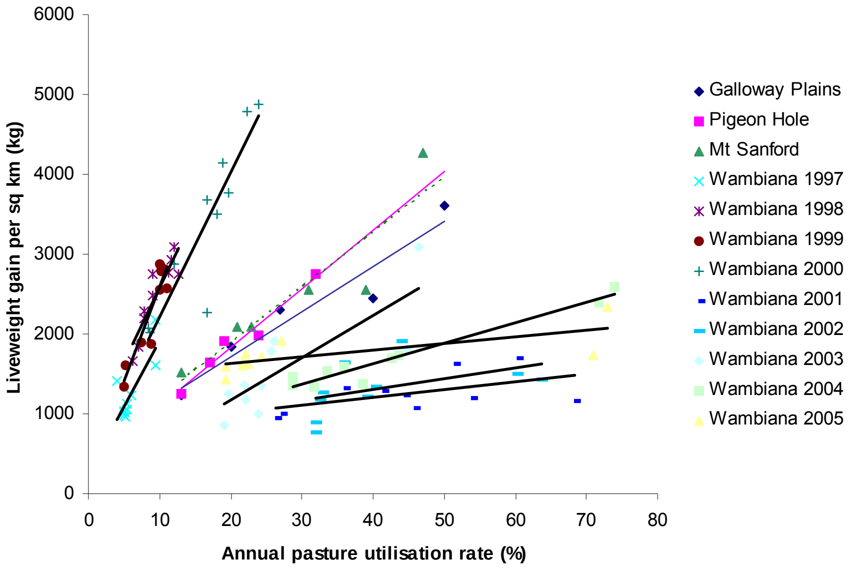

Figure 4.3. Livestock production per land area against pasture utilisation rate for four grazing studies in northern Australia, with yearly results presented for the Wambiana study (black lines). The first four years for Wambiana (1997-2000) experienced very good seasonal conditions, with results grouped to the left of the graph. Very poor seasonal conditions occurred in 2001, and results for that and subsequent years are grouped to the right.

Other studies have also shown variation amongst years in the relationship between pasture utilisation (or stocking) rate and livestock production per unit land area (e.g. Fig. 4.4). This variation indicates that relying on summaries of production over the life of an experiment can potentially be misleading in terms of the level of livestock production that can be expected in a given year. Variation in this relationship from year to year occurs in part because of varying seasonal conditions. Gillard (1979) found that the level of livestock production was related to the availability of green plant material, and Orr (2005) reported that variation in the amount and timing of rainfall (and management factors) resulted in a large variation in LWG between years at all stocking rates.

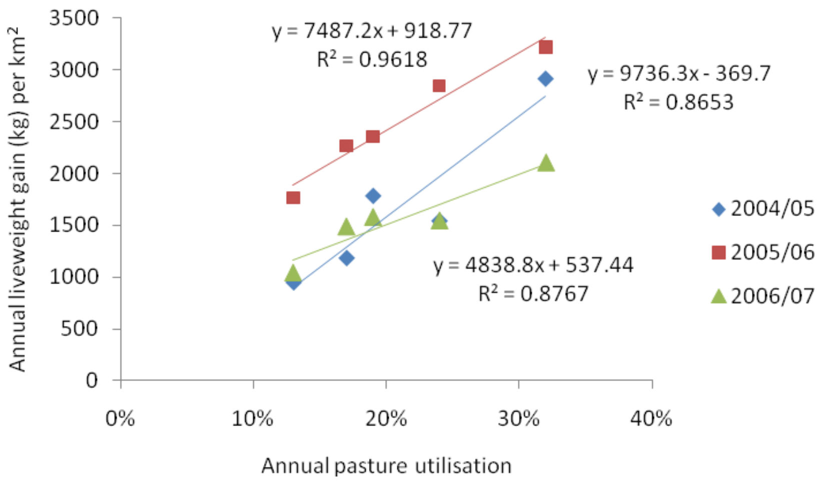

Figure 4.4. Annual liveweight gain versus pasture utilisation rate for individual years in the Pigeon Hole study.

It is difficult to reconcile the varying livestock production (and pasture) responses to pasture utilisation across the various studies. This is likely to be due to factors related to regional characteristics (e.g. pasture type, annual rainfall, rainfall variability, length of the growing season), and also the considerable variability in livestock production response to utilisation rate among years within a study (e.g. see Fig. 4.3) owing to seasonal variation. Relating livestock production to pasture utilisation rates is also problematic because pasture consumption at a given utilisation rate will vary among sites and seasons depending on the available pasture biomass. Thus, even predicting livestock production responses at a given utilisation rate under different seasonal conditions is also likely to be difficult.

4.2.2. Effect of stocking rate on pasture and land condition

In a number of the studies stocking rate had no effect on key pasture attributes such as yield (i.e. pasture productivity), perennial grass basal area, frequency of species and species composition despite many of the studies encountering a drought. In contrast, high pasture utilisation rates reduced pasture production and perennial grass basal area in the Ecograze and Wambiana projects (in conjunction with poor seasonal conditions). The results from these studies suggested an annual pasture utilisation rate of 25% with continuous grazing is sustainable and minimises the risk of pasture degradation in most years. However, based on the Ecograze results Ash *et al.* (2001) suggested annual spelling for about eight weeks in the early wet season can lead to improvement in pasture productivity, and may allow higher utilisation rates to be used.

Notably, the Galloway Plains project detected little or no effect of utilisation rate on the yield, frequency and basal area of pasture species, but more detailed data on the population dynamics of key perennial grasses indicated recruitment of new plants was restricted by higher stocking rates. These results highlighted the potential for deleterious changes in population processes of the grasses, which have implications for sustainability in the long term and which were not reflected in paddock-level measures of pasture and livestock productivity in the short term.

Other studies have also reported on the effect of stocking or utilisation rates on the pasture. Medium to high grazing (30-45% utilisation) during the growing season can suppress productivity in subsequent years (Ash *et al*. 1997), possibly through declines in plant vigour, root mass and tiller number. Over longer time frames, high levels of pasture utilisation can result in the loss of perennial grasses (Mott *et al*. 1992). Differences in the resilience of landscape types to grazing may contribute to variation in the responses observed in grazing studies.

Recommended long-term carrying capacities have been developed for various land types or regions in northern Australia using a range of methods:

- Tothill and Gillies (1992) rated the safe carrying capacity of 46 pasture communities across northern Australia based on observations of long-term grazing effects.
- Some state government agencies have completed rangeland surveys of land and vegetation type, range condition and climate to provide rated safe carrying capacities (or safe pasture utilisation rates) for different regions and range types.
- Quantitative methods based models that incorporate historical rainfall records, soil moisture, an understanding of plant growth rates and knowledge of rates of forage consumption by livestock have been used to estimate carrying capacity in various regions in Queensland (e.g. Scanlan *et al*. 1994, Johnston *et al*.

> 1996, Hall *et al*. 1998) The experience of pastoralists who have maintained good land condition on their properties over the medium to long term has also been an important contribution in determining long-term carrying capacity in a given region, and also demonstrating the wisdom of operating at close to the long-term carrying capacity (e.g. Johnston *et al*. 1996).

Despite the often equivocal pasture (and livestock production) results, most studies recommended a safe pasture utilisation rate. These conclusions were usually justified on the response of only one or two attributes, such as ground cover levels in October or a decline in one aspect of individual animal production (or in some cases economic returns). Prior knowledge of recommended safe utilisation rates from other studies may also have influenced the conclusion about what is a safe utilisation rate. Given the potential for slow response of pastures to grazing that was apparent from the few population dynamics data, some recommended utilisation rates should be treated with caution. It is possible current recommendations either under- or over-estimate long-term sustainable utilisation rates. Particular caution is warranted with respect to what are safe utilisation rates during drought years.

It follows that there is not necessarily a strong basis for recommended long-term safe utilisation rates for some regions. Nevertheless, it would appear that safe annual utilisation rates are usually in the order of 25-30% for the more productive country.

In conclusion, long-term productivity and sustainability for a grazing enterprise rely on the maintenance of good land condition. Various studies suggest that operating at around the long-term carrying capacity of the land helps to maintain land in good condition.

Guideline 2.1. 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.

4.2.3. Effect of stocking rate on financial returns

Financial returns reported for the studies that were reviewed were largely related to livestock production per unit area, which tended to increase with an increase in stocking rate. Declines in individual performance at higher stocking rates were usually compensated for by the greater number of animals. However, where there were market penalties (e.g. weight for age) or market incentives forgone, or there was a need to feed the cattle in dry years, then higher stocking rates could result in lower overall financial returns than moderate or low stocking rates (e.g. the Wambiana and Glenwood studies).

In addition, at Wambiana 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 the study period. This is consistent with other findings. Ash *et al*. (1995) reported that short-term returns can be improved by using stocking rates above the long-term carrying capacity, but a modelling study based on a property near Charters Towers suggested that declines in land condition from using 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).

This study also suggested that there would be limited prospects for profitable livestock production on land in poor condition.

The potential for more conservative (or lower) stocking rates to be more profitable in the medium to long term has received support from some producers (e.g. Purvis 1987, Landsberg *et al*. 1998). Several modelling studies have also resulted in similar conclusions (e.g. Buxton and Stafford Smith 1996; Pratchett and Gardiner 1993).

4.2.4. Managing variable seasonal conditions

The high degree of inter-annual variability in rainfall (and hence pasture growth) in much of northern Australia presents a difficult challenge in setting stocking rates to optimise livestock production whilst maintaining land condition. The coefficient of variation of annual rainfall ranges between approximately 25 and 42% across the region, tending to be higher in the east. Two broad options are possible to manage for varying conditions: 1) maintaining stocking rates at or below the long-term carrying capacity or 2) varying stocking rates around the long-term carrying capacity in accordance with changing conditions.

As described earlier, a primary objective of the Wambiana study (O'Reagain *et al*. 2007 was to compare different strategies for coping with seasonal variation. There have been no other field studies that have investigated approaches for managing for seasonal variability, although some modelling studies have occurred. The main conclusions in relation to managing stocking rates in relation to varying seasonal conditions (drawn primarily from the Wambiana study) are:

- The most profitable and least risky strategy appears to be constant light stocking around the long-term carrying capacity.
- Varying stock numbers around the long-term carrying capacity may help avoid overgrazing in very dry years and allow higher production in wetter years when forage production is greater.
- Variable stocking can generate good financial returns but has increased ecological and economic risk compared with constant light stocking. The transition from good to poor years is the period of greatest risk, and rapid action is required to reduce stocking rates to avoid pasture damage that can reduce future productivity.

A variable stocking rate strategy may be a better option as one moves from more reliable to more variable environments with lower average production, since it is possible that operating with continuous conservative stocking rates may not generate enough livestock production to be profitable. A tactical stocking approach may prevent land degradation in dry times and take advantage of years with higher rainfall and pasture production, although the logistics and increased cost of trucking cattle associated with a tactical approach may make it a less attractive option.

The Northern Stocking Rate Demonstration Project reported that livestock production and financial returns were more variable with a variable stocking rate strategy but this approach was generally more profitable than fixed conservative stocking rates. However, managing breeders within a variable system is more difficult than for a grower enterprise. A possible strategy is for breeder numbers on a property to be at a level where substantial reductions are not needed except in a major drought, and for some of the herd to be made up of dry animals that can be traded more readily.

At this stage, the question of whether varying stock numbers over time to cope with variable seasons (and take advantage of above average seasons) is generally a better option than continuous stocking at around the long-term carrying capacity remains to be clarified. The greater management complexity and increased ecological and financial risks associated with a variable stocking rate strategy are important factors affecting the potential value of this approach.

Research to date suggests that constant light stocking at close to the long-term carrying capacity appears to be the most profitable and least risky stocking rate strategy. However, some variation in stocking rates will be necessary to account for poor seasons and to take advantage of high pasture growth.

Guideline 2.2. Regularly assess the need to adjust stocking rates in relation to current and anticipated feed supply and feed quality. Some variation in stocking rates over time is required to manage periods of below-average pasture growth. Capacity to vary numbers over time also 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.

4.2.4.1. Timing of stocking rate changes

Adopting a variable stocking rate strategy will require the use of criteria for making decisions about when to adjust livestock numbers and by how much. Given the elevated risk associated with variable stocking, having a clear plan for making adjustments would seem to be wise.

In many regions of northern Australia (particularly in the more extensive areas) it is common practice is to adjust cattle numbers once a year. This is often at the end of the wet (growing) season as part of the first round muster. This adjustment would more commonly involve a reduction in numbers in accordance with low feed availability than for numbers to be increased. However, delaying this decision until the end of the season may result overgrazing or surplus pasture going unused, and some producers will adjust numbers earlier in the growing season depending on how the wet season is progressing. Some researchers are also now advocating that stocking rates be reviewed and if necessary adjusted more than once a year. For example, O'Reagain *et al.* (2007 proposed a system with two stocking rate adjustment points: a primary adjustment in May-June to set stocking rates for the next 12 months based on standing feed and expected growth in the next wet season; a secondary adjustment point in November (late dry early wet) using animal performance, pasture availability and seasonal forecasts (with the expectation that only downward adjustments would occur if needed).

Reviewing progress during a year would also appear to be sound action since a number of factors may require a readjustment in stocking rates. For example, unexpected rain, fire and insect damage may all alter pasture availability and/or quality. Uneven grazing distribution across a paddock that results in some areas being very heavily grazed may also dictate that stocking rates be adjusted.

The reasons for reviewing and adjusting stocking rates during the year include:

1. ensure there is adequate ground cover at the start of the wet season;
2. to evaluate progress against earlier expectations of pasture availability and stocking rates;

3. to ensure stocking rates match feed availability until the next expected growth;
4. to prepare for the coming wet season so that stocking rates are based on an expectation of pasture growth;
5. to facilitate the completion of vital life cycle processes by 3P grasses (e.g. flowering and seed set);
6. to avoid heavy defoliation of perennial grasses during below average wet seasons or drought.

There is good scientific evidence to support these objectives. For example, there is relatively good evidence for the need to maintain a minimum degree of ground cover to protect the soil from early wet season storms (e.g. Gardener *et al*. 1990; McIvor *et al.* 1995; Scanlan *et al.* 1996a) although specified minimum cover levels have increased for some land-pasture type combinations (e.g. 60-70% for Indian blue grass [*Bothriochloa pertusa*] pastures). Advisers from given regions also tend to provide locally specific minima.

The level of pasture utilisation that is safe is influenced by seasonal conditions during the growing season. Scattini (1973) and Mott *et al*. (1992) showed that pastures are more robust in favourable growing seasons. Pasture utilisation rates of up to 80% during good growing seasons had little effect on basal area in Scattini's study whereas utilisation above 50% during poor growing seasons resulted in substantial declines in basal area. O'Reagain *et al*. (2007 also noted the importance of the timing of pasture utilisation in relation to seasonal conditions. They found that grazing prior to and during drought had a larger effect on pasture condition that at other times. They also recommended consideration be given to adjusting stocking rates part way into the wet season since this is a critical period for perennial grasses.

Based on studies of the population dynamics of perennial grasses in the Galloway plains study, Orr recommended that stocking rates be reduced in the autumn (i.e. late growing season) to allow 3P grasses to flower and set seed.

Although perennial grasses appear to be more resilient to grazing during the dry season when they are not actively growing, heavy grazing during this period might also be deleterious to 3P grasses and reduce subsequent production. This might happen through the removal of axillary buds low on the plant, the damaging of rhizomes at the base of the plant and changes to the microenvironment and soil due to greater exposure to solar radiation and increased soil temperatures [see Hunt (2008)] for a discussion of these issues).

O'Reagain *et al*. (2007) recommended dry season feed budgeting incorporating the use of a wastage factor and a minimum buffer of total standing dry matter so that the palatable perennial grasses will not be entirely consumed. Plant indicators of maximum grazing levels might also be useful in this situation.

4.2.4.2. Indicators for stocking rate adjustments

Implementing a variable stocking strategy will require criteria upon which to make stocking rate decisions. Currently available tools to support stocking rate decision-making have the objective of matching stocking rates to forage availability. For example, Stocktake can be used to generate a dry season forage budget following the end of the growing season. Some of the recommendations such as upper limits for stocking rates and rate of change of numbers appear to be arbitrary but are probably reasonable estimates in the absence of specific data.

O'Reagain *et al*. (2007) also developed an approach for setting stocking rates during the coming wet season based on standing forage and seasonal forecast. O'Reagain *et al*. (2007) also recommend adjusting stocking rates downwards in March if rains have failed and pasture growth is poor. An alternative approach is to not increase numbers during a good wet season but allow the plants to grow and the use the extra forage later in the season. This would also favour an increase in vigour in the perennial grasses and allow them to set seed.

Monitoring of range condition and responding to current conditions is a fundamental aspect of rangeland management. Maintaining or improving land condition relies on appropriate short-term decision making with stocking rates based on current conditions. Matching stocking rates to forage available is an important part of this, but decisions should also be based on ecological indicators. To date, there has been little emphasis on identifying and developing the necessary criteria in northern Australia. Further work is required to develop and test such indicators. Indicators could be related to minimum safe stubble heights for 3P grasses and the incidence of flowering (and hence seed production) in 3P grasses. Managers should then be encouraged to adopt such indicators and understand issues such as spatial patterns of grazing and appropriate locations for monitoring to occur within paddocks.

Two indicators recommended in grazed savannas in South Africa (O'Reagain, pers. comm.) may also be useful in northern Australia to guide decisions concerning the adjustment of stocking rates to maintain land condition:

1. livestock should to be moved from a paddock when 7 out of 10 tussocks of preferred grass species are grazed;
2. In the longer term, the density of tussocks of preferred species per square metre is used to assess the need for a paddock to be destocked.

The capacity for properties to adopt a variable stocking rate strategy will vary amongst regions and types of enterprise. One difficulty with frequent adjustment of stocking rates is having somewhere for excess animals to go when reducing numbers and, conversely, having access to additional livestock when wishing to increase stocking rates. Properties in more settled regions with close access to livestock markets are more likely to be able to be flexible with stocking rates. More remote regions such as central Australia will not have that flexibility because of the high cost of freight to distant markets. For these properties, flexibility in stocking rates will need to be accommodated within the property, which will usually mean maintaining 'spare' paddocks (i.e. the property may not be fully stocked at the long-term carrying capacity).

Because of the issue of uneven grazing within paddocks, partially reducing stocking rates during the growing season may not provide much benefit to pastures since the livestock remaining in the paddock will continue to put pressure on preferred parts of the landscape (O'Reagain *et al*. 2007). It is possible that reducing stocking rates might be beneficial in above-average growing seasons where pasture growth outstrips consumption. However, complete destocking will be more likely to facilitate improvements in pasture condition. Efforts should also be made to distribute grazing pressure evenly across paddocks (see infrastructure section).

4.3. Other considerations in the choice of stocking rates

Forage supply is a primary consideration in determining the stocking rates for a given time. However other factors may need to be considered in setting and adjusting stocking rates.

- Reducing stocking rates to provide fuel for prescribed fire as part of managing woody species may be necessary in some situations.

- Reducing stocking rates or destocking may be needed to arrest declines in land condition or to improve land condition.
- Total grazing pressure should also be considered, so that stocking rates should take into account any feral or native herbivores that may be present (and reducing domestic or wild herbivores as necessary).
- The need to maintain adequate levels of ground cover to protect the soil may also require that stocking rates be lowered.
- Pastoralists who are risk averse may 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 the animals (ensuring they are receiving adequate nutrition) and the management of pests and diseases may warrant reductions in stocking rates.

Guideline 2.3. 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.

4.4. Effects of climate, land type and land condition on stocking rates

Climate, land type and land condition all influence the capacity of the land for supporting livestock and the optimum level of stocking. Thus, safe utilisation rates are not generally transferable across regions, climates, land types and vegetation types. Safe utilisation rates tend to be higher in regions of more favourable pasture growth, for example areas of higher soil fertility, more resilient vegetation types or longer growing seasons (McKeon *et al*. 2009). To a large extent, it is the factors that affect pasture growth that determine what is a safe level of utilisation for a given location.

4.4.1. Climate

Climate affects the long-term carrying capacity by determining the average number of pasture growth days (i.e. growing season length) in a region. Hall *et al*. (1998) developed a relationship between the number of pasture 'growth' days and safe pasture utilisation level based on the finding that 77% of the variation in carrying capacity across a wide range of pasture and soil types and climatic zones in Queensland could be attributed to variation in pasture growth. For a given property, the safe utilisation level could be calculated as follows:

% safe pasture utilisation = -11.2 + 0.385 x % growth days

where % growth days is the percentage of days in the year when growth is expected based on a growth index. Thus, lower utilisation rates are associated with regions with fewer growth days. The finding that safe carrying capacity is correlated with the percentage of growth days is a potentially useful tool for assessing the long-term carrying capacity for a given area (when calibrated for the land and vegetation type), but this approach has not been extended to many regions in northern Australia.

Average stocking rates should be lower in climatically more variable systems to provide capacity for coping with seasonal fluctuations in pasture growth. Ash and Stafford Smith (1996) concluded that average production levels will be lower as annual variability in forage production increases. Lower safe utilisation rates are also associated with regions with greater inter-annual variation in rainfall (e.g. Hall *et al*. 1998).

Orr (2005) also noted that an observed trend of increasing liveweight gains from north to south within the black spear grass country of Queensland is due to soils being more fertile and there being more green days in the south (the latter because of the more even distribution of rainfall during the season in the south). Thus, the length of growing season appears to be an important determinant of safe stocking rates and livestock production.

4.4.2. Land type

Differences in the long-term carrying capacity of different land types have already been mentioned. This variation is related to the fertility and productivity of the land type and its resilience to grazing, and is reflected in different safe pasture utilisation rates. In the VRD, for example, annual utilisation rates of 20% are recommended for the relatively robust and fertile black cracking clay soils (Cowley *et al.* 2007), 10-15% for less productive red soils (Ash *et al*. 1997) and 5% for low productivity rocky Spinifex communities (T. Oxley pers. comm.).

4.4.3. Land condition

Lower levels of pasture utilisation will be required for land in poorer condition to limit further degradation and facilitate recovery. As land condition deteriorates the basal area of palatable perennial grass species and the contribution they make to total pasture biomass decline. Thus, declines in land condition reduce long-term safe stocking rates. Total pasture biomass may or may not be lower depending on the extent to which less palatable or annual species increase. Where the proportion of palatable forage on offer is diminished, there is the risk that if pasture utilisation rates are not reduced (or alternatively are calculated on the palatable biomass only) the palatable perennial component will be subject to increased grazing pressure, accelerating the rate of pasture damage. Achieving an increase in the abundance of palatable perennials is also likely to require defoliation rates that are sufficiently low to maximise the opportunities for existing plants to flower and set seed and for seedlings to establish. Current tools for estimating long-term carrying capacity account for poorer land condition by discounting the amount of 'useful' pasture growth. However, lower actual levels of defoliation of palatable species may be necessary to encourage recovery.

Land condition also appears to alter the relationship between stocking rate and livestock production. One study found that production was higher on land in poorer condition at low stocking rates than on land in good condition, but the reverse was true at higher stocking rates (Ash *et al*. 1995). This was because of greater feed availability when the land was in good condition and feed shortages occurred less often (MacLeod *et al*. 2004).

Seasons also affect this response. Where annual vegetation has replaced perennial dominated vegetation herbage and livestock production can be greater in favourable years compared with unchanged vegetation, but in poor seasons the effect is reversed. Livestock production from perennial dominated pasture is also likely to be more stable from year to year (Ash *et al*. 1995).

Declines in land condition associated with a loss of perennial grasses and an increase in short-lived grasses and forbs will increase the importance of forage budgeting at the end of the growing season. However, due to the reduced persistence of annual plant species, the time horizon for forage budgeting is likely to be shorter than if the pasture is dominated by perennial species. Poor land condition may require more frequent or a more rapid response to a poor wet season than for land in good condition.

4.4.4. Environmental determinants of safe utilisation rates

A conceptual model of how environmental factors might determine the safe utilisation rate for a given location may be a useful way to generalise our current understanding (Figure 4.5). There are few data on which to derive the relationships amongst these factors and safe utilisation rates, but the following diagram is an attempt to represent how various factors determine safe utilisation rates, based on our current understanding. Further work is required to better understand how the various factors interact to determine safe utilisation rates (interpreted as long-term carrying capacity).

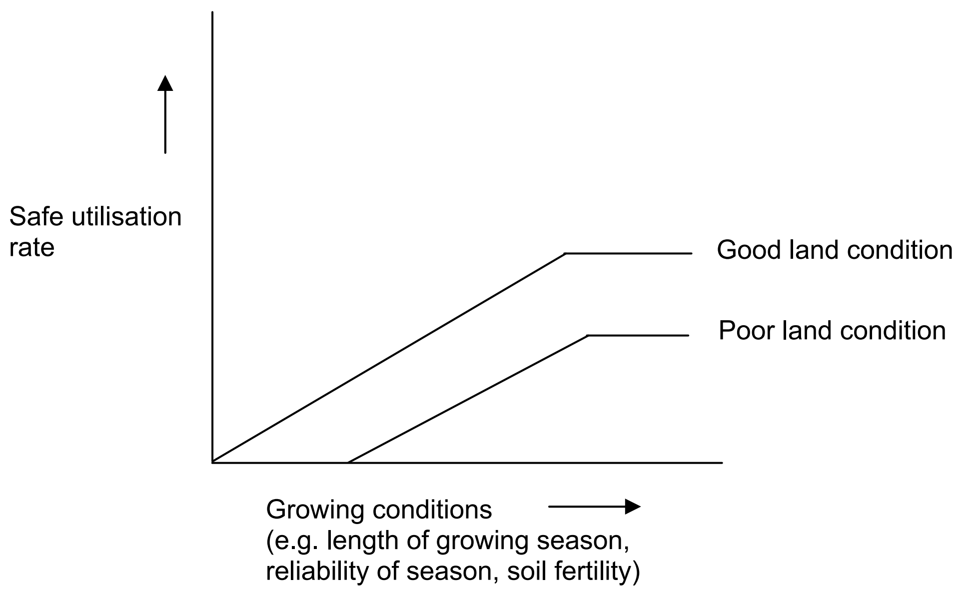

Figure 4.5. Hypothetical relationships between land condition, growing conditions and safe utilisation rates.

Thus, as growing conditions improve safe utilisation rates increase. On the other hand, as variability in growing conditions increases there is a decrease in safe utilisation rates (because of lower average pasture growth and to allow for years with low pasture growth). This model suggests that a loss of land condition moves this system to a situation where the relationship between environmental factors and safe utilisation rates is different.

On the sole basis of rainfall amount and reliability this model suggests that safe utilisation rates will be higher in southern Queensland than elsewhere in the state. This is consistent with modelling results that suggested safe annual utilisation rates of 22.0% for south-east Queensland, 14.5% for south-west Queensland and 19.3% for north-east Queensland (Hall *et al*. 1998).

Further development and testing of this model would be useful in allowing estimates for safe utilisation rates to be made for regions where local data are not available.

4.5. Production system, management intensity and stocking rate strategies

The problems of spatial heterogeneity and uneven grazing by livestock in paddocks mean that the grazing pressure experienced by plants in a paddock often has little relationship with the overall stocking rate intended for the paddock. A greater proportion of a paddock is likely to be subject to the intended stocking rate in more intensive production systems (i.e. those with relatively small paddocks), and in more homogenous landscapes. However, some unevenness in grazing pressure will occur even in quite small paddocks. Therefore stocking rates and utilisation rates may need to be reduced for larger paddocks where grazing distribution is less uniform. Discounting stocking rates for the effect of distance to water is one approach to this problem.

The feasibility of adopting a variable stocking rate strategy will need to be assessed on a regional and a property basis. Operating with relatively constant livestock numbers at the long term carry capacity is a relatively simple management system that requires less management effort and potentially less movement or trading of livestock than a system that involves varying stocking rates. The latter can present problems in terms of being able to readily reduce livestock numbers as conditions deteriorate and will be dependent on having somewhere for the removed cattle to go, either within the same enterprise, on agistment or to market. Similarly, having cattle available to allow an increase in numbers when desired can also be problematic. These issues are less of a problem for the more settled areas such as south-eastern Queensland, compared with remote areas that are far from markets and face higher freight costs and the need to move cattle greater distances. The ease of mustering on more intensively developed properties should also facilitate making relatively rapid adjustments to numbers. These systems are therefore more likely to be able to take advantage of an above average season by increasing livestock numbers and implementing tactical grazing strategies. Grower operations are also more suited to varying livestock numbers than breeder operations. As a result, large poorly developed properties in remote locations are best suited to relatively constant stocking around the long-term carrying capacity. More intensive management systems in more reliable regions should allow more precise control of actual utilisation rates, and adjustment of stocking rates.

It has been suggested that wet season spelling will allow substantial increases in stocking rates over continuous stocking (e.g. up to 50% utilisation of annual growth in north-east Queensland; Ash *et al*. 2001). However, there have been no studies that have demonstrated whether this is achievable and sustainable within a practical production system and over an extended period.

4.6. Interactions between stocking rates and other management factors

The management of stocking rates interacts with other management factors. Key considerations include:

- Infrastructure (paddocks and water points)
    - The number of head per water point should be limited, and this may mean that a paddock cannot be stocked at its long term safe carrying capacity.
    - There should be 2-3 waters per paddock to help spread grazing pressure across the entire paddock.
    - The size of paddocks should not be so large that cattle are unable to reach most areas or result in large concentrations of cattle in preferred areas.

- Fire
    - Where country is burnt (either when fire is used as a management tool or in the case of wildfire) paddocks should carry no livestock to allow the recovery of the pasture (usually resting for one wet season is needed).

- Resting
    - Resting of paddocks is preferable to a reduction in stocking rates
    - An increase in stocking rates in a paddock to allow resting elsewhere might be acceptable, and result in net benefits to overall land condition, if done in good seasons only.

4.7. Strength of evidence and understanding of stocking rate management

4.7.1. Strength of evidence

Many of the reviewed studies did not provide conclusive evidence of the effect of different utilisation rates on livestock production or pastures. As a consequence, the evidence for the appropriateness of certain utilisation rates in a given region is often weak, and recommendations for safe stocking rates appear to incorporate a degree of conventional wisdom. The evidence for the pros and cons of variable stocking rate strategies (in terms of ecological and financial implications) compared to light constant stocking is also generally poor. Our understanding of how best to manage a variable stocking rate system also requires further effort. Specific aspects of these gaps in our knowledge are discussed in the next section.

4.7.2. Gaps in understanding optimal stocking strategies

4.7.2.1. Reconciling stocking rate – livestock production relationships

As discussed earlier, our understanding of the relationship between stocking rates and livestock production and how environmental factors modify that relationship across time and regions is poor. Our failure to reconcile the results of the different studies highlights our limited understanding of these relationships and the effects of stocking rate on livestock production. This limits our ability to predict the level of livestock production that can be expected for a particular set of circumstances and thus allow managers to assess the consequences of various stocking rate regimes. Research is therefore needed to reconcile the results from the diversity of completed studies. The development of a model that incorporates the data from the various studies and uses standardised variables for defining the regional (or site) and growing season characteristics would appear to be a logical first step in this process (although not all data will be suitable for this because of the varying ways grazing pressure has been described, and the way the data have been recorded or presented). Attempting to combine and model the data from the various studies should also highlight any further gaps in our understanding of the factors affecting these relationships.

4.7.2.2. Maximum safe pasture utilisation rates

Another key gap relates to the uncertainty about what is the average annual utilisation rate (for different land types) above which pastures, livestock production and financial returns suffer. Past research has provided a broad indication of what grazing pressure is safe, but few insights about the tolerance for higher utilisation rates or how this is affected by the run of years. Few studies have used utilisation rates high enough to have resulted in reduced total livestock production, so it is not clear what the upper limit is for many land types. Thus, the extent to which stocking or utilisation rates can exceed the long-term carrying capacity without reducing economic returns and/or reducing land condition is unclear.

Further work is also required to better understand how various environmental factors (including land condition) interact to determine safe utilisation rates (i.e. long-term carrying capacity) for a particular situation, and the degree of tolerable variation around recommended utilisation rates. The development of a generalised model of the determinants of safe utilisation rates would allow the estimation of safe utilisation rates for regions where local data are not available.

4.7.2.3. Variable stocking strategies

There are other gaps in our knowledge that relate to the use of variable stocking rate strategies. It remains unclear whether variable stocking strategies offer benefits over set stocking strategies in particular regions, and whether the increased ecological and financial risk of variable strategies might outweigh any benefits. Key research needs in this area include:

- Modelling of variable versus set stocking rate strategies (modelling the climate-land type- land condition- production interactions under different strategies and associated trade-offs).
- The development of better pasture and soil based indicators to guide stocking rate decisions (for use with both set stocking and variable stocking systems), and the relationship of these indicators to thresholds in rangeland condition.
- The development of better decision tools to alert producers to changing conditions and the need for rapid destocking (based on rainfall, pasture growth, seasonal forecasts).

4.7.2.4. Perennial grass population dynamics and grazing management

There is a need for modelling of palatable perennial grass population dynamics (e.g. using David Orr's data) under various climate, grazing and utilisation scenarios. This will provide a better understanding of the long-term effects of grazing strategies on perennial grass populations and provide insights into the way in which grazing affects population processes in these grasses as a basis for developing grazing practices that encourage their long-term persistence. Population level studies have advantages over the usual coarse plant community-level assessments of grazing effects since they address the processes of population change and can detect incipient changes in population processes that may have long-term consequences for plant populations.

4.8. Conclusions

Land type, land condition, and length of the growing season appear to be the key determinants of safe stocking rates.

Although not all reviewed studies demonstrated the negative effects of higher stocking rates on land condition and livestock production over the longer term, there is reasonably good evidence that continued use of high stocking rates above the long term carrying capacity will result in declines in land condition and livestock production (Figure 4.6). Most grazing studies in northern Australia appear to have been on the increasing part of the production curve.

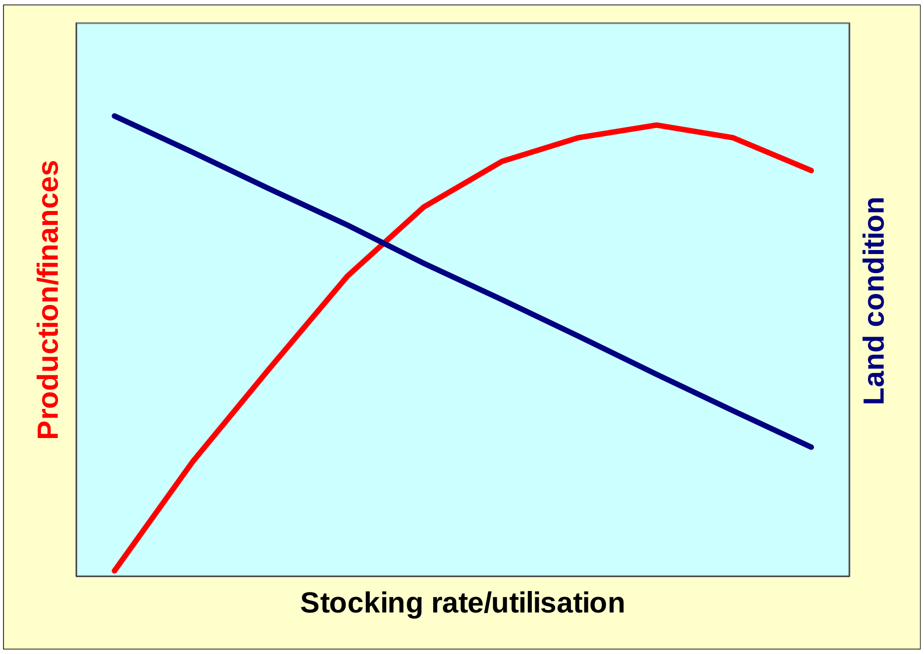

Figure 4.6. Generalised relationship between stocking rate and livestock production/financial returns (red line), and stocking rate and land condition (blue line). Note that the land condition line is hypothetical and the relationship between stocking rate and land condition is not necessarily linear but could take a number of forms.

The effects of stocking rates are greatest in average to poor years. Most studies showed little effect of stocking rate on production or land condition in above-average seasons. Thus, there is some opportunity for stocking rates to be increased in good years to take advantage of more abundant forage. However, rapid reduction in stocking rates is needed as forage availability and seasonal conditions deteriorate. Heavy grazing in association with drought presents a high risk of a transition of the land to a state of poor condition and lower productivity.

Over the medium to long term, the use of constant stocking at around the long-term carrying capacity of the paddock helps to maintain land in good condition, and may well be the most profitable and least risky stocking strategy. For some regions, markets and freight costs limit the capacity for adopting a highly flexible stocking rate strategy.

For strongly seasonal areas, adjustments (or at least reassessment) of stocking rates are needed more than once a year. At the least, an assessment is needed at the beginning of the dry and beginning or early wet season. Reduced grazing pressure in autumn may also facilitate seed production by 3P grasses. Both set and variable stocking strategies require on-going assessment of progress using critical indicators to account for spatial patterns of grazing and poor years.

5. Pasture resting

Pasture resting (or spelling) occurs when animals are removed from the pasture for a period of time and there is no grazing. This period of non-grazing usually lasts less than one year. This is different to the use of the term in USA where rest is non-use for 12 consecutive months rather than just part of the growing season, and the term deferment is used for a period of non-grazing during part of the growing season (Howery *et al.* 2000).

Resting has been suggested or recommended by many authors e.g. at the State and Transition workshop in Gympie in 1993, models were developed for seven pasture types in northern Australia; six of these models mention strategic or seasonal resting.

There are two broad reasons for pasture resting – to maintain or improve land condition and to accumulate biomass (for various purposes). Land in good condition (no erosion, little bare ground, dominated by 3P grasses, few weeds) will grow more pasture than land in poor condition (severe erosion, bare ground, few perennial grasses, many weeds). Studies at a number of sites in northern Australia showed production from poor condition land may be only 10-20% of that from the same land type in good condition (Figure 5.1) (McIvor *et al.* 1995a). The 3P grasses are the major components of these pastures and are the main targets of spelling since they are reduced by heavy grazing. As well as being the major source of animal forage and organic material inputs to the soil, 3P grasses provide both the semipermanent architecture necessary to trap and retain litter, sediment and nutrients and also the deep infiltration pathways necessary to improve sub-soil moisture.

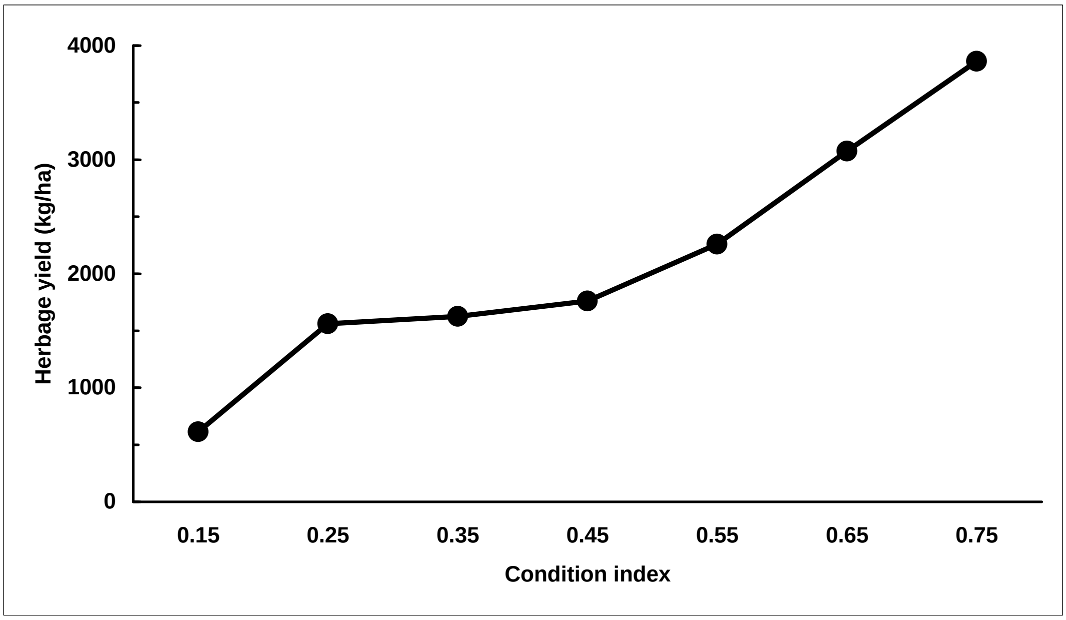

Figure 5.1. Herbage yield in relation to a land condition index in northern Australia (mean values over 10 sites). The condition index was based on soil and vegetation characteristics. Approximate index values for condition classes are: A (>0.7), B (0.4-0.7), C (0.1-0.4) and D (<0.1). (From McIvor *et al.* 1995a)

In this chapter, the experimental evidence for impacts of pasture resting are presented and used to develop principles and guidelines for its use. Applications of pasture resting to widespread grazing management issues are discussed in Chapter 7.

5.1. Experimental results

Evidence concerning the impacts of pasture resting come from two broad sources – trials that have explicitly studied the effects of resting on pasture performance, and exclosure studies that were established for other reasons but provide useful information about the effects of absence of grazing.

5.1.1. Northern Australia – studies of pasture resting

A number of trials have examined pasture resting. These are listed in Table 5.1 and their locations are shown in Figure 5.2.

Table 5.1. Trials and locations of studies of pasture resting.

Trial	Location(s)	Reference(s)
1. Ecograze	Charters Towers (Hillgrove/Eumara Springs, Cardigan, Lakeview/ Allen Hills)	Ash *et al.* (2001, 2010)
2. Virginia Park	Charters Towers	Post *et al.* (2006); Corfield and Nelson (2008); Bartley *et al*. (2007, 2009)
3. Wambiana	Charters Towers	O’Reagain *et al.* (2007, 2009)
4. Brian Pastures (small plots)	Gayndah	Paton and Rickert (1989); Orr *et al.* (1991); Orr and Paton (1997)
5. SWAMP	Monto, Mundubbera, Proston, Esk	Paton (2004)
6. Pigeon Hole	Victoria River District	Unpublished data
7. Kimberley	East Kimberley	Hacker and Tunbridge (1991)
8. Queensland – multi site	Injune, Theodore, Charters Towers, Rockhampton, Nebo and Charleville	Orr *et a*l. (2006)
9. Mareeba	Mareeba	Cooksley (2003)
10. Ecobeef	Kidston, Einasleigh, Georgetown	Shaw *et al.* (2009)
11. Narayen	Mundubbera	Tothill *et al.* (2009)

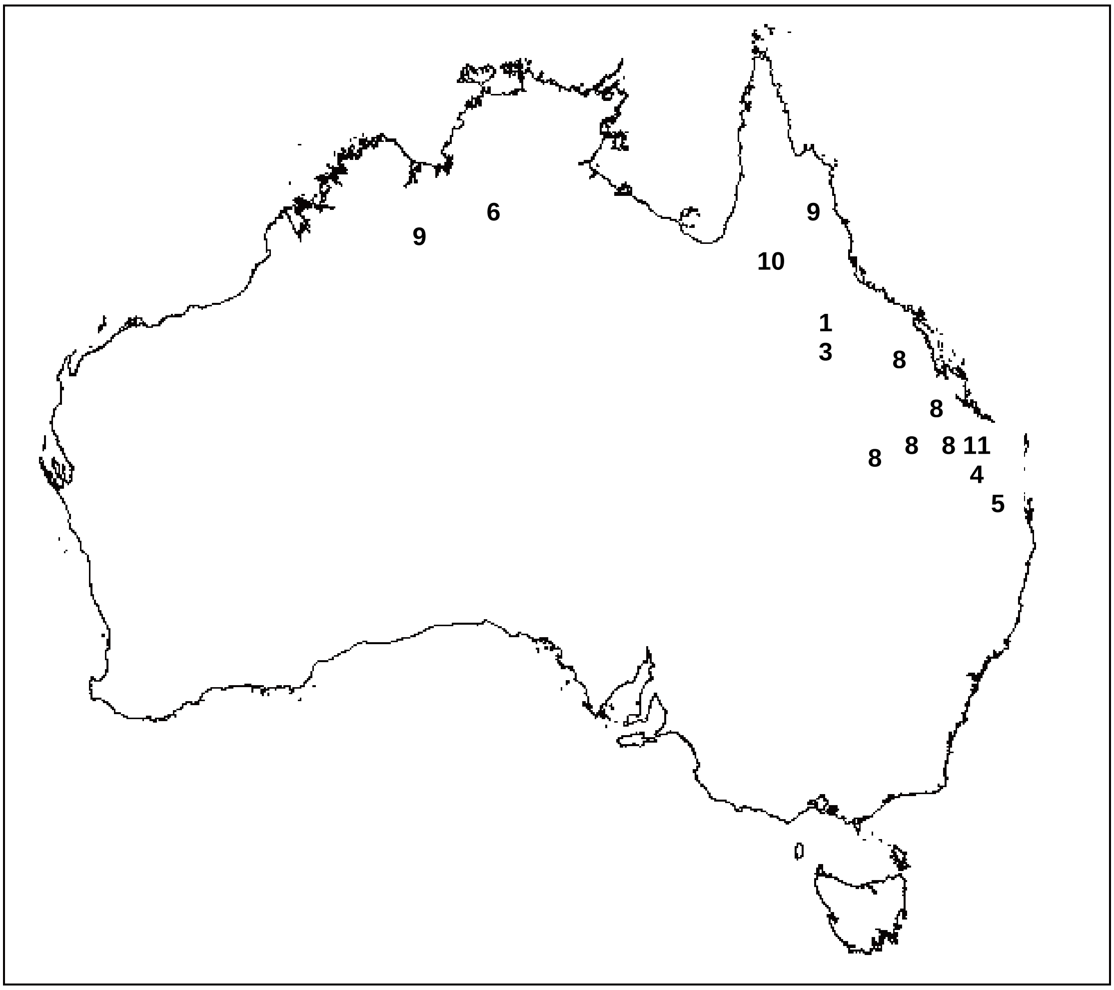

Figure 5.2. Locations of sites where pasture resting has been studied (see Table 5.1 for names of studies and sites).

5.1.1.1. Ecograze

The Ecograze project (Ash *et al.* 2001, 2010) examined rates of annual pasture utilisation (nominally 25, 50 and 75%) and early wet season resting (every year for eight weeks after the first significant rainfall event [>50 mm over two days from November onwards]) at three sites near Charters Towers. The sites were on a fertile red basalt soil, a moderately fertile red duplex soil, and an infertile yellow earth. At each site there was an area in good land condition (State I or A/B) and another area in poorer (State II or B/C) condition. Growing conditions were variable with severe drought for the first four years followed by an average year and then three high-rainfall years. Pastures could be maintained in good condition by either light utilisation (25%) or moderate utilisation (50%) combined with wet season rest; high utilisation (75%) led to pasture degradation. Pastures in poor initial condition recovered with both light utilisation and moderate utilisation combined with wet season rest but remained in poor condition with high utilisation. This is illustrated by the yields of 3P grasses during the experiment in Figure 5.3 and during the final year in Figure 5.4.

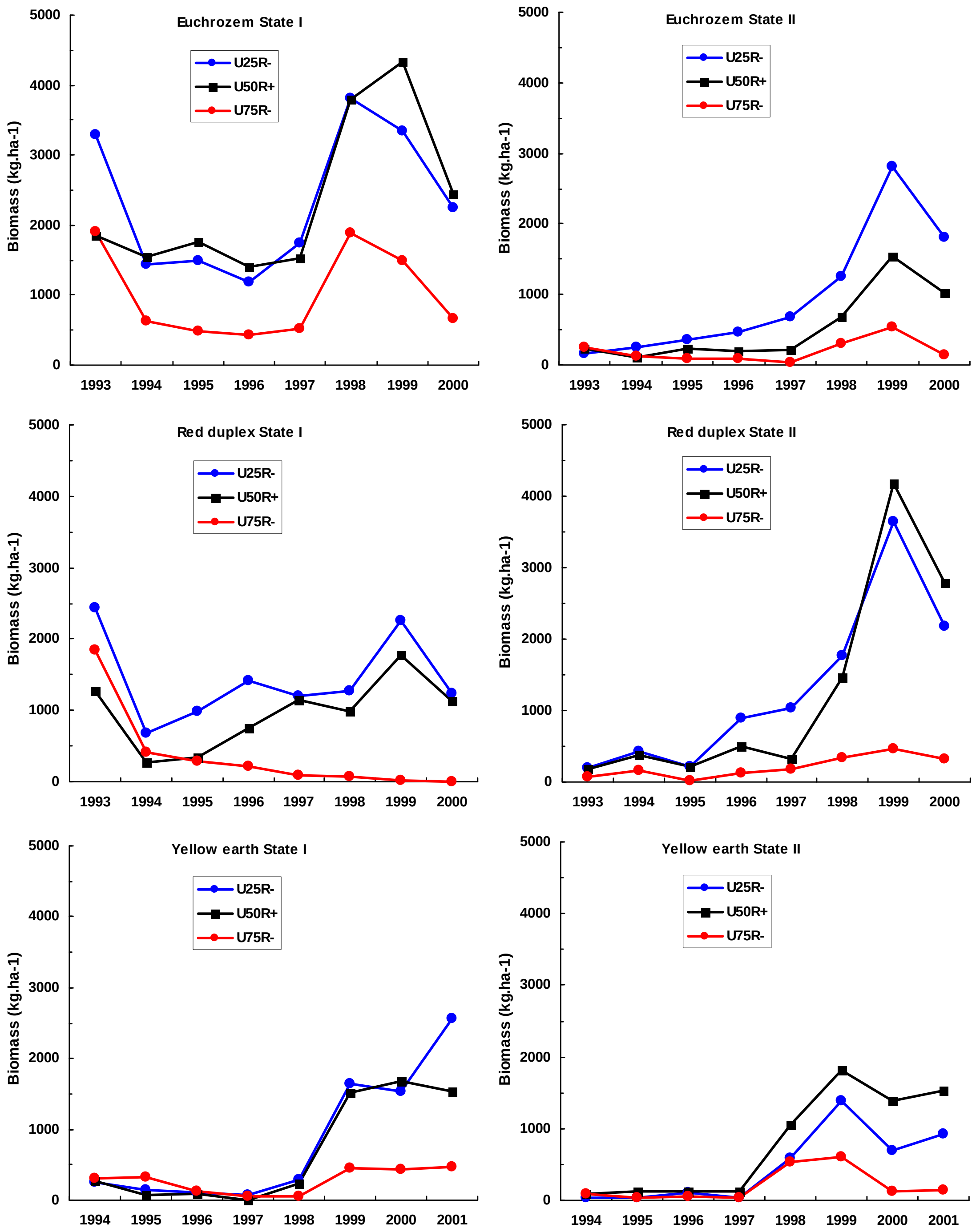

Figure 5.3. The effect of utilisation rate and wet season resting on yield of 3P grasses during the Ecograze project. U25R- = 25% utilisation, no rest; U50R+ = 50% utilisation, rest; U75R- = 75% utilisation, no rest.

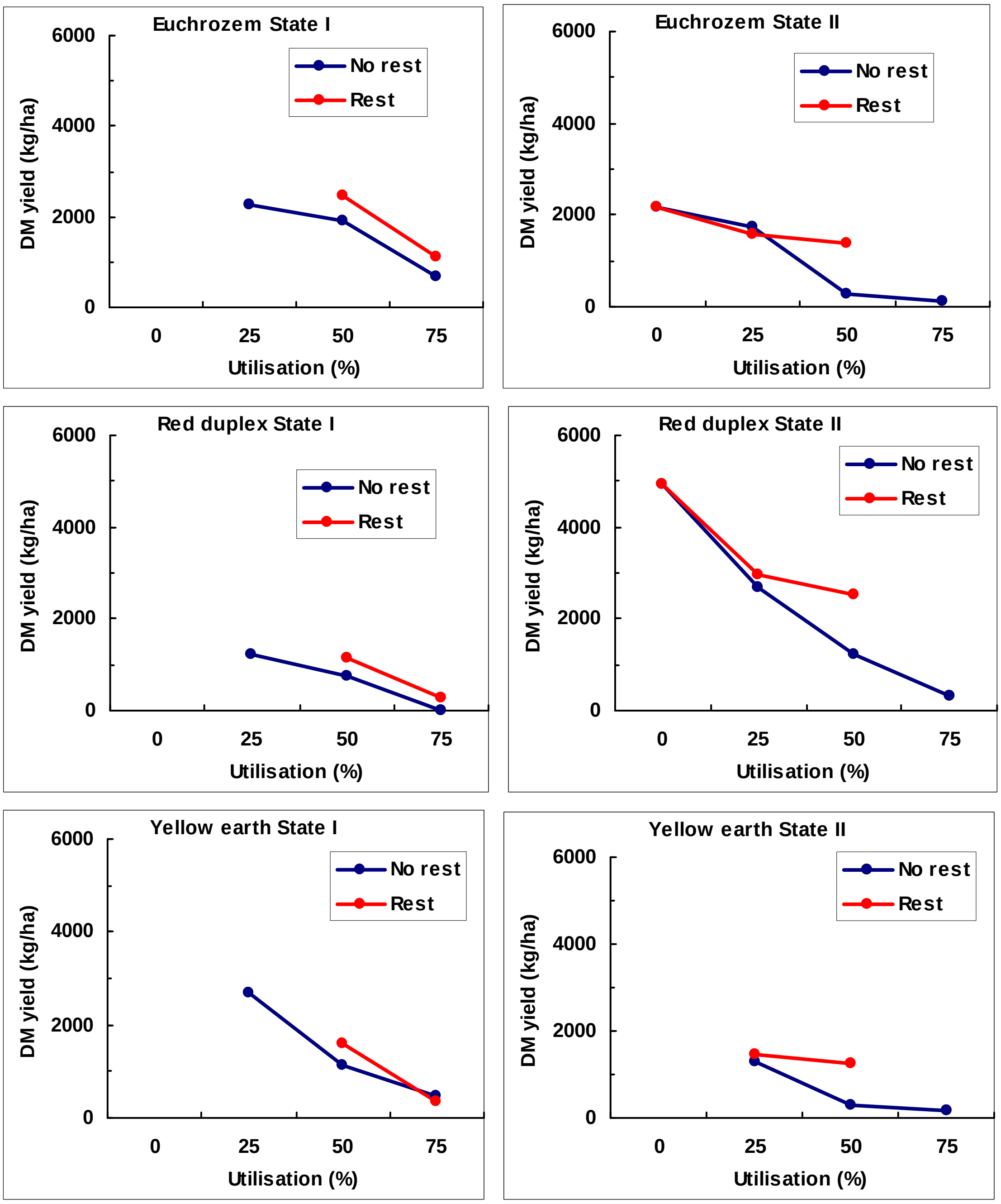

Figure 5.4. The effect of utilisation rate and wet season resting on yield of 3P grasses in the final year of the Ecograze project.

The results in Figure 5.4 for the 25% utilisation plots in State II show little or no benefit for resting. This may be a reflection of the small plot sizes and it is likely that in large, commercial paddocks that resting will be beneficial by preventing the selective grazing of small, highly preferred patches.

5.1.1.2. Virginia Park

Commercial scale studies at Virginia Park near Charters Towers followed on from the Ecograze project and aimed to recover C condition paddocks using practical spelling strategies. The studies examined how wet season resting and moderate utilisation rates affected pastures (forage production, ground cover) and runoff of water, sediments and nutrients (Post *et al.* 2006; Corfield and Nelson 2008; Bartley *et al*. 2007, 2009). The early years of the trial were very dry but rainfall was higher and above average during the final two years.

There was no grazed control to compare the experimental paddocks with but there were substantial improvements in pasture condition (total yields, 3P grass yields, ground cover) over the six years of the trial (Table 5.2 and Figure 5.5).

Table 5.2. Changes in pasture biomass and ground cover in managed paddocks at Virginia Park. The values are the means of three hillside flume areas in one paddock (Bottom Aires). (From Bartley *et al*. 2009)

Year	Pasture biomass (kg/ha)	Ground cover (%)
2002	350	63
2003	60	39
2004	180	42
2005	500	54
2006	790	73
2007	1030	74

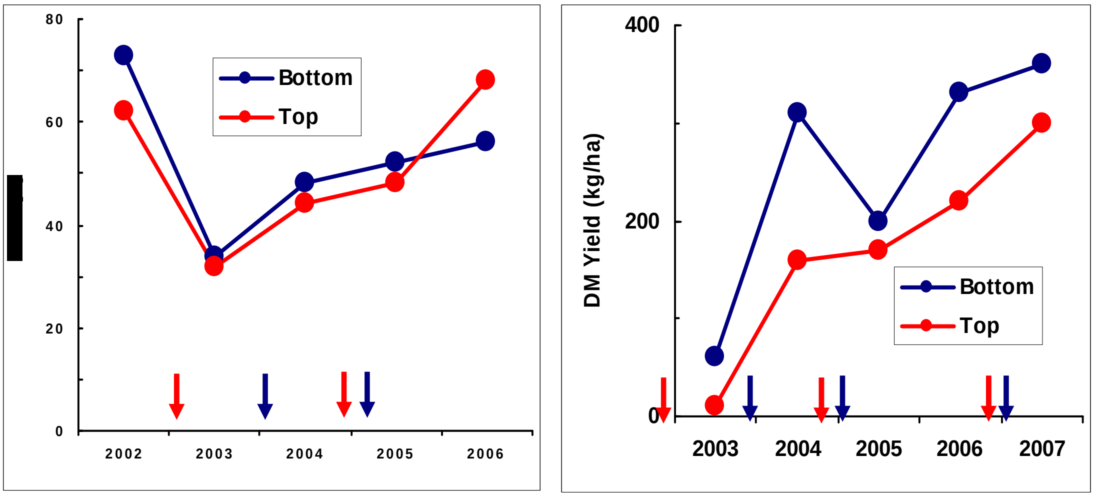

Figure 5.5. Changes in ground cover (end of dry season) and yield of 3P grasses (end of wet season) in Bottom and Top Aires paddocks at Virginia Park. Arrows indicate the timing of wet season rests in the two paddocks. (From Post *et al.* 2006 and Bartley *et al.* 2007)

There were different resting regimes between the paddocks with biennial rests in Top Aires (2002-03 and 2004-05) and consecutive wet season rests in Bottom Aires (2003-04 and 2004-05). Post *et al.* (2006) concluded that there was some evidence from the Bottom Aires results that consecutive wet season spells may help consolidate recovery although they stressed more extensive and longer term data were required to confirm the observation.

Recovery was spatially and temporally patchy due to the interaction of land condition, land type, topography and grazing preference operating at the grazed patch scale. Patches with a high proportion of bare ground have the highest risk of continuing to degrade and those with some 3P grasses have the highest chance of improvement (Post *et al.* 2006).

5.1.1.3. Wambiana

At Wambiana, O'Reagain *et al.* (2007, 2009) tested the impacts rotational wet season resting at an intermediate level of utilisation (1.5 times long term carrying capacity) on production and land condition. The pastures were initially in B condition. Paddocks were divided into three sections with a different section rested annually for the full wet season (November-June). During the dry season animals grazed the whole paddock. The rest period meant that the stocking rate in the two sections grazed during the wet season was 50% higher than if the whole paddock was grazed at this time, and these paddocks were effectively a "heavy grazing" treatment during this time. Resting was combined with fire before resting in 2000 and 2001. Recovery from the 2001 fire was very poor due to low rainfall and the burnt sections had to be rested for three consecutive wet seasons so the remaining sections had three years of heavy wet-season grazing. This heavy grazing combined with the below average rainfall adversely affected pasture cover and condition and a reduction in overall stocking rate was needed for this treatment. This led to a subsequent improvement in pasture condition. Despite these problems the rotational wet season resting strategy had a satisfactory economic performance.

5.1.1.4. Small plot studies of *Heteropogon contortus* and *Aristida* spp. at Brian Pastures

Paton and Rickert (1989) used cages to rest areas that had been burnt in February 1982 from October 1982 for 19 months. In May 1984 (after rest for two growing seasons) pasture yields were trebled and the proportion of spear grass (*Heteropogon contortus*) and forest blue grass (*Bothriochloa bladhii*) increased from 22 to 72% and that of wire grasses (*Aristida* spp.) decreased from 32 to 8% in the rested areas compared to grazed areas outside the cages.

In another study Orr *et al.* (1991) found that annual burning for four years plus no grazing during this period gave a major increase in spear grass from 20% to 70% and a reduction in wire grasses from 70% to 16%. One burn and four years rest gave no major changes in composition.

Orr and Paton (1997) examined the effects on pasture composition for 5 years of annual spring burning followed by rest for 0, 2, 4 or 6 months or grazing at half the stocking rate used on the other grazed plots. The yield of spear grass was higher with 4 and 6 months rest or half stocking rate (approximately 2000 kg/ha) than with 0 or 2 months rest (<1000 kg/ha), and the proportion of spear grass increased from about one quarter of the herbage with 0 or 2 months rest to more than half with 4 and 6 months rest or half stocking rate. In the final year, the basal area of spear grass was higher in plots with a 6 months rest or half stocking rate than in those with no rest, but the total basal area and basal area of wire grasses and forest blue grass were not affected by treatment.

5.1.1.5. SWAMP (Spear grass, Wire grass, Animal Management Project)

The SWAMP project (Paton 2004) examined the effects of burning and reduced stocking rates on commercial pastures in south-east Queensland. Results were variable between the four properties but demonstrated that reduced stocking rates and burning could improve pasture composition (and profitability) but recovery was slow for

C condition land (although the results were confounded in terms of spelling by differences in treatments and also variation in initial pasture composition).

5.1.1.6. Pigeon Hole

A wet season spelling system (WSS) was included in an unreplicated comparison of grazing systems (set stocking, set utilisation, cell grazing) at Pigeon Hole. The spelling system consisted of three paddocks (each 5 km^2) with a single herd rotated through the paddocks so that one paddock was rested during the early wet season, another during the late wet season, and all three paddocks were grazed during the dry season. The spelling periods were rotated between paddocks so that over a three year period each paddock had an early wet season and a late wet season rest. Cattle were removed from the early wet season spell paddock before rain or just after the first minor falls of rain. The end of the early wet season spell and the start of the late wet season spell were based on pasture growth in the spelled paddocks. The early wet season spells commenced between September 25 and December 10 and lasted for 89-140 days, and the late wet season spells commenced between February 3 and March 24 and lasted for 36-69 days. The study aimed for a utilisation rate of 25% and the average achieved was 22%.

The pastures were initially in C condition. There were no definitive trends in land condition that could be attributed to the grazing systems. Cover was lowest (<40%) in the WSS in the first year (2003) and greatest in the WSS in the final year (approximately 70%) but this was confounded by fire – almost all the WSS area and lesser proportions of the other systems were burnt in November 2002 and there were variable amounts of fire in all systems in subsequent years. Grass basal area was lowest in the WSS in the first year and subsequent trends were similar for all systems. There were no significant differences in mean annual measures of diet quality (crude protein, proportion of non-grass species, and *in vitro* digestibility) between systems.

WSS had slightly better animal production than other systems. Mean annual liveweight gain was highest for WSS (142 kg compared to 130 kg for set stocking) and the liveweight gain was higher during the dry season than the wet season whereas in the other systems it was lower in the dry season. Weight changes of breeders were variable with lowest gains in the WSS during the wet season but no weight loss during the dry season by the breeders in the WSS in contrast to losses in both the set stocked and set utilisation systems. Only two years of reproductive data were analysed due to incomplete data sets in other years. WSS had a high branding percentage (76%) but the lowest weaning percentage (65% compared to 68-72% in the other systems).

WSS had the greatest earning before interest and tax of the systems but the smaller paddocks required additional capital for fencing and WSS gave a lower return on capital (6.8%) than the set stocking (8.1%) and set utilisation systems (8.7%).

Overall, rainfall effects were greater than grazing effects on pasture performance. Interpretation of the results is complicated by variable amounts of wildfire in the different systems, initial differences between paddocks (proportion of different soil types, basal area), and issues with controlling cattle distribution – the gate was opened at end of spell period but cattle were not moved to the new paddock and they often continued grazing in the other paddocks increasing the grazing pressure in those paddocks.

5.1.1.7. Kimberley

Hacker and Tunbridge (1991) used temporary exclosures to compare wet season (December 1 to March 31) and dry season (August 1 to November 30) rest over four years in a regenerating pasture at the Ord Regeneration Research Station. The exclosures were in unreplicated paddocks continuously grazed at six different stocking rates that aimed to utilise 20-70% of the end of wet season forage in a poor year by the end of the dry season. Vegetation change was measured in areas initially dominated by Birdwood and buffel grasses (*Cenchrus* spp.) or by bottle washer grass (*Enneapogon polyphyllus*) and wire grass (*Aristida contorta*). Seasonal conditions were generally poor. Interpretation of the results is difficult due to some inconsistencies in the responses, incomplete sampling, and the need to destock some paddocks but overall there were similar patterns for the different resting treatments and resting was much less important than stocking rate in determining vegetation change.

5.1.1.8. Queensland – multi-site trial

Unreplicated exclosures were established at six sites in Queensland with pastures in good (Theodore), fair (Injune, Rockhampton, Nebo) or poor condition (Charters Towers, Charleville) to examine rest for (notionally) 0, 3, 6 or 12 months (Orr *et al*. 2006). The exclosures were established in autumn 2003 following widespread extreme drought in 2002 and recovery was followed for a year. Rainfall was generally low and there was little recovery of the pastures particularly where the pastures were in poor initial condition. Changes in basal area were small at all sites except Rockhampton where basal area of the desirable grasses doubled (from 3.8 to 7.6%) in the 12 month exclosure plot during a period of above average summer rainfall; on the grazed plot basal area only increased to 4.1%. This did not occur in the other treatments which were not exclosed at that time. The increase was due to an increase in plant size rather than seedling establishment. The authors concluded “Pasture condition will not improve following drought simply by excluding livestock for short periods, especially during winter, and particularly when rainfall is only average or below.”

5.1.1.9. Mareeba

Cooksley (2003) included wet season resting (from the start of the wet season until spear grass commenced flowering, a period of 9-12 weeks) in a trial near Mareeba. Although the spelling treatments were confounded with experimental burning treatments, and the results were influenced by oversown stylo and wild fire, 3P grass yields were higher in the rested plots than the continuously grazed plots by the end of the trial.

5.1.1.10. Ecobeef

Wet season resting was studied in commercial paddocks on three properties in north Queensland (near Kidston, Einasleigh and Georgetown) in the Ecobeef project (Shaw *et al.* 2009). The Georgetown site has been spelled for three wet seasons and the other two sites for one wet season only (2008/09). Growing conditions have been favourable during the trial and land condition has improved in all cases.

5.1.1.11 Narayen

A trial on Siratro (*Macroptilium atropurpureum*)-buffel grass (*Cenchrus ciliaris*) pastures at Narayen (Tothill *et al.* 2009) compared continuous grazing with 2-paddock rotation systems where Paddock A was rested until early January while Paddock B was grazed at double the stocking rate; from early January Paddock B was rested and Paddock A was stocked at double the stocking rate. Rest periods (and periods of double grazing) were either 2 or 3 months long. The rest periods were designed to test their role in tick control rather than pasture performance. The “early” rest periods commenced in early October or early November thus most of this rest period was before the main growing season (late December to late March). The “late” rest period (early January to early March or early April) was during the growing season. Utilisation levels over the five-year trial period were estimated to be 45% (continuous), 51% (early rest) and 39% (late rest).

The grazing systems had no effect on the frequency of buffel grass (more than 90% in all paddocks in all years), but Siratro was more frequent with “late” rest (from early January onwards) in all years and in the final year Siratro frequency was 59% in the late rest treatment compared to 25% (continuous) and 34% (early rest). Pasture production was highest in the late rest paddocks, with the continuous paddocks intermediate, and the early rest paddocks the least productive. Liveweight gain per head was 23% higher in the continuous than the rested treatments due to differences during the summer (when the paddocks were double stocked); gains were similar in autumn-winter. The authors concluded that resting could improve Siratro performance and yields but at the expense of reduced animal performance.

5.1.2. Northern Australia – exclosure studies

In addition to trials looking specifically at pasture resting, there are a number of other trials that used exclosures to prevent grazing that provide useful and relevant information even though they did not explicitly study resting. These are listed in Table 5.3 and their locations are shown in Figure 5.6.

Many of these studies did not have grazed sites for comparison (Table 5.6), and in trials where there was a grazed comparison, the actual grazing was not controlled and in most cases was not described. Care is needed in interpreting the results for their relevance to pasture resting as no difference between the exclosure and the grazed area could merely reflect a low stocking rate in the grazed area and hence little difference in grazing pressure from the exclosure. Alternatively a “response” could be due to very heavy pressure having a deleterious impact rather than resting having a positive impact.

Table 5.3. Pasture exclosure studies in northern Australia.

Trial	Location(s)	Reference(s)
1. Regeneration study (Hillgrove)	Charters Towers	McIvor (2001)
2. Exclosures (Kerale)	Collinsville	McIvor and Gardener (1990)
3. Recovery study (Galloway Plains)	Calliope	Bray, Fraser and Stone (unpublished data)
4. Mitchell grass exclosures (Toorak)	Julia Creek	Orr and Phelps (in preparation)
5. Mitchell grass exclosures (Blackall)	Blackall	Orr (1980); Orr and Evenson (1991)

6. Multi-site (South-west Queensland)	South-west Queensland	Silcock and Beale (1986)
7. Exclosures (Kidman Springs)	Victoria River District	Foran *et al.* (1985)
8. Erosion study (Charters Towers)	Charters Towers	Scanlan *et al*. (1996b)
9. Mulga lands	Cunnamulla	Cowley (2001)
10. *Aristida-Bothriochloa* project	Injune, Rubyvale	Silcock *et al.* (2005)

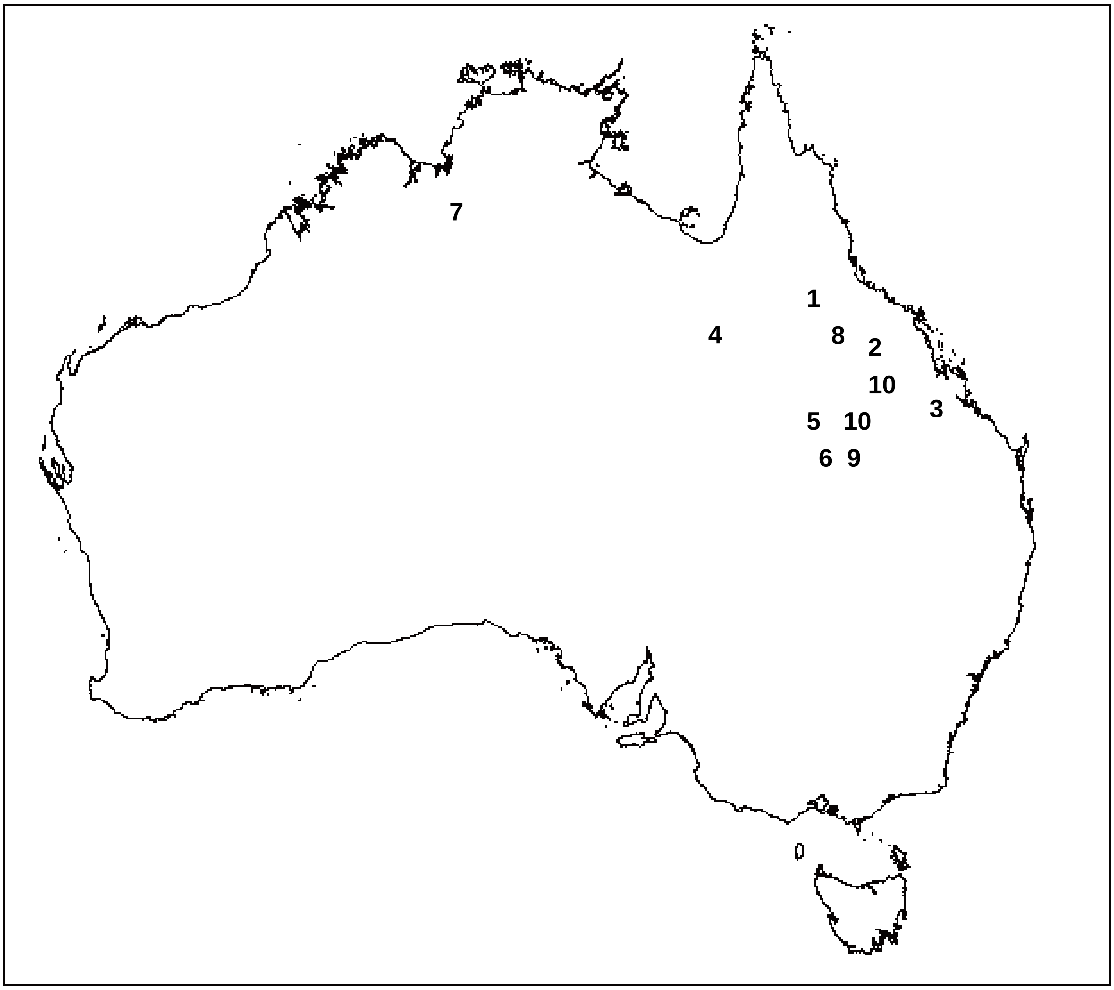

Figure 5.6. Locations of pasture exclosure sites (see Table 5.3 for names of studies and sites).

5.1.2.1. Regeneration study (Hillgrove)

McIvor (2001) studied the recovery of 24 plots of native pasture with different initial land condition at Hillgrove over three years of grazing exclusion. The plots had been exposed to a range of different grazing pressures prior to exclosure. Growing conditions were poor in the two years prior to exclosure (annual rainfalls [July-June] of 472 and 355 mm) but much better during the three years of exclosure (annual rainfalls [July-June] of 686, 625 and 834 mm compared to a long-term mean of 546 mm). The plots were rated as A, B, C or D condition on the basis of the proportion and basal area of perennial grasses, and total ground cover. In the published results, site condition was described by an index (values between 0 and 1.0) calculated from herbage yields and botanical composition of the plots during each of the three years of exclosure. These values were used as a guide to allocating each plot an ABCD condition rating during each year of exclosure. Of the 10 plots in A condition when they were exclosed, all but one were in A condition after one years rest and the other plot was in A condition after two years rest. For the 8 plots initially in B condition, 4 recovered to A condition after one year and the other four after two years rest. For the 2 plots initially in C condition, one plot recovered to A condition after two years, and the other plot after three years rest. All 4 plots initially in D condition remained in D condition. Thus under the conditions of this trial on a fertile soil with good growing conditions, we can conclude that B condition land needed one to two years rest, and C condition land needed two to three years rest, to recover to A condition.

5.1.2.2. Exclosures (Kerale)

McIvor and Gardener (1990) studied the recovery of 20 plots of native pasture with different initial land condition at Kerale near Collinsville during a year of exclusion of grazing. The plots were rated as A, B, C or D condition on the basis of the proportion and basal area of perennial grasses. Both of the plots initially in A condition remained in A condition. All of the 3 plots initially in B condition recovered to A condition after one year. For the 9 plots initially in C condition, 3 plots recovered to B condition, and the other 6 plots remained in C condition. All 6 plots initially in D condition remained in D condition. Thus under the conditions of this trial with good growing conditions, we can conclude that B condition land needed one years rest, and C condition land needed more than one years rest to recover to A condition.

5.1.2.3. Recovery study (Galloway Plains)

Bray, Fraser and Stone (unpublished data) studied the productivity of native pasture plots at Galloway Plains that had been grazed at 5, 4, 3, or 2 ha/animals for 14 years (1988 to 2001) plus an additional degraded area in one paddock that had been heavily grazed. Measurements were made after one, three and four years of exclosure. Initial land condition of the plots varied with their recent stocking rate history, being lower in plots from heavier-stocked paddocks. Rainfall was below average for the 2001/2002 growing season but higher in subsequent years, particularly 2002/2003 and 2003/2004.

Changes in land condition after 1, 2 and 4 years exclosure in relation to initial land condition are shown in Table 5.4. Changes in relative pasture production and proportion of 3P grasses are shown in Figure 5.7. There was little change during the first year of exclosure. Over the experimental period, the two plots initially in A condition remained in A condition. The four plots initially in B condition remained in B condition after two years, but after four years three of these plots were in A condition; the other remained in B condition. Of the five plots initially in C condition, four were in B condition after two years exclosure while the other plot remained in C condition; after four years exclosure one plot was in A condition, two were in B condition and two were in C condition. The herbage production of the previously heavily grazed plots increased over the exclosure period but did not reach that of the previously lightly grazed plots even after 4 years exclosure. There was only a small increase in the proportion of 3P grasses during exclosure and the values for the heavily graze plots remained below those for the lightly grazed plots.

Table 5.4. Changes in land condition (A, B, C, D) during exclosure at Galloway Plains. The plots were in different initial condition following grazing at different stocking rates for 14 years. From Bray, Fraser and Stone (unpublished data).

Previous treatment (ha/an)	Replicate	Land condition			
		Initial	2002	2003	2005
5	E	B	B	B	A
	W	A	A	A	A
4	E	B	B	B	A
	W	A	A	A	A
3	E	C	C	B	A
	W	B	B	B	A
2	E	C	C	B	B
	W	C	C	B	C
2 + burn	E	C	C	B	B
	W	B	B	B	B
Degraded	E	C	C	C	C

5.1.2.4. Mitchell grassland exclosures

Exclosures were established in 1994, 1995 or 1996 in the 80% utilisation plot of a long-term utilisation rate trial at Toorak (Orr and Phelps 2003). The utilisation treatments had commenced in 1984 and by 1993 the density and basal area of Mitchell grass was substantially reduced by the 80% utilisation rate compared to the lighter utilisation treatments. The exclosures remained in place until 2000 and results from them were compared with those from grazed plots with 50% and 80% utilisation. In 1997 the basal area fell in the grazed treatments but remained the same or increased slightly in the three exclosure treatments. During 1998-2000 basal area increased rapidly in all treatments and by 2000 basal area was similar in all treatments. These results show the importance of above average growing conditions for pasture response (Orr and Phelps, in preparation).

The growth of Mitchell grass in an exclosure and a paired grazed site was followed from 1975 to 1986 at Blackall. The first year was a good growing season and individual tussocks increased in size (Orr 1980). During subsequent years, basal area and yield of Mitchell grass varied widely between years in response to summer rainfall with few differences between the exclosure and grazing treatments. Survival of seedlings depended on adequate summer rainfall and grazing tended to enhance cohort survival (Orr and Evenson 1991).

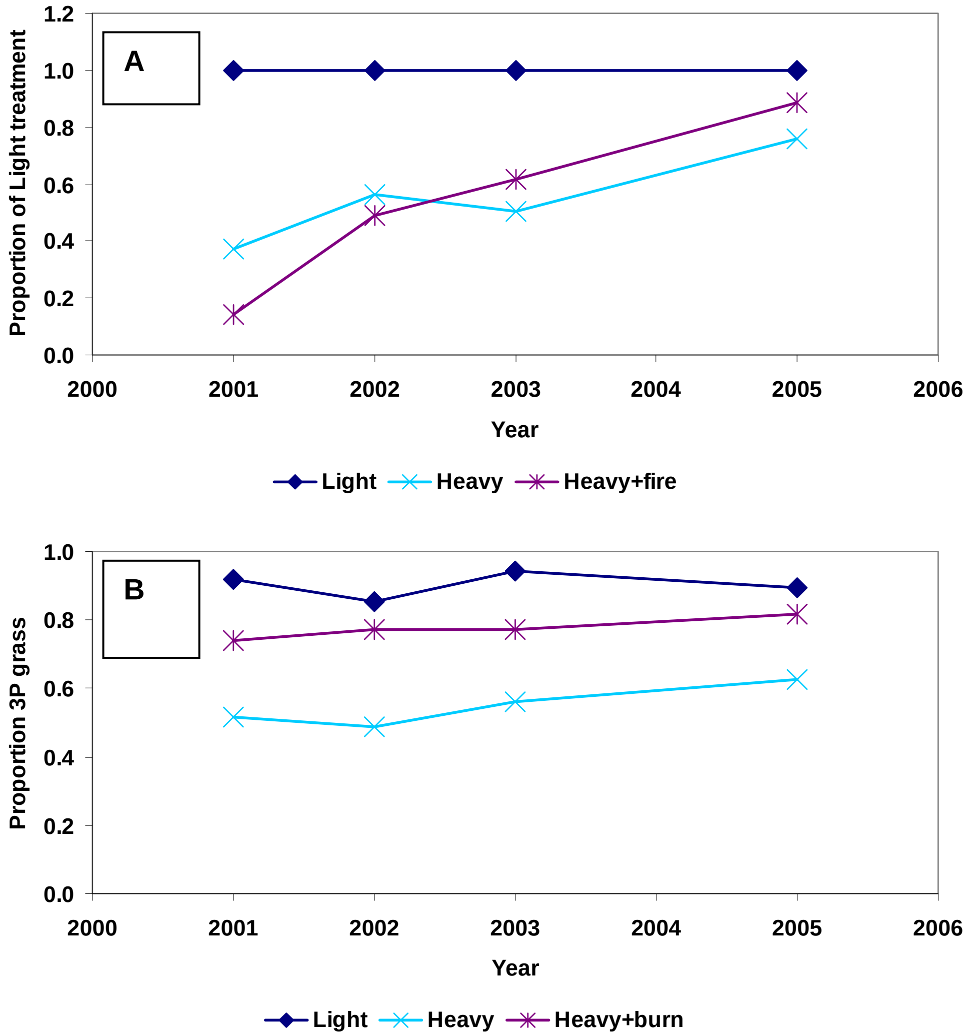

Figure 5.7. Recovery of annual pasture production (A) and proportion of 3P grasses (B) in previously heavily stocked paddocks (2ha/animal; C/B land condition) compared to a lightly stocked treatment (5.3ha/animal; A land condition) following continuous resting (exclosure) and burning to remove old pasture after the 2001 measurement. The experiment was conducted at the Galloway Plains grazing trial. The exclosures were burnt to remove the previous years pasture growth in late 2001, 2002 and 2004 (Bray pers. com.).

5.1.2.5. Multi-site study in South-west Queensland

Unreplicated exclosures were established on degraded country on 17 properties in south west Queensland in 1960s and pasture performance followed for approximately 20 years (Silcock and Beale 1986). Recovery was variable and they concluded “Expect slow recovery in arid lands and very dependent on rare good seasons.”

5.1.2.6. Exclosures (Kidman Springs)

Exclosures were established at two sites on calcareous soils in July 1973 and the pastures monitored until 1979 to compare their performance with grazed areas outside the exclosures (Foran *et al.* 1985). One site was in good condition and the other eroded site was virtually bare and in poor condition (C/D). Grazing kept the poor condition land in poor condition. The exclosed plots were initially dominated by annual grasses, but limestone grasses (*Enneapogon* spp.) then increased, followed in later years by perennial grasses, blue grasses (*Dichanthium* spp.) and spear grass. After five years exclosure (but not previously), there were similar amounts of the desirable limestone grasses and total biomass in the two exclosures despite a cattle break-in to the poor condition exclosure causing short-term heavy grazing. The density of herbage plants was also similar although the plants were smaller at the poor condition site so basal area remained lower. Recovery depended on the density of limestone grass plants and growing conditions. With a good wet season (such as occurred in 1976 and 1977) recovery of limestone grass could take as little as one year. However, the perennial grasses continued to increase for a longer period as monitoring of the exclosures up to 2002 has shown (Bastin *et al.* 2003).

5.1.2.7. Erosion study (Charters Towers)

Exclosures were installed at six sites in 1985 and followed for six years with drought during the early years and above average rainfall during the later years (Scanlan *et al*. 1996b). Two sites were initially dominated by Indian couch grass (*Bothriochloa pertusa*) (82% Indian couch, 17% perennial grasses); two sites were dominated by perennial tussock grasses (2% Indian couch, 96% perennial grasses); and two sites were a mix of the two components (47% Indian couch and 50% perennial grasses). At these mixed sites Indian couch increased steadily under grazing; in the exclosures there was little change in the amount of Indian couch during the initial dry years but a rapid increase with good seasons so that the amounts of Indian couch were similar in both treatments after 6 years (80%). Basal area declined at all sites under grazing in dry years but increased during good growing seasons. In the exclosures, the basal area decline was less or basal area increased during the dry years but after the period of good growing conditions basal area levels were similar inside and outside the exclosures. In summary, exclosure raised basal area and initially slowed the increase in Indian couch but there was little difference between the grazed and exclosed areas after six years.

5.1.2.8. Mulga lands

Cowley (2001) installed exclosures at three distances from a new water trough and followed changes for over two years. The land was in good initial condition with a high frequency of mulga grass (*Thyridolepsis mitchelliana*) and bandicoot grass (*Monachather paradoxa*). Compared to the grazed areas, in the exclosures there was a large increase in shrub density, an improvement in soil surface condition and erosion features, but no difference in basal area or plant density.

5.1.2.9 Aristida-Bothriochloa Project

Ungrazed exclosures (1 ha in area) were included at both sites (Glentulloch near Injune and Keilambete near Rubyvale) of the *Aristida-Bothriochloa* project (Silcock *et al.* 2005). The exclosures were located in one block at Glentulloch but interspersed with the grazed plots at Keilambete. Differences in location, replication and initial condition limit the inferences that can be drawn, but comparisons of the results from the grazed plots and the burnt and unburnt plots in the exclosures in the first three years provide some information on possible responses to pasture resting.

At Keilambete, ground cover levels in the lightly grazed (25% utilisation) plots were similar to those in the burnt, but lower than those in the unburnt plots, in the exclosures. There are no data for basal area in the exclosures in Years 1 and 3 but in Year 2, basal area was lower in the unburnt plots than the burnt plots or the grazed plots which had similar levels. There were no data for the proportion of 3P grasses in the exclosures in Years 2 and 3.

At Glentulloch, cover levels were higher in the lightly grazed plots than in the exclosures (both unburnt and burnt) in Year 1 but in Year 2 they were higher in the exclosures (both unburnt and burnt). In Year 3 they were again higher in the grazed plots. Basal area levels varied between treatments in Year 1 but in Years 2 and 3 they were higher in the grazed plots than the exclosures. No data were presented on proportions of 3P grasses during the early years of exclosure.

5.1.3. Other studies

5.1.3.1. South Africa

Kirkman (2002a, b) compared resting for the whole growing season or for the late growing season (both treatments every second year) with continuous grazing by sheep or cattle over four years. Animal species had marked effects – palatable species increased with cattle grazing but decreased with sheep grazing; unpalatable species showed little change with cattle but increased with sheep. The effects of resting were smaller than those of animal species but still important – when averaged over animal species, the palatable species increased with a whole season rest, increased slightly with late season rest, and declined with continuous grazing (Kirkman 2002a). Growth during the following growing season was used to measure the impact of resting or grazing for a growing season on the vigour of a mixed pasture. Overall, the grazed plots produced only 47% of the dry matter produced on the rested plots with large differences between the impacts on different species – on the grazed plots, palatable [e.g. kangaroo grass (*Themeda triandra*)], intermediate [e.g. African love grass (*Eragrostis curvula*) and spear grass]) and unpalatable species [e.g. wire grasses *Aristida* spp.)] produced 38, 6 and 96% of the yield they produced on the rested plots (Kirkman 2002b).

5.1.3.2. Mt Riddock

A trial on buffel grass dominated pastures at Mt Riddock (200 km north-east of Alice Springs) compared an 8 paddock rotation with a continuously grazed paddock (Kain and Cowley 2008). After two years it was difficult to assess impacts due to the short time period and differences between grazing systems (stocking rates and distance to water). It will take some years for the impacts on the pastures but early results suggest that rotational grazing has the potential to improve evenness of use.

5.1.3.3. Gilruth Plains

A grazing trial conducted on Mitchell grass pastures near Cunnamulla with sheep provides some evidence on effects of rest (Roe and Allan 1945, 1993). The trial compared continuous grazing with a rotational system at three stocking rates. The rotation system involved two paddocks where one paddock was grazed for six months during summer and not grazed during winter, and the other paddock was grazed during winter and not during summer. The stocking rates were the same over the year but were twice as high during the grazing period in the rotation paddocks. The paddocks grazed only during winter can be considered to represent six months rest during summer followed by grazing at twice the stocking rate of the continuously grazed pastures. The trial ran for 12 years consisting of two five year grazing periods with an intervening two year period where the pastures were unstocked. The pastures were not grazed in the year after the trial was completed and during that year the forage on offer in the paddocks grazed during winter was approximately 90% of that in the paddocks that had been continuously grazed and the proportion of Mitchell grass was slightly higher in the winter-grazed pastures. For each stocking rate the number of grazing days per hectare over the year was the same for the continuously grazed and summer rested pastures. Any increase in the stocking rate during the winter grazing would likely have some deleterious impacts. (For the summer- grazed winter-rested pastures forage on offer was 60% of that in the continuous paddocks and the proportion of Mitchell grass was 20% lower.)

5.1.3.4. Mt Sanford

Ridley and Schatz (2006) reported a short term trial comparing continuous grazing with a system of no grazing (rest) for 1 year every 3 years with half the ungrazed area burnt during each non-grazed period (each area burnt 1 year in 6). The same overall stocking rate was used for both systems but this meant the stocking rate on the remaining two-thirds of the resting system that was grazed at any one time was 50% higher. The trial did not run long enough to assess effects on pasture composition or woody plant numbers. The plots needed to be destocked for periods during the first two years due to water supply problems and flooding, but liveweight gain data were collected in the final two years. Over these two years the annual liveweight gains on the continuously grazed plots were 9 kg higher than those on the plots with periods of no grazing. The authors ascribed this difference to the impacts of the higher stocking rates on the grazed areas in the resting system.

5.1.3.5. Belmont

A trial at Belmont (Orr 2010) in central Queensland compared continuous grazing for the whole year with grazing only during winter (April-September) on a pasture sown to shrubby stylo (*Stylosanthes scabra* cv. Seca) and sown grasses [green panic (*Panicum maximum* var. *trichoglume*), buffel grass (*Pennisetum ciliaris* cv. Biloela and Rhodes grass (*Chloris gayana* cv. Callide). The winter grazing can be considered a summer rest treatment. The frequency of buffel grass increased, and the frequencies of the increaser species, Indian couch grass (*Bothriochloa pertusa*) and snake weed (*Stachytarpheta jamaicensis*), decreased with winter grazing compared with yearlong grazing. Orr (2010) considered the continuous grazing created gaps in the pasture with were colonised by the increaser species, and predicted that five to eight years of average or good rainfall would be needed to have large changes in composition.

5.1.3.6. Upper Burdekin

Hassall (1976) described a system used on basalt country with predominantly kangaroo grass pastures in the Upper Burdekin. Half of a paddock was burnt in alternate years. The animals preferentially grazed the burnt half in the early growing season and grew rapidly on the young green pasture. The rest of the pasture was ungrazed and grew to maturity ready for burning at the end of the year. By April the grazed area was 12-14 cm tall and animals were removed to another paddock which had also been similarly burned and grazed there for three months before returning to the original paddock for the remainder of the year when the paddock was again burned and cycle repeated.

5.2. Analysis

The experimental results described in the preceding section and producer experience show pasture resting can play a major role in determining land condition.

Principle 3. Rest pastures to maintain them in good condition or to restore them from poor condition to improve pasture productivity

Three factors determine the effectiveness of pasture resting

- Season (timing)
- Duration
- Number of rest periods (or frequency)

In the following sections, the relevant experimental evidence is summarised and recommendations on these factors are presented. While many of these recommendations are not based directly on experimental evidence, they are conclusions drawn by experienced pasture workers and contain their considered wisdom.

5.2.1. Season of rest

A number of studies have shown that pastures are more sensitive to defoliation during the early growing season than at other times of the year (see Section 2.5 for details). Briefly:

- For plots at Katherine defoliated in December and January the regrowth in the following year was less than 60% of that from plants clipped later in the growing season (Mott 1987).
- When plots were cut to 1 cm above ground level at various times during the growing season the impact was greatest (estimate approximately 60% reduction) when the cut was in the early growing season and declined with later cuts (Tainton *et al.* 1977)
- In the year after different rates of utilisation were applied in either the early wet, late wet or dry season, pastures at Katherine with medium and high utilisation in the early wet season had only 80% and 60% of the yields of those treatments that were grazed at low levels of utilisation. Grazing during the dry season had no impacts and the effects of grazing in the late growing season were intermediate (Ash and McIvor 1998).
- After two years grazing in the early wet season (December-February) pastures produced only 290 kg/ha of perennial grass compared to 3100 kg/ha for pastures that had not been grazed during the wet season but then grazed during the dry season for the same number of grazing days (Norman 1965).

In addition to these defoliation effects, 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.

5.2.1.1. Experimental results on season of rest

- The Ecograze results (see Figures 5.3 and 5.4) show that plots with 50% utilisation and rest during the early growing season were generally superior (higher yields and proportions of 3P grasses) to those with 50% utilisation without rest, and similar to those with 25% utilisation and no rest. With 50% utilisation and rest, pastures in good condition remained in good condition, and pastures in poor initial condition recovered. High utilisation (75%) led to pasture degradation on plots in good initial condition, and no recovery on plots in poor initial condition.
- A number of trials in south-east Queensland (Section 5.1.1.4) showed improvements in pasture composition (increases in spear grass and decreases in wire grasses) and basal area of spear grass with rest (and

burning) (Paton and Rickert 1989; Orr *et al.* 1991; Orr and Paton 1997; Paton 2004) but this is not a universal result (Orr 2004; Silcock *et al*. 2005).

- In the multi-site trial by Orr *et al.* (2006) (Section 5.1.1.8), the only substantial improvement occurred with rest during the growing season - basal area doubled (3.8 to 7.6%) at Rockhampton with good growing conditions during the growing season compared to small increase (3.8 to 4.1%) on grazed plots. There was little or no improvement with rest at other times.
- Commercial scale demonstrations have shown improvements in pasture condition with time under wet season rest and moderate utilisation at Virginia Park (see Figure 5.5) and in the Ecobeef project (see Section 5.1.1.10). However, in both these comparisons the improvements are confounded with seasonal conditions as the comparisons lack a grazed control.
- A comparison of wet season versus dry season spelling in the Kimberley (Section 5.1.1.7) found little difference between spelling regimes (Hacker and Tunbridge 1991).

5.2.1.2. Recommendations on season of rest

- Excluding stock will be most effective during summer when plants are actively growing (Tainton 1999) - resting in summer can improve pasture composition by increasing both the number and size of desirable species by promoting seed production and seedling development and promoting tillering.
- To improve plant vigour, pastures need <u>spring</u> rest to accumulate leaf and increase photosynthesis so sufficient carbohydrate is available to replace reserves used initiating growth, <u>summer</u> rest primarily for seed production but also to promote vigour and productivity, and <u>autumn</u> rest for storage of carbohydrate and root growth (Tainton 1981).
- The timing of rest depends on the purpose (for seeding, seedling establishment, plant vigour, or to accumulate herbage) but whatever the purpose, rests are needed during growing seasons; resting during dry seasons does little good (Pratt and Gwynne 1977). Rest periods are especially important immediately after burning or close grazing in order that the plant can manufacture needed reserve substrates.
- Since vegetation can consist of many components which have different responses to grazing and resting during different seasons of the year (Bosch and Tainton 1988), rests are needed in different seasons for each paddock.
- Pratt and Gwynne (1977) recommended rest periods so grass (in particular the more palatable species) could grow undisturbed encouraging root growth and building up reserves of carbohydrates and nitrogen; therefore, to be effective the rest period must include at least part of the wet season.
- From their evaluation of the empirical basis for grazing management recommendations in southern Africa, O'Reagain and Turner (1992) concluded that, although there was only sparse experimental evidence on benefits of rest, periodic resting for all or part of the growing season is considered essential to maintain land condition.
- Dry season spelling is generally regarded as having no beneficial impact upon land condition or animal production. However, anecdotal evidence from graziers indicates that while wet season spelling is far more beneficial, dry season spelling does have some positive impact upon pasture condition (O'Reagain *et al.* 2007).
- Silcock *et al.* (2005) – if forced to graze heavily for a while, then rest during the next wet summer which will quickly restore perennial grass vigour.
- Silcock *et al.* (2005) - perennial grass pastures are best encouraged by wet season spelling; only need 6-8 weeks any time November-March but must coincide with good rains.

- Silcock *et al.* (2005) recommended strategic spelling during the growing season on a regular rotating basis.
- Phelps *et al.* (2007) studying the death of Mitchell grass found a site with wet season spelling was in better condition than a continuously grazed paired site. Although the mechanisms promoting Mitchell grass survival are unclear, they suggest wet season spelling (coupled with high short term grazing pressure in the dry season) can alleviate the effects of drought.

5.2.1.3. Rest during the non-growing season

Although resting during the growing season is generally favoured, resting during the non-growing or dry season may have some benefits:

- there will be greater ground cover during the late dry season and better protection of the soil surface
- resting will prevent repeated grazing of regrowing shoots if there are small falls of rain sufficient to initiate some growth but not enough to signal the start of the growing season
- resting can prevent the removal of aerial buds that are common in some species (e.g. buffel grass, desert blue grass [*Bothriochloa ewartiana*]) resulting in more growing points being available for regrowth at the start of the following growing season.

5.2.1.4. Conclusions on season of rest

To improve the vigour and/or composition of a pasture, resting will be most effective during the growing season and particularly during the early growing season when grasses are most susceptible to heavy defoliation. Dry season rest, by comparison, is not likely to assist pasture recovery. This does not infer that dry season grazing pressure does not need to be managed to retain sufficient groundcover or for fuel management. However, to promote improvements in condition, growing season rest should be the focus.

These conclusions are drawn from both experimental results, and observations and opinions. There is only one northern Australian study comparing season of rest (Hacker and Tunbridge 1991) and there is a need for additional studies of the effect of time of year on response to spelling.

Guideline 3.1. Rest pastures during the growing season. As a rule of thumb commence the rest period after 38-50 mm of rain or sufficient to initiate pasture growth at the beginning of the growing season. If it is difficult to access country after rain then resting should commence before the wet season starts.

5.2.2. Duration of rest

5.2.2.1. Experimental evidence of duration of rest periods

- In the Ecograze project (Section 5.1.1.1.), rest for 8 weeks in the early growing season each year maintained pastures in good condition and improved pastures in poor condition (Ash *et al.* 2001, 2010).
- Orr and Paton (1997) (Section 5.1.1.4) rested plots at Brian Pastures for 0, 2, 4 or 6 months after a spring burn for 5 years. The yield of spear grass was higher with 4 and 6 months spell than with 0 or 2 months. In the final year, the basal

area of spear grass was higher in plots with a 6 months spell compared to those with no spell, but the total basal area and basal areas of wire grasses and forest blue grass were the same.

5.2.2.2. Recommendations on duration of rest periods

Although Tainton (1981) considered it is not possible to prescribe generally the period of absence of grazing required there have been many suggestions. These have been based on both periods of time and also plant characteristics that have to be achieved.

Recommendations vary from a few weeks to the whole year. Long rest periods increase the persistence of species sensitive to grazing (Norton 1998). The time needed for a grass to restore root growth and reserves depends on the plant growth rate – thus the faster the plant growth rate the shorter period of time that will be necessary: short rest periods when growth is rapid, long rest periods when growth is slow.

It should be noted that many of these recommendations refer to the periods of absence of grazing in rotational grazing systems rather than to situations where pastures were rested for a specific purpose.

- Although period of rest was not tested experimentally at Virginia Park (Section 5.1.1.2), the authors concluded whole of wet season rest (rather than just an early spell for 6-8 weeks) appears to be required to recover C condition paddocks in years of below-average rainfall (Post *et al.* 2006). The large paddocks at Virginia Park contained a variety of land types including riparian and sensitive areas, and whole of wet season rest was needed to avoid regrazing of preferred patches (Post *et al.* 2006; Corfield and Nelson 2008).
- Dankwerts and Aucamp (1985) recommended 12-13 weeks based on leaf dynamics (as part of rotational grazing systems).
- Lauder and Price (2008) recommend 4-6 weeks rest after plant growing rain.
- A rest period of 4 to 9 weeks, depending on the situation, is, for practical purposes, sufficiently close to ideal management from a consideration the growth and physiology of grass, patterns of utilisation, and animal performance (as part of rotational grazing systems) (Gammon 1984).
- O'Reagain *et al.* (2007) recommended spelling paddocks after fire for a full wet season, although in very good seasons shorter periods of spelling (6 - 8 weeks) may be sufficient to allow recovery.
- Mitchell grass seedlings are sensitive to defoliation - even when there was no defoliation for the first 6 weeks, seedlings were severely affected and needed a whole wet season to get well established (David Phelps).
- Dankwerts (1991) recommended resting for a full year since erratic rainfall may prevent shorter rests from achieving their objectives. Long rests increase the probability of rains during the rest period.
- To recover after severe grazing, Savory and Butterfield (1999) suggest a period between grazing in rotational systems of approximately 4 weeks for tussock grasses with good growing conditions but 9 to 17 weeks or even a year or more when growth rates are slow.
- Tainton (1981) – as part of rotational grazing systems, decisions need to consider both the growth rate (shorter periods with higher growth rates) and the rate at which grass loses its quality and acceptability (shorter periods where losses are rapid). In intensive irrigated pastures during peak growth periods, 2 weeks may be adequate. Periods of absence between 5 to 6 weeks may be recommended for sourveld during peak growth period in summer – with longer periods in

autumn and spring when growth is slower. In sweetveld where forage quality decline is slow, the rest period may be as long as 10 weeks.

A number of plant characteristics have been suggested to determine how long a rest period should be and/or when grazing can re-commence.

- Grazing can commence when regrowth reaches one fourth to one third of the plant's mature size. At this stage plants are in Phase 2, enough energy is captured through photosynthesis to support growth and to begin replenishing the roots (Pratt 1993).
- The rest period should be long enough for plants to complete the stage of rapid regrowth and physiological recovery (Gammon (1984).
- Rest for the period of time it takes to accumulate the maximum numbers of green leaves per tiller. For kangaroo grass and *Sporobolus fimbriatus* growing under unstressed conditions there were 4-6 leaves per tiller and leaves appeared at 2-3 week intervals so resting for 12-13 weeks would be suitable (Dankwerts and Aucamp 1985).
- Range readiness is an American concept that may be relevant although it has received little attention in the subtropical and tropical regions. Range readiness refers to range being ready for grazing at the start of the grazing season and is that point in the plant growth cycle at which grazing may begin without permanent damage to vegetation and soil. Guidelines include (Heady 1975):
    - When certain showy spring flowers are fading
    - When growth of key perennial grasses has reached a stipulated height or number of leaves
    - When a standard proportion of full growth has been made by the leaves and twigs of browse species
    - A certain amount of standing herbage (x kg/ha) has accumulated and/or a specified daily growth rate has been achieved
- Height of an important grass e.g. SWAMP groups used height of spear grass (10 or 15 cm for two different groups) to determine when to end the rest period and to start grazing (Paton 2004).
- From the start of the growing season until black spear grass began flowering (Cooksley 2003).
- Rest until most of the Mitchell grass has set seed or March 1. This balances what is good for plant with feed available for animals – longer periods would be better for plants but there would be no grazing until herbage is dry and mature (David Phelps, pers. comm.).

5.2.2.3 Conclusions on duration of rest

The duration of the rest period is a balance between benefit to the pasture (greater with longer rests but with declining marginal benefit as the period increases) and loss of grazing during the rest period combined with the lower quality of the herbage accumulated over the rest period.

Resting for the whole wet season is suggested as a starting point. This has the following advantages:

- Long period so likely to get some good growing conditions
- Rest during the early growing season when grasses particularly susceptible to grazing, and also later when setting seed and accumulating reserves
- Allow new seedlings to establish, grow and set seed, and existing plants to expand

- Includes a range of flowering times
- Allow increase in the plant's root reserves (mostly in the late wet season)
- Cattle do not need to be moved during the wet season

It would be advantageous to have well established plant criteria for different plant communities that could be used to determine the effectiveness of resting.

Guideline 3.2. 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.

5.2.3. Number of rest periods

The required frequency of resting or number of rest periods to achieve a certain goal will be determined by both initial land condition (resting alone is insufficient to restore D condition land) and growing conditions experienced during the rest period (pasture maintenance and recovery are boosted by good growing conditions and the duration and number of rest periods need to be higher under poor growing conditions).

Increasing the number of rest periods can be expected to give a greater pasture response but represents a trade-off as grazing is foregone during the rest period.

5.2.3.1. Evidence relating to number of rest periods

There are no experiments in northern Australia dealing explicitly with comparisons of the frequency of rest periods but a number of other trials provide useful information.

- McIvor (2001): under good growing conditions at Hillgrove B condition land took 1-2 years and C condition land took 2-3 years to recover to A condition (Section 5.1.2.1)
- At Kerale near Collinsville: under good growing conditions B condition land took 1 year to recover to A condition but C condition land needed more than one year recover to A condition (Section 5.1.2.2)
- Galloway Plains: After two years with no grazing the four plots originally in B condition remained in B condition; after four years three of these were in A condition but one remained in B condition. There were five plots originally in C condition. After two years four of these were in B condition and one remained in C condition; after four years one was in A condition, two were in B condition and two were in C condition. The two plots originally in A condition remained in a condition over the four years. (Section 5.1.2.3)
- From the Wambiana trial, O'Reagain *et al.* (2007) concluded that in dry years the response of pasture condition to wet season resting is often minimal, and areas being rested for pasture recovery may therefore need repeated resting, particularly if rainfall is below average. (Section 5.1.1.3)
- Pasture condition will not improve following drought simply by excluding stock for short periods, especially during winter, and particularly when rainfall is only average or below (Orr *et al.* 2006). Orr *et al.* (2006) further suggested that from their results, above long-term mean rainfall in at least two months during summer may be required to achieve large-scale increases in yield and perennial grass basal area. (Section 5.1.1.8)
- Studies in Mitchell grasslands at Toorak and Blackall have shown the importance of summer growing conditions for the growth of Mitchell grass and

the relatively small effects of exclosure (Orr 1980; Orr and Evenson 1991; Orr and Phelps, in preparation). There is some conflict with results for Mitchell grass. Mitchell grass seedlings are particularly sensitive to defoliation (Phelps, personal communication) suggesting rest would be beneficial to them, but Orr and Evenson (1991) found grazing tended to enhance cohort survival.

- Ecograze: growing conditions were poor in the first three years and there was little or no response (Figure 5.8 for first year results) but there was a response in later years. However it took three to six years before there were substantial differences in the yields of 3P grasses in the different resting regimes (Figure 5.9).

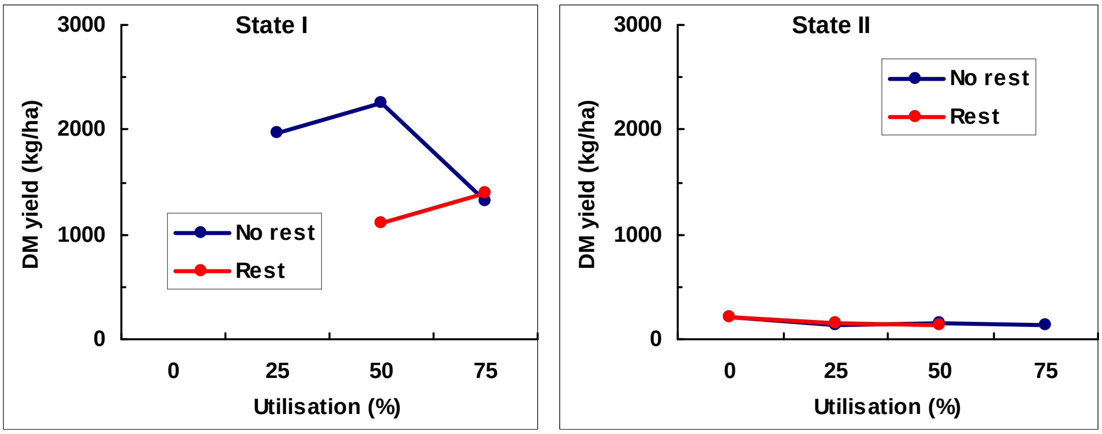

Figure 5.8. The influence of one years rest on the yield of 3P grasses in the Ecograze plots (means of three sites).

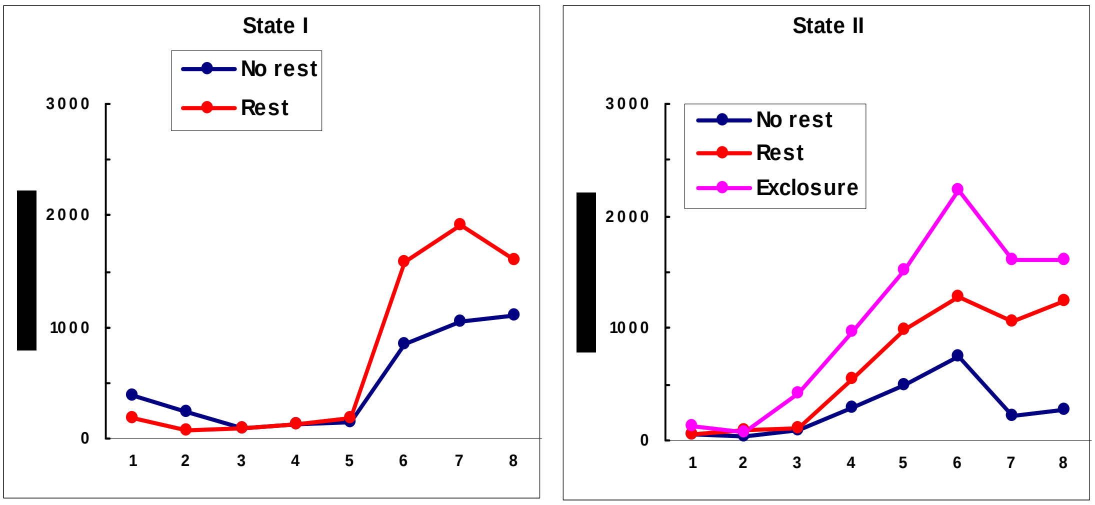

Figure 5.9. Changes in the yield of 3P grasses in the Ecograze plots (means of three sites) for plots grazed at 50% utilisation.

5.2.3.2. Recommendations on number of rest periods

- General recommendations from South Africa are that one years rest in four may be sufficient for range in good condition (Pratt and Gwynne 1977; Tainton 1981) although more frequent rests may be needed where land has been mismanaged (Tainton 1981).
- Land in C condition needs consecutive years rest to recover under drought conditions whereas biennial rest is sufficient for B condition land (Jeff Corfield, personal communication).

- Managing recovery brochure: "To recover land in poor (C) condition requires the removal of all grazing animals over the full length of the wet season. Full wet season rest for two successive years is necessary to speed up the recovery process."
- While steady recovery may be achieved with biennial wet season resting, consecutive wet season spells in the early years will accelerate this response especially during drier periods when the 3P grasses appear to have a competitive advantage over the more drought sensitive Indian couch (Post *et al*. 2006).
- David Phelps – may need two years rest in a row to improve land in C condition.
- Drought-weakened perennial pastures in the Maranoa region need two consecutive good summers to fully rejuvenate (Silcock and Hall 1996).
- Managing recovery brochure: Recovery of poor condition, Indian couch dominated country is likely to be slower and patchier than equivalent paddocks with a higher occurrence or scattering of 3P tussock grasses. 3P tussock grass patches provide the architecture necessary to trap and accumulate resources such as litter, where Indian couch pastures have a tendency to collapse during drought conditions. It is important to allow build-up and connectivity between recovering patches to slow the flow of water, capture and retain sediment and nutrients, and reduce landscape leakiness.
- Silcock *et al*. (2005): Short term spelling of pasture in fair condition during a good season can result in a very rapid return to good pasture condition. If grass crown area has slipped to very low levels, two consecutive wet season rests are required – the first to set seed and establish new seedlings and second to grow these seedlings into robust crowns. To retain a pasture in A condition, after drought destock the most stressed paddocks for the next growing season.
- D condition land exists in two states – patches where the soil is still satisfactory and which will recover eventually with rest, and scalded areas which may continue to get worse even if the paddock is rested (Jeff Corfield; personal communication)

5.2.3.3. Conclusions on number of rest periods

Although there is limited experimental evidence, there is general agreement that as land condition declines pasture rests need to be more frequent if land condition is to be improved.

Drawing on evidence that mainly comes from exclosure studies rather than trials concerned with pasture resting, we can tentatively conclude that resting for one or two growing seasons can move land from B to A condition provided growing conditions are good. Recovery of C condition land will take longer and will likely need two to four years of rest; for planning purposes four years is suggested. Combining these we have a principle that pastures need two growing season rests to improve by one ABCD condition class under good growing conditions. Where growing conditions are poor, more rest periods will be required. In more arid areas (e.g. Mitchell grasslands) recovery is dominated by growing conditions and there may be little response to rest.

From the published data it is not possible to quantify the impacts, and due to different techniques and approaches it may not be possible to reach any further conclusions from published results. All the exclosure studies had rest every year and no grazing. It is dangerous to extend these results to frequency of rest periods as the intervening grazing may have significant effects e.g. Kirkman (2002a) in South Africa showed grazing treatment during the period between rests had a marked effect on pasture composition.

Resting alone is insufficient for restoring land in D condition.

Guideline 3.3. 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.

5.2.4. Pasture and soil recovery

Improvement in land condition involves both pasture and soil recovery. Soil recovery may taker longer than pasture recovery. Studies at Virginia Park (Corfield and Nelson 2008; Bartley *et al*. 2009) showed that after eight years of wet season rest and low utilisation, land condition was better (ground cover increased from approximately 35% to approximately 75%, biomass levels from 60 to 1000 kg/ha, and yields of 3P grasses were higher), but infiltration had not fully recovered. Hillslope runoff did decline over the study period for early wet season events up to approximately 200 mm of rainfall, but after this point the amount of runoff was no longer strongly related to the amount of cover on the hillslope. Hence there was no reduction in hillslope runoff at the annual time scale with the improved cover. This was attributed to limited soil hydrological capacity, and suggests that soil condition recovered at a slower rate than ground cover. Sediment yields declined by approximately 70% on two of the three hillslopes in the study. However, where bare patches (<10% cover) were connected to gullies and streams, sediment yields increased. Extrapolation of the hillslope results to the catchment scale showed that hillslope sediment yields did not decline between 2003 and 2007. This was due to the disproportionately high yields from scald sites particularly in high runoff years. In 2007, when there was above average rainfall, 83% of the hillslope derived fine sediment came from less than 5% of the catchment.

Managing recovery: Landscapes do not recover evenly across paddocks. Recovery in C condition landscapes will be patchy, with some areas of a paddock responding quickly in terms of increased cover, pasture yield, 3P species composition and ability to trap water and nutrients. However, other areas may remain static or continue to degrade for some time. Full wet season rest for two years in a row, combined with conservative dry season grazing, is the best way to speed up the recovery process, especially in the early years. Benefit will be seen from opportunistic wet season spelling but, in recovering landscapes, the growth of new 3P grass seedlings and formation of new patches from the initial spell will be delayed and therefore recovery will be slower.

Recovering paddocks also remain relatively vulnerable to the impacts of renewed grazing pressure due to the reduction in, and disjunct distribution of, 3P grass basal cover, root, organic matter and nutrient reserves, all of which take much longer than ground cover to re-build (Northup *et al*. 1999, 2003).

In the *Aristida-Bothriochloa* project (Silcock *et al*. 2005), when cattle were removed from the ironbark site near Rubyvale, cover increased to >90% within two years and runoff was reduced to negligible amounts. However, at the poplar box site it took 3 years exclusion to cause a major reduction in runoff. This suggests short term rest (3-6 months) is unlikely to produce measurable improvement in infiltration and soil loss. Removal of grazing for 7 years had no effect on organic matter levels in surface soil at the poplar box site near Injune. Roth (2004) showed degraded pastures can fully recover their hydrological function within 15-20 years although visual impacts of sheep grazing on soils at Wycanna were still evident 16 years after removal of sheep (Braunack and Walker 1985).

5.2.5. Pasture resting: factors influencing success

5.2.5.1. General issues

- The benefits of spelling a paddock depend on the balance between the improvements made in the spelled paddock and the costs incurred from having the cattle elsewhere – these could be financial (e.g. agistment), or reduced production per animal as stocking rate is raised somewhere else on the property, or pasture damage in this more heavily stocked area. From the results of a modelling analysis, MacLeod *et al.* (2009) concluded that resting could be economically attractive but very dependent on the assumptions of changes in condition and their impacts on animal production. Resting will involve some planning to get a workable rotation e.g. sufficient paddocks or agistment if there is insufficient feed. If seasons are favourable and animals can be retained on the property then profits are much higher, but the grazing could further exacerbate degradation. Reduced frequency of resting may reduce the economic sacrifice but would be traded off against a longer period of recovery.

- The benefit of rest is likely to increase as the difference in overall utilisation rates on grazed and rested pastures increases. Where this difference is small, resting may not always be effective. Hacker and Tunbridge (1991) ascribed the failure of wet season rest to improve pastures in a Kimberley trial to the generally low utilisation levels – apart from during the very early wet season, animals were unable to keep pace with the rapid growth of the pastures so that even at high stocking rates, utilisation levels were relatively low at the end of the growing season.

- Can reducing stocking rate give the same benefit as pasture resting? Reducing stocking rate does not eliminate selective grazing. It may give some benefit as the heavy grazing of preferred patches will affect a smaller area due to the lower animal numbers, but some effects of selective grazing will be incurred. However the results of Orr and Paton (1997) show reduced stocking rates can give a similar response to resting – plots gazed at half stocking rate were similar (yields and basal area of spear grass) to plots rested for 4 or 6 months after burning, and superior to plots with no rest or 2 months rest.

5.2.5.2. Growing conditions

Pasture maintenance and recovery are boosted by good growing conditions and the duration and frequency or rest periods need to be higher under poor growing conditions. As discussed above, trials show the general impact of growing conditions but it is not possible to quantify the impacts.

5.2.5.3. Land type

There is a lack a consistent data set to draw firm conclusions but it is possible to make some comments.

.

- Since grasses grow faster on better soil types they should be able to recover in a shorter time on these soils than on poorer soils.
- Heavy soils may get some rest during the wet season as cattle prefer to graze lighter, better drained soils at this time.
- Mitchell grass seedlings are particularly sensitive to defoliation.

5.2.5.4. Initial land condition

As discussed above, as initial land condition declines, frequency and duration of rest periods need to increase but the data is insufficient to develop quantitative relationships.

5.2.5.5. Property size

Property size and infrastructure do not have a direct impact on the responses to rest but they strongly influence ability to spell pastures.

5.2.5.6. Duration and number of rest periods

Some hypothetical responses to duration and number of rest periods are examined in Figure 5.10. Likely benefits to land condition (e.g. increases in cover, basal area, proportion of 3P grasses) are shown in Figure 5.10(a) – these show an increase in benefits with increasing duration of rest. Benefits are greatest under good growing conditions and initially increase rapidly with an increase in duration. However, with a further increase in duration the rate of increase in benefits slows and reaches a maximum value with rests of long duration. Benefits are less with average growing conditions and with poor growing conditions there may be little or no benefit of rest. This latter sentence should be treated with caution – benefits will be less than with good growing conditions but there may still be a benefit of rest under poor growing conditions. Although the land condition may be the same after a rest period as it was before the rest period, it could be higher than it would be if the area had been grazed during that time and land condition continued to decline.

Assuming the benefits of rest periods are additive (i.e. resting in two consecutive years gives twice the benefits on rest in one year only), then the benefits of various combinations of duration and number of rest periods are shown in Figure 5.10(b) (good growing conditions) and Figure 5.10(c) (average growing conditions). Under good growing conditions there are no additional benefits from long rest periods and only small additional benefits under average conditions. Only combinations of long duration and many rest periods give a large benefit under average conditions.

Due to the shape of the response curves in Figure 5.10(a), increasing the number of rest periods gives a greater increase in benefits than increasing the duration of rest i.e. say for example a paddock has been rested for 10 weeks and the choice is to either:

a) continue the rest period for another 10 weeks and then graze the paddock for all of the following year, or to

b) commence grazing immediately but then rest the paddock the following year for 10 weeks.

There are a total of 20 weeks rest during a two year period in both cases but (b) would give a greater benefit.

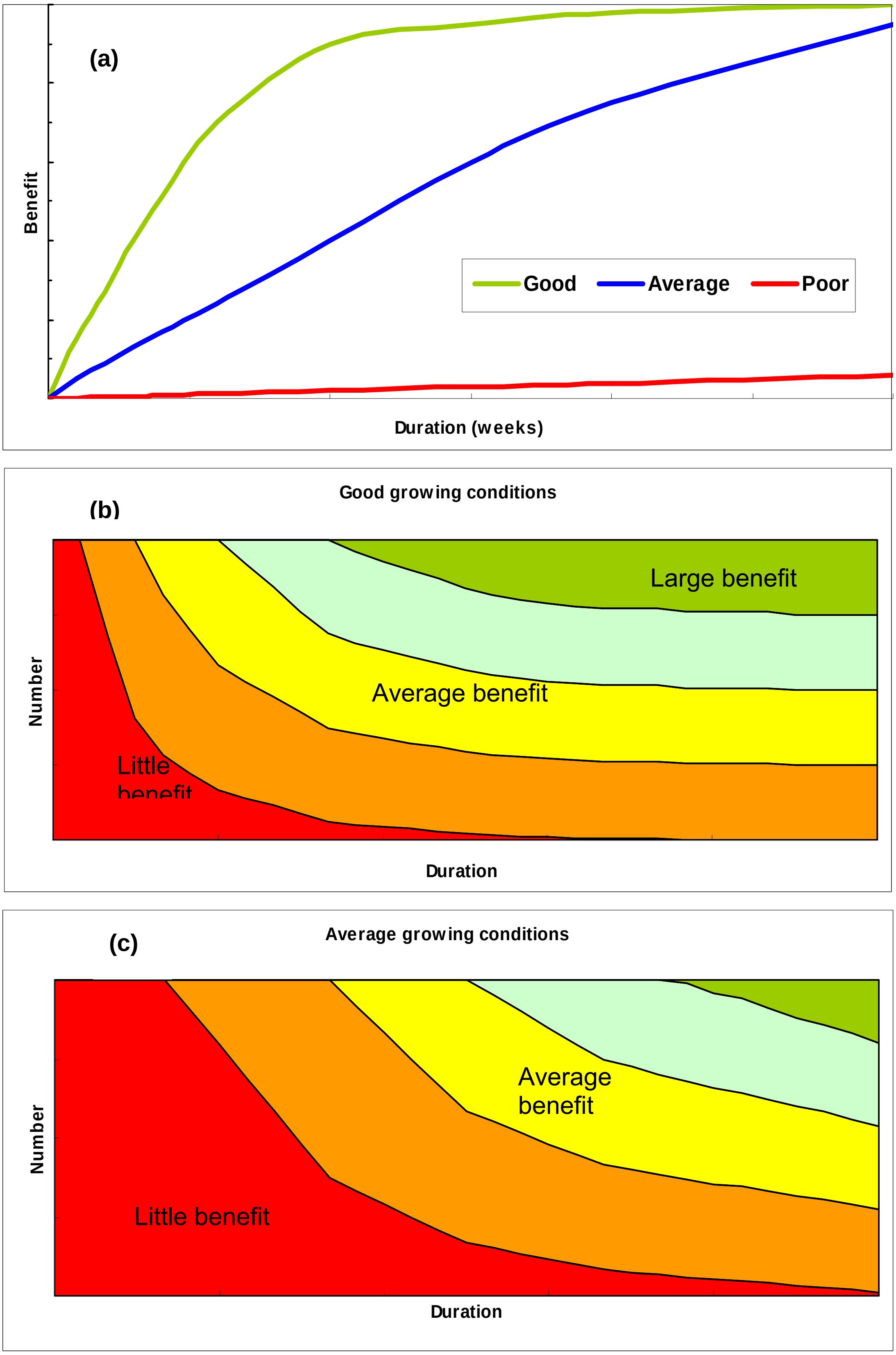

Figure 5.10. Hypothetical relationships between number and duration of rest periods and the benefits derived from resting.

5.2.5.7. Stocking regime

Stocking regime during the interval between rest periods

There is limited information on how utilisation rates during the grazing periods between rest periods affect impacts of resting. First principles suggest responses to resting will be greatest at intermediate levels of utilisation. At light utilisation rates, defoliation levels will already be low overall in these pastures and reducing this level to zero is expected to have little impact. At intermediate and high levels of utilisation resting does give a positive response. However, at high utilisation rates the benefit during resting is negated by the high utilisation rates during the remainder of the year so over all there is little net benefit from the rest period.

There is some experimental evidence to support this suggestion. Hacker and Tunbridge (1991) ascribed the failure of wet season rest to improve pastures in a Kimberley trial to the generally low utilisation levels – apart from during the very early wet season, animals were unable to keep pace with the rapid pasture growth so that even at high stocking rates utilisation levels were relatively low at the end of the growing season. For the State II plots in the Ecograze project, responses to resting were greater at 50% utilisation than at 25% utilisation (Figure 5.11). There was no treatment combining rest with 75% utilisation on the State II plots. In the State I plots with 75% utilisation, resting gave a much smaller absolute increase in yield of 3P grasses than did resting with 50% utilisation (Figure 5.12).

Conclusion: these results suggest responses to resting will be greatest at intermediate levels of utilisation. At low utilisation rates pastures will not be overstocked over the whole year and during the rest period there will be only small differences in effects of grazing between plots rested with no grazing and those grazed at low rates. (However, it is likely that in large paddocks resting during the growing season would avoid the selective grazing of preferred areas.) At high utilisation rates, the damage done to the pastures outside the rest period cannot be fully overcome by gains made during the rest period. These are tentative conclusions as we lack the data to establish quantitative relationships.

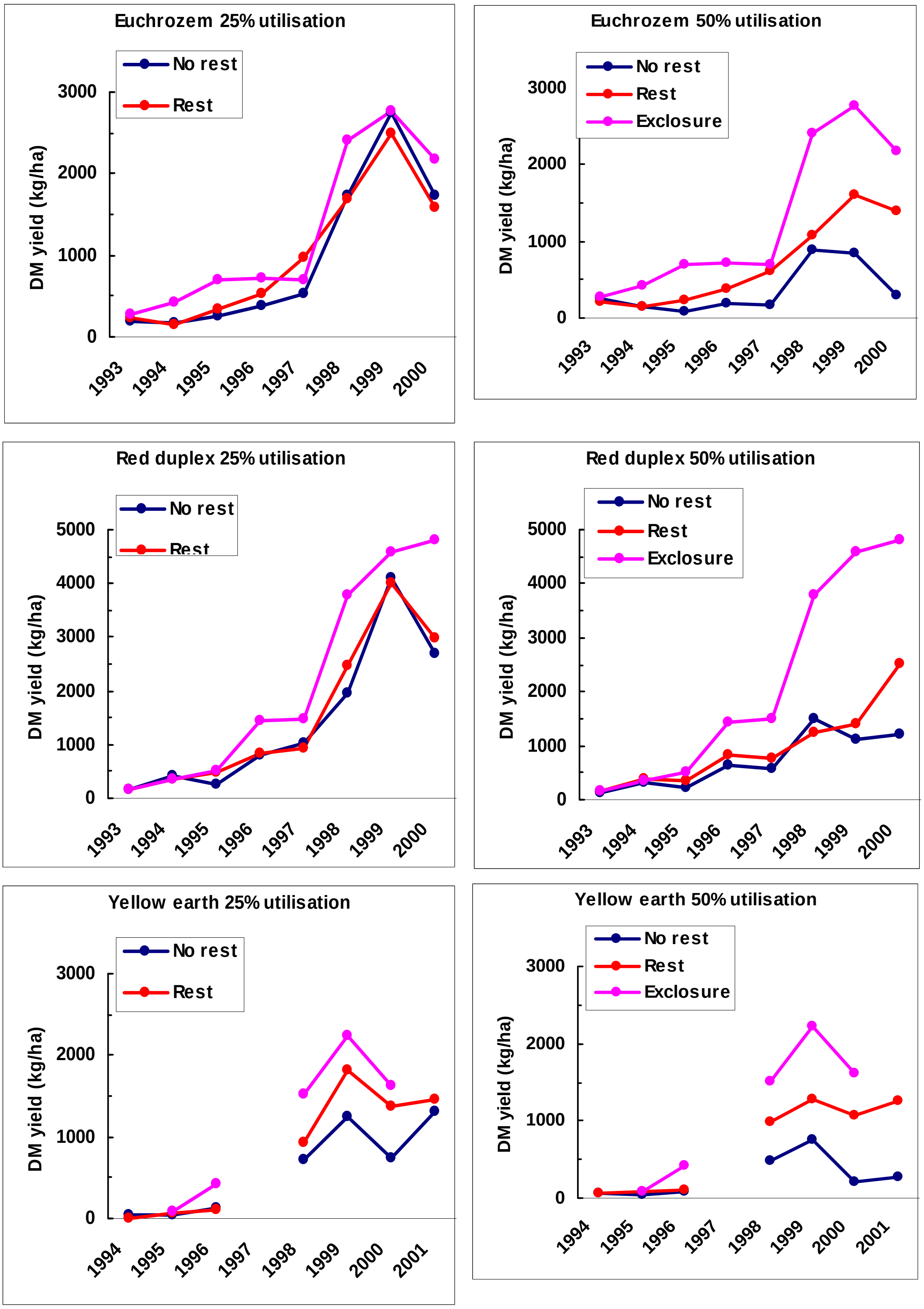

Figure 5.11. The influence of utilisation rate and pasture resting on changes in the yield of 3P grasses on State II plots (from Ecograze).

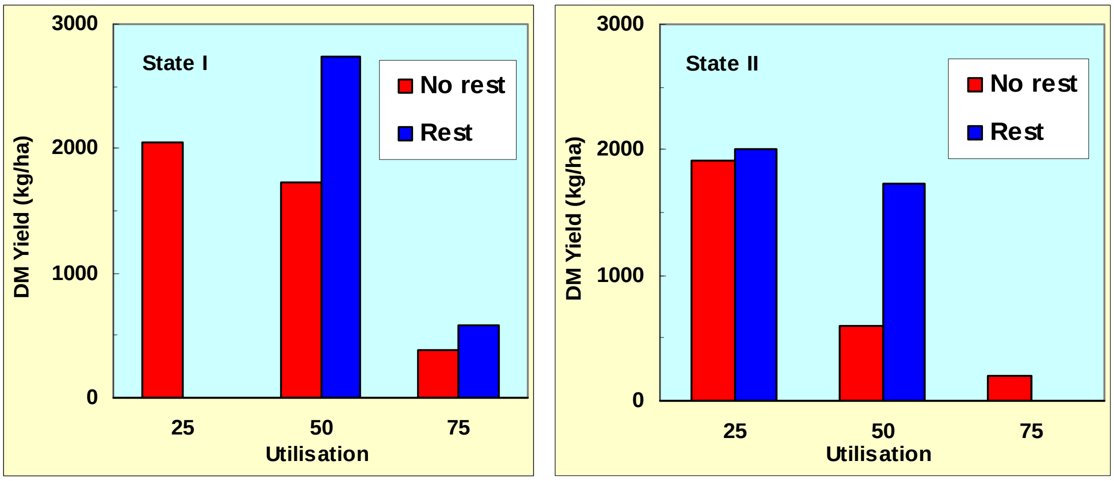

Figure 5.12. The influence of utilisation rates (25, 50 or 75%) and pasture resting on changes in the yield of 3P grasses in the final year on State I and State II plots (means of all sites from Ecograze).

Carrying capacity

Can a spelling regime permit net increases in carrying capacity independent of effects on pasture condition per se? First principles suggest that a pasture should be able to withstand a higher utilisation rate if it is rested in the early wet season for two reasons:

- Defoliation is avoided during the early growing season when grasses are particularly sensitive. Having a higher utilisation rate when they are less sensitive is expected to have a lesser impact.
- More feed will be available in the pasture when grazing commences after the spell and pasture availability should not be limiting for animals as it may be when pastures are regrowing in the early growing season.

Supporting evidence from the Ecograze project showed plots with 50% utilisation plus early wet season rest performed similarly to plots with 25% utilisation and no rest. They concluded a long-term average utilisation rate of 35% should be safe when combined with early wet season spelling (Ash *et al.* 2001). The Wambiana and Pigeon Hole reports offer some limited support with "Spelling may buffer the effects of increased utilisation rates on pasture condition in some areas but the exact nature of this relationship on different land types is unclear" (O'Reagain *et al*. 2007) and "Higher utilisation may be possible but needs testing" (Pigeon Hole).

The grazing trial conducted on Mitchell grass pastures at Gilruth Plains provides some evidence. The pastures were grazed at three stocking rates for 10 years. The total number of grazing days during the year was the same for both the continuously grazed and summer rested plots. There was no grazing during the year after the trail was completed. During that year there were no significant differences in the forage on offer between the paddocks that were rested in summer and grazed during winter and those that had been continuously grazed at the same stocking rate (Figure 5.13). Forage on offer was slightly less in the summer rested paddocks at all stocking rates and there was no suggestion that the summer rested pastures could support a higher stocking rate.

Conclusion: some increase in carrying capacity should be possible but unable to make any firm recommendations.

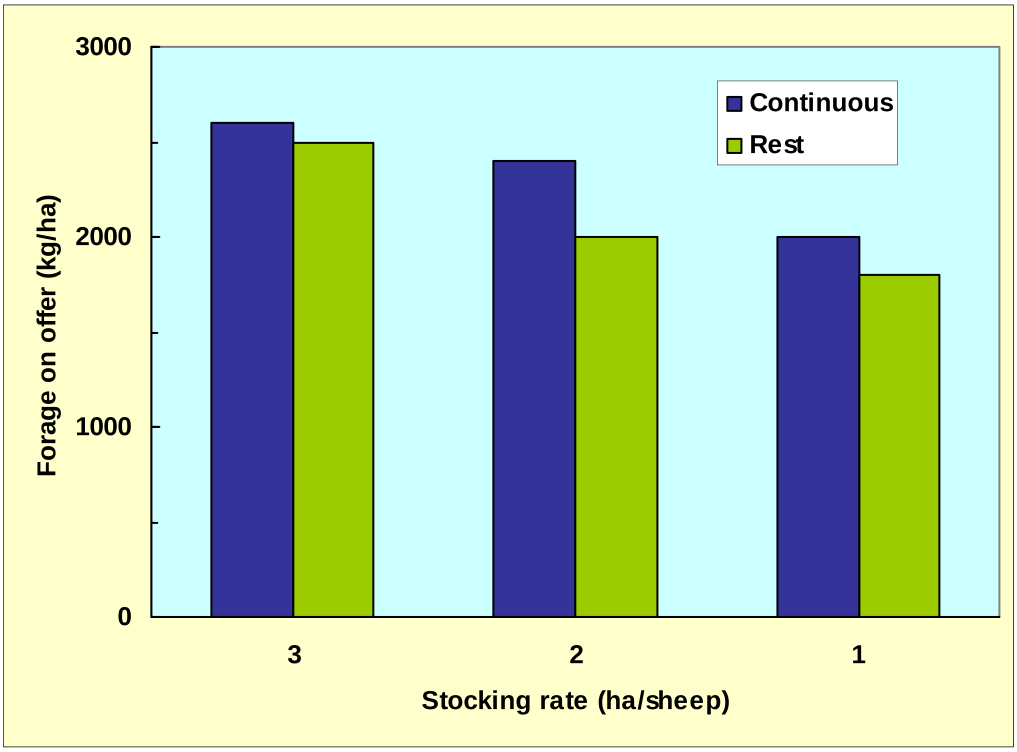

Figure 5.13. Forage on offer after 10 years of grazing for continuously grazed plots and plots rested in summer and grazed only in winter (drawn from Roe and Allan 1993).

Additional grazing impacts in non-rested paddocks

An important consideration is what happens to the pasture(s) being grazed when another pasture is rested. Animals from the paddock being rested must either be removed from the property in some way (e.g. sale or agistment) or be grazed elsewhere on the property. Does the grazing impact on this pasture outweigh the gains from the rested pasture? The increased stocking rate in the pasture means a reduction in production per head is likely. There may also be deleterious impacts on land condition. The Wambiana trial provides some relevant information. In the three-paddock system tested at Wambiana, the stocking rate in the two non-rested paddocks was increased by 50% during the rest period. Recovery from the 2001 fire was very poor due to low rainfall and the burnt sections had to be rested for three consecutive wet seasons so the remaining sections had three years of heavy wet-season grazing. This heavy grazing combined with the below average rainfall adversely affected pasture cover and condition and necessitated a reduction in the overall stocking rate for the treatment.

Any effects are expected to be detrimental with level determined by stocking rates and growing seasons. The results for wet season spelling treatment Wambiana shows how bad they can be.

5.3. Quality/certainty of conclusions

The quality of the evidence supporting the above conclusions can be assessed against a number of criteria.

5.3.1. Studies of pasture resting

Five criteria have been chosen:

- Did the trial have a grazed control so that responses to rest could be separated from changes due to seasonal differences or grazing?
- Did the trial test a grazing system (i.e. support animals for the whole year) or was resting studied in isolation?
- Were measurements made of animal production?
- Were the treatments replicated?
- How long did the trial go for?

Details of the experiments examining pasture resting are shown in Table 5.5.

5.3.2. Exclosure studies

Four criteria have been chosen:

- Did the trial have a grazed control so that responses to rest could be separated from changes due to seasonal differences or grazing?
- Were the treatments replicated?
- How long did the trial go for?
- How large were the plots?

Table 5.6 gives details of exclosure experiments.

Table 5.5. Details of experiments in northern Australia relating to pasture spelling.

Study and location	Experimental details	Duration (years)	Grazed control	Reps	Plot size	Comments	
1. Charters Towers Ash *et al.* (2001, 2009)	Ecograze - comparison of early wet season rest for 8 weeks and utilisation rate in grazed plots with different initial land condition at three sites	8	Yes – range of utilisation rates	2	1-5 ha	Y N N Y Y	1. Grazed control 2. Grazing system 3. Animal production 4. Replication 5. Duration (long term) Other: • Mix of growing conditions – poor early and good in later years • Plots were rested every year • Large invasion of exotic perennial grasses at two sites
2. Virginia Park (Charters Towers) (Post *et al.* 2006; Corfield and Nelson 2008; Bartley *et al*. 2007, 2009)	Applied results from Ecograze (moderate utilisation and wet season rest) at commercial scale. Three spelling sequences examined.	6	No	No	Commercial paddocks	N N N N Y	1. Grazed control 2. Grazing system 3. Animal production 4. Replication 5. Duration (long term) Other: • Pastures were dominated by Indian couch grass • Mix of growing conditions – poor early and good in later years
3. Wambiana (Charters	Compared complete wet season rest every	10	Yes	2	c.100 ha	Y Y	1. Grazed control 2. Grazing system

Towers) O'Reagain *et al*. (2007, 2009)	three years with other grazed plots					Y Y Y	3. Animal production 4. Replication 5. Duration (long term) Other: • Rest was combined with fire and poor recovery after fire in 2001 meant burnt pastures had to be rested for three years. Consequent high grazing pressure on other pastures meant stocking rates needed to be reduced
4. Brian Pastures Paton and Rickert (1989)	Used cages to rest areas in a grazed pasture for 19 months	2	Yes	No	Cages	Y N N N N	1. Grazed control 2. Grazing system 3. Animal production 4. Replication 5. Duration (long term) Other: • Only one rest for a long period (two growing seasons)
Brian Pastures Orr *et al.* (1991)	Combined no grazing for 4 years with one burn or annual spring burns	4	Yes	No	120 m^2	Y N N N Y/N	1. Grazed control 2. Grazing system 3. Animal production 4. Replication 5. Duration (long term)
Brian Pastures Orr and Paton (1997)	Compared resting for 0, 2, 4 or 6 weeks after a spring burn	5	Yes	2	600 m^2	Y N N Y Y	1. Grazed control 2. Grazing system 3. Animal production 4. Replication 5. Duration (long term)

5. SWAMP (South-east Queensland) Paton (2004)	Compared fire and early growing season rest on 4 commercial properties	7	Yes	No	Commercial paddocks	Y N Y N Y	1. Grazed control 2. Grazing system 3. Animal production 4. Replication 5. Duration (long term) Other: • Differences between paddocks including different starting condition • Different treatments at different sites
6. Pigeon Hole	Compared resting in the early or late wet season with other grazing systems	4	Yes	No	5 km^2	Y Y Y N Y/N	1. Grazed control 2. Grazing system 3. Animal production 4. Replication 5. Duration (long term) Other: • Differences between paddocks (soil type, pasture composition) • Variable fire effects • Cattle distribution and management issues
7. Kimberley Hacker and Tunbridge (1991)	Continuous grazing, wet season rest or dry season rest on regenerating pastures	4	Yes	No	0.25 ha	Y N N N Y/N	1. Grazed control 2. Grazing system 3. Animal production 4. Replication 5. Duration (long term)
8. Queensland Orr *et al*. (2006)	Rested pastures at six sites for 0, 3, 6 or 12	1	Yes	No	600 m^2	Y N	1. Grazed control 2. Grazing system

	months					N N N	3. Animal production 4. Replication 5. Duration (long term) Other: • Rest periods commenced in autumn so most were not during the growing season • Severe drought at some sites
9. Mareeba Cooksley (2003)	Early wet season resting, stocking rate and fire were examined on stylo-grass pastures	8	Yes	2	0.5-1.0 ha	Y N N Y Y	1. Grazed control 2. Grazing system 3. Animal production 4. Replication 5. Duration (long term) Other: • Treatments confounded (not full factorial) • Wildfire during the trial • Sown to stylo and exotic grasses
10. North Queensland Shaw *et al.* (2009)	Ecobeef – rested paddocks at three sites during the wet season	1-3	No	No	Commercial paddocks	N N N N N	1. Grazed control 2. Grazing system 3. Animal production 4. Replication 5. Duration (long term)
11. Narayen (Tothill *et al.* 2009)	Continuous and 2-paddock resting systems	5	Yes	2	c.4 ha	Y Y Y Y	1. Grazed control 2. Grazing system 3. Animal production 4. Replication

		Y	5. Duration (long term) Other: • Siratro-buffel grass pastures • Only two paddocks for rest treatments

Table 5.6. Details of experiments in northern Australia relating to pasture growth in exclosures.

Study and location	Experimental details	Duration	Grazed control	Replication	Plot size
1. Regeneration study - Hillgrove (Charters Towers) McIvor (2001)	Growth of pastures in different initial condition	3 years	No	No	60 m^2
2. Exclosures - Kerale (Collinsville) McIvor and Gardener (1990)	Growth of pastures in different initial condition	1 year	Yes	No	600 m^2
3. Recovery study - Galloway Plains Bray *et al*. (Unpublished data)	Growth of pastures in different initial condition following grazing at different stocking rates	4 years	No	Yes	1 ha
4. Mitchell grass exclosures - Toorak (Julia Creek) Orr and Phelps (unpublished data)	Growth of pastures that had been heavily (80%) utilised in previous years	6 years	Yes	Two	???
5. Mitchell grass exclosures - Blackall Orr (1980), Orr and Evenson	Growth in an exclosure and a grazed area in a previously heavily used pasture	11 years	Yes	No	400 m^2

(1991)					
6. Multi-site - South-west Queensland Silcock and Beale (1986)	Exclosures on degraded areas on 17 properties	*c.*20 years	No	No	330 m^2
7. Exclosures - Kidman Springs Foran *et al.* (1975)	Exclosures at two sites on calcareous soils in poor and good initial condition	29 years	Yes	No	25 ha
8.Erosion study - Charters Towers Scanlan *et al.* (19960	Exclosures at six sites in different initial conditions	6 years	Yes	No	4 ha
9. Mulga lands Cowley (2001)	Exclosures at three distance from a new water trough	3 years	Yes	Yes	3600 m^2
10. *Aristida-Bothriochloa* project (Injune and Rubyvale)	Exclosures compared to grazed plots	8 years	Yes	Yes	1 ha

5.4. Rest for reasons other than pasture condition

In addition to resting pasture to improve land condition there are a number of other reasons why a pasture may be rested from grazing to accumulate a supply of herbage.

- To provide a mass of herbage for burning (both by accumulating fuel and not removing fuel that is there), especially where fuel is needed for intense fires to kill woody seedlings
- To allow pastures to recover after a fire
- To conserve forage as drought or fodder reserve in seasons when pastures are not growing, or for special purposes (e.g. weaning)
- To make hay (or for other forms of fodder conservation)
- Pastures may be rested when they are beginning to regrow to accumulate sufficient herbage to ensure adequate intake by animals during subsequent grazing
- To accumulate herbage to compete with seedlings of woody species
- To enable seed production and harvest
- To increase ground cover
- To increase input of organic material to improve the soil
- In winter for sawfly control in ironbark country of the north Maranoa

6. Prescribed burning

Fire has long been an important ecological factor in many northern Australian ecosystems. The rainfall regime and vegetation are such that grass that grows during the distinctive wet season becomes increasingly available as fuel during the ensuing dry season (Dyer *et al.* 2001). In the absence of other sources, lightning is a significant source of ignition during storms associated with the onset of the wet season. For thousands of years fire was extensively used by Aboriginal people for various purposes and fashioned the structure and composition of the native vegetation. Aboriginal people used fire for hunting, to encourage food plants, to facilitate travel etc. Fire has remained an important factor since European pastoral settlement though there have been shifts in fire regimes as a result of the changed nature and distribution of Aboriginal peoples, and changed land uses, especially developments and infrastructure (e.g. roads) associated with pastoralism (Figure 6.1). Northern Australian pastoralists have themselves used fire for various purposes though the extent of, and purposes for fire, differ between regions (Dyer *et al.* 2001).

Figure 6.1 Areas of Australia burnt between 1997 and 2003 (from http://www.savanna.org.au/all/fire.html).

There is an extensive literature (more than 800 publications) on fire in northern Australia. This covers a wide variety of issues from conservation, woody vegetation management and weed control, mostly in Queensland and the Northern Territory. In this review we have not covered all of this literature but have focused on that which is relevant to pastoral lands. We have not attempted to review the considerable literature on fire as a factor relevant to conservation of northern Australian species and ecosystems though we have attempted to capture the essence of that literature by examining some key reviews of this field. We have identified around 80 publications that are especially pertinent to the effects and use of fire in pastoral areas of northern Australia.

6.1. The basis of northern Australian fire regimes

Fire should be considered in terms of both the characteristics of individual fires and the regimes of fires that occur in any one location. Fire requires a source of fuel and a source of ignition. These prerequisites exist frequently across large areas of northern Australia though there is considerable geographic variation.

The nature of an individual fire is dictated largely by the amount of fuel available, its moisture content, atmospheric temperature and humidity and wind speed at the time of the fire. There are geographic patterns in these factors, driven in part by climate, as well as a great deal of temporal variation. Furthermore, land management can be important; in particular, in grazed systems herbivores and fire compete for the available fuel/forage so that there is a strong grazing-fire interaction.

A fire regime is the pattern of fires occurring in a landscape at broad temporal scales and can be described in terms of the timing, frequency, intensity and type of fires (Grice and Slatter 1996). Fire regimes, prehistorical, historical and current, vary widely across northern Australia, directly or indirectly as a function of climatic factors. They are also influenced by sources of ignition and by land use.

Northern Australia has a strongly seasonal rainfall pattern with distinct ‘summer’ wet season and ‘winter’ dry season. This pattern drives the growth of the vegetation. In contrast to much of southern Australia, most fires in northern Australia are largely fuelled by perennial, less commonly annual, grasses rather than by woody plants and their litter. Typically, perennial grasses grow during the hot and humid wet season but are inactive during the dry season. The grass biomass produced during each wet season gradually cures over the ensuing dry season and, as its moisture content falls (Figures 6.2 and 6.3), the prospect of it burning, and the intensity of any fires that arise, increase (Dyer *et al.* 2001; Figures 6.4 and 6.5).

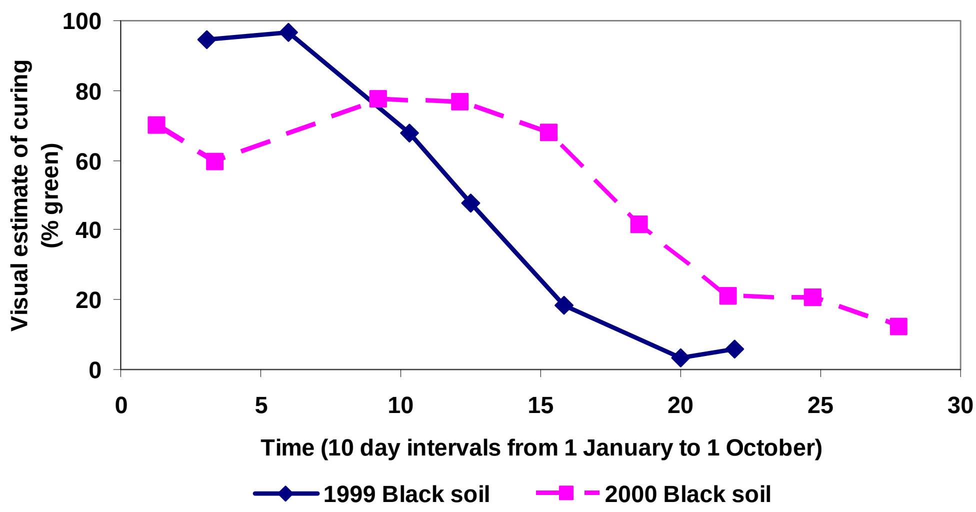

Figure 6.2. The pattern of vegetation curing following the wet season varies from year to year depending on seasonal rainfall patterns (from Allan *et al.* 2003).

February – 2500 kg/ha fuel 20% cured,
65% moisture content

March – 4000 kg/ha fuel 25% cured,
60% moisture content

May – 3000 kg/ha fuel 65% cured,
20% moisture content

July – 3000 kg/ha fuel 80% cured,
20% moisture content

Figure 6.3. Progressive curing of fuel in typical savannas of northern Australia – fuel loads, curing and moisture contents of a pasture as the dry season progresses (from Dyer *et al.* 2001).

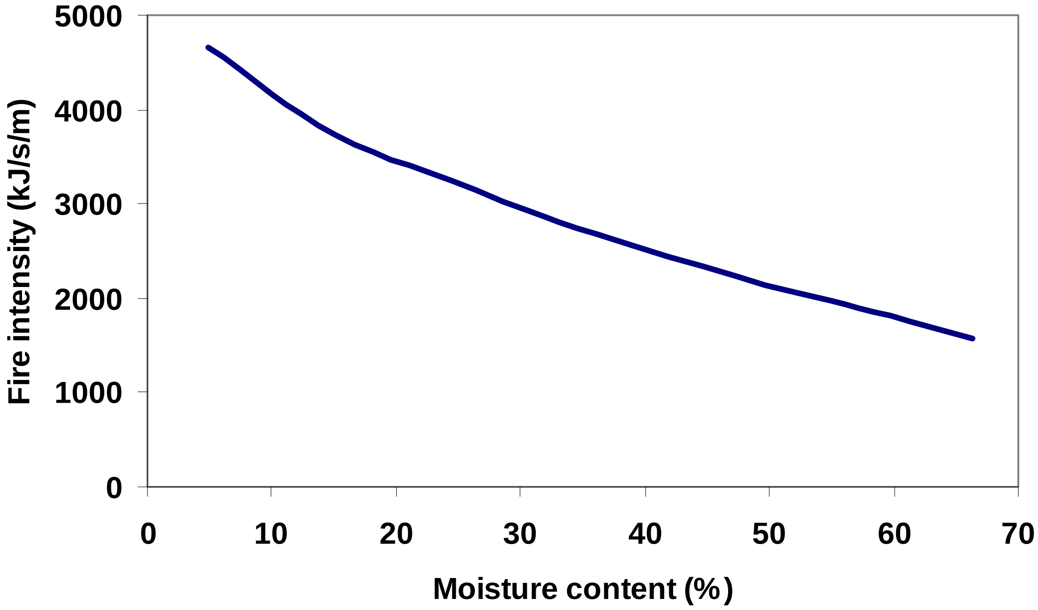

Figure 6.4. Relationship between fire intensity and fuel moisture (from Grice and Slatter 1996).

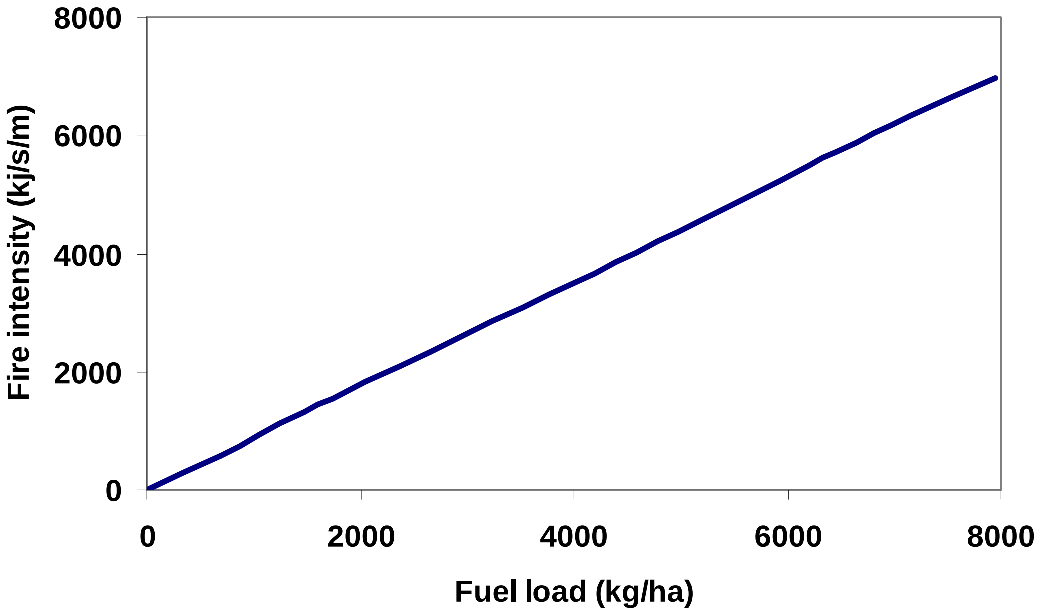

Figure 6.5. Relationship between fuel load and fire intensity (from Grice and Slatter 1996).

The broad geographic, long-term patterns of rainfall in northern Australia mean that there is a more regular fuel production and curing cycle in more northerly parts of the region. Further inland, where average annual rainfall is lower and rainfall is less reliable, total productivity is lower, the fuel production and curing cycle is more erratic, and fires less frequent as a result (Russell-Smith and Stanton 2002).

There are two general sources of ignition for fires in northern Australia: lightning and people. Lightning is common, particularly in association with storms during the wet season. Lightning-initiated fires are especially common during the early stages of the wet season, particularly in monsoonal areas.

There are many sources of anthropogenic fires. They may be deliberate or accidental. Prior to occupation by Europeans, Aboriginal burning was extremely important in most of northern Australia. With changes in the distribution of Aboriginal populations, particularly as the number of Aboriginal people living 'on country' has declined, the regimes of Aboriginal burning have changed, but Aboriginal burning remains important. In some regions there are active attempts to facilitate the return of Aboriginal people to country and, more specifically, reinstate some semblance of Aboriginal burning regimes. Fire has also been used or managed for pastoral purposes.

6.2. Fire and pastoralism in northern Australia

Fire has been an important tool for pastoral management in northern Australia in general although there is great inter-regional variation in its perceived importance, the frequency of burning, and reasons for using fire. Moreover, superimposed on the broad inter-regional variation are major differences between individual pastoralists, within a region or district, in their attitudes towards and experiences of fire, and in the way (or whether) fire is used.

The purposes for which fire has been used on pastoral lands include:

- Promoting 'green pick', that is, promoting the growth of nutritious new shoots (Ash *et al.* 1982; Craig 1999)
- Removing 'moribund' grass material to facilitate access by livestock to more nutritious components of the herbage sward (Ash *et al.* 1982; Craig 1999)
- Controlling herbaceous weeds, whether they be less desirable native components of the herbage or introduced species (Orr *et al.* 1997)
- Controlling the woody components of the vegetation to reduce the competition faced by grasses and other herbage and improve access for effective animal husbandry (Back 2005; Grice 2008)
- Manipulating pasture composition, for example, the ratio of grasses to legumes (McIvor *et al.* 1996)
- Preparation of a seed-bed to facilitate the establishment of sown pasture species (Stocker and Sturtz 1966; Cameron and Wildin 1976; Shaw and Ticknell 1993; Cook *et al.* 1993)
- To help muster livestock
- Controlling pests such as ticks (Baars 1999)
- Reducing the risk of destructive wildfires
- Controlling the distribution of animals at fine or coarse scales

The presence of an item on this list does not imply that burning for this reason is effective, either in general or in a particular situation (Dyer 2000). It is also important to recognise that many land-holders do not use fire or use it rarely. Reasons given for not burning include the following:

- Smoke affects air quality which is of particular concern near urban centres
- Fire reduces the litter layer and creates bare ground which increases susceptibility to soil surface erosion and evaporation
- Fire deplete supplies of nutrients, particularly nitrogen and sulphur (Cook 1994)
- Negative impacts of burning on stream water quality (Townsend 1997; Townsend and Douglas 2000)

- Negative impacts on fire sensitive vegetation particularly along riparian areas, softwood scrub, acacia forests (e.g. brigalow (*Acacia harophylla*)) and habitat trees (old, hollow trees) (Butler and Fairfax 2003)
- Risk of fire escaping and causing damage to infrastructure (building, fences, water pipes), death of livestock, burning neighbour's country
- Risk to staff
- Risk of forage shortages after burning, particularly if poor (dry) seasons follow the burn
- Sometimes unpredictable response of vegetation to burning (stimulate wattle germination, flush of suckers, damage to perennial grass tussocks)
- In some area undesirable species can be promoted by fire
- Extra costs of equipment, labour and firebreak maintenance to implement a fire regime
- Perception that fire is destructive and dangerous
- Perception that burning grass that could be grazed is a 'waste'
- Burning contributes to the greenhouse effect (Russell-Smith *et al.* 2006)
- Complying with legislative requirements is difficult

While there is considerable inter-regional variation in the use of fire as a land management tool, and the extent to which it is used, within any region individual land-holders differ greatly from one another in their attitudes toward the use of fire, and how and whether to employ it.

Fire is widely regarded as a tool to manage woody vegetation on pastoral land. A reduction of woody vegetation generally leads to greater pasture production and this relationship is often referred to as the tree-grass relationship (Figure 6.6).

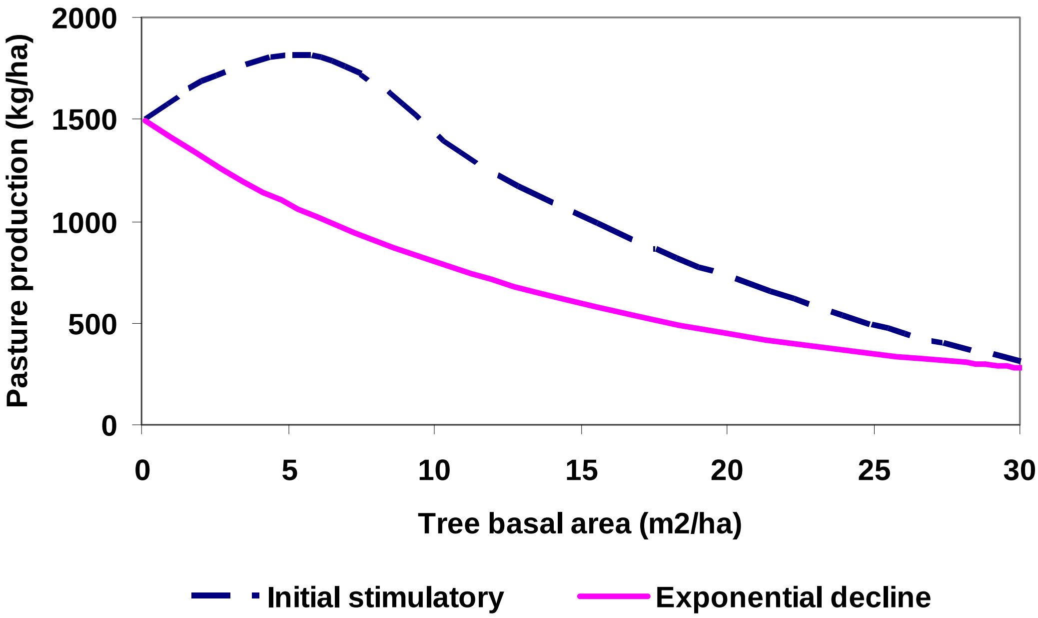

Figure 6.6. Relationship between tree basal area and pasture production (from Scanlan 2002). Some communities may show a stimulatory effect of tree cover at low tree basal area, whereas other communities compete with the pasture even at low tree basal area.

6.3. Plant responses to burning

The effectiveness of burning for any of the purposes listed in the previous section depends on how the plant species that constitute the community respond to individual fires and to fire regimes. Broadly speaking, plants either die or survive when they are burnt (Dyer *et al.* 2001). These general response categories apply to individual plants but particular types and intensities of fire often produce characteristic mortality rates in any given species. The long evolutionary history of burning in Australia has selected for species that are generally fire tolerant whether or not individual plants survive particular fires or fire regimes.

Annual plants are species whose individuals survive less than 12 months regardless of whether they are burned or not. They rely upon recruitment from seed; in areas with regular, reliable wet seasons, some germination of annual species takes place every year. Annual plants are likely to die if they are burned during their growing season, though some may survive in unburnt patches. Seeds that are held on annual plants during a fire are also likely to be killed, as are those that are in the litter layer if it is consumed. Seeds that are buried in the soil are insulated from the effects of the fire and the population survives because of this seed-bank. Many annual species have a persistent seed-bank, that is, seeds can survive for more than one year in the soil, so that individual plants do not risk all their seed reserves in a single year.

Individuals of most species of perennial grass generally survive fire. Their growing points are close to or below ground level and sufficiently well insulated to be protected from fires that are typical of northern Australia. Individuals of some perennial grasses, for example, some Spinifex (*Triodia* spp.), are killed by fire and the population relies on recruitment from seed to recover following fire. Fire can be useful in promoting one perennial grass species over another. In the Burnett region regular fire with spelling promotes black spear grass (*Heteropogon contortus*) while reducing the proportion of wire grass (*Aristida* spp.) in the pasture (e.g. Figure 6.7; Orr *et al.* 1991).

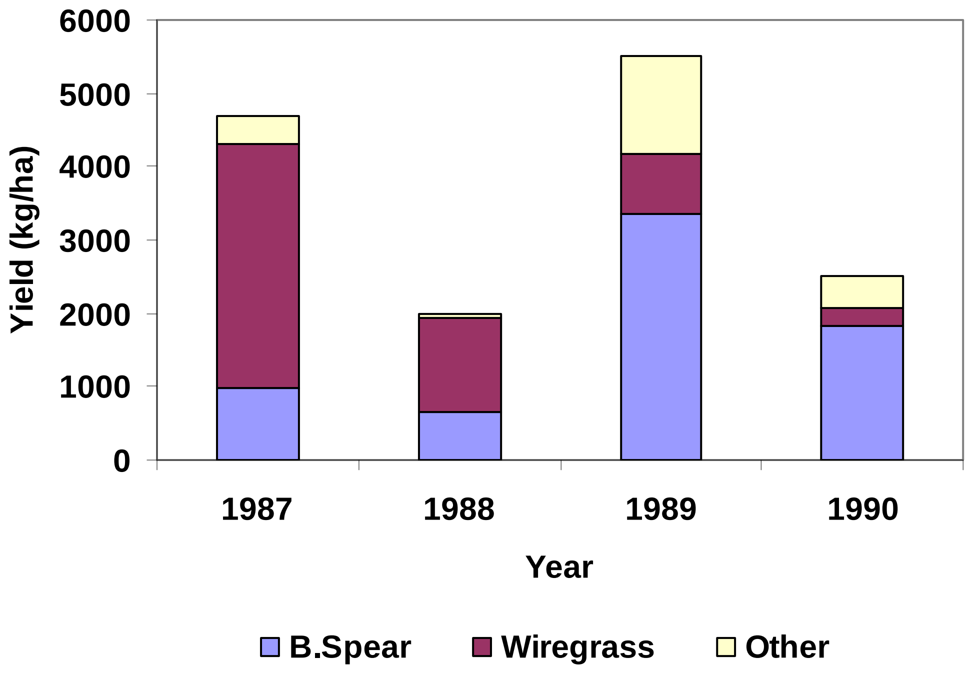

Figure 6.7. Black spear grass increases in proportion of yield under a regime of annual burning and protection from grazing (from Orr *et al.* 1991). Total yield varies with seasonal rainfall.

Shrubs and trees fall into one of two categories as regards their responses to being burnt. Individuals of some species are killed and their populations rely on recovery from seeds – these are often referred to as "obligate seeders". Individuals of other species – referred to as "sprouters" or "resprouters" – generally survive fire. Their growing points are protected by thick or corky bark or by the soil. Depending on the species and the intensity of the fire to which they are subjected, these species produce new shoots from the roots or stem base (top-kill), from epicormic buds on the trunk and/or branches or from the branch tips. Fires often fail to scorch all the foliage on shrubs and trees depending on their size and intensity of the fire (Figure 6.8).

Obligate seeders may store their seed either on the plant inside protective fruits (e.g. woody capsules) or in the soil.

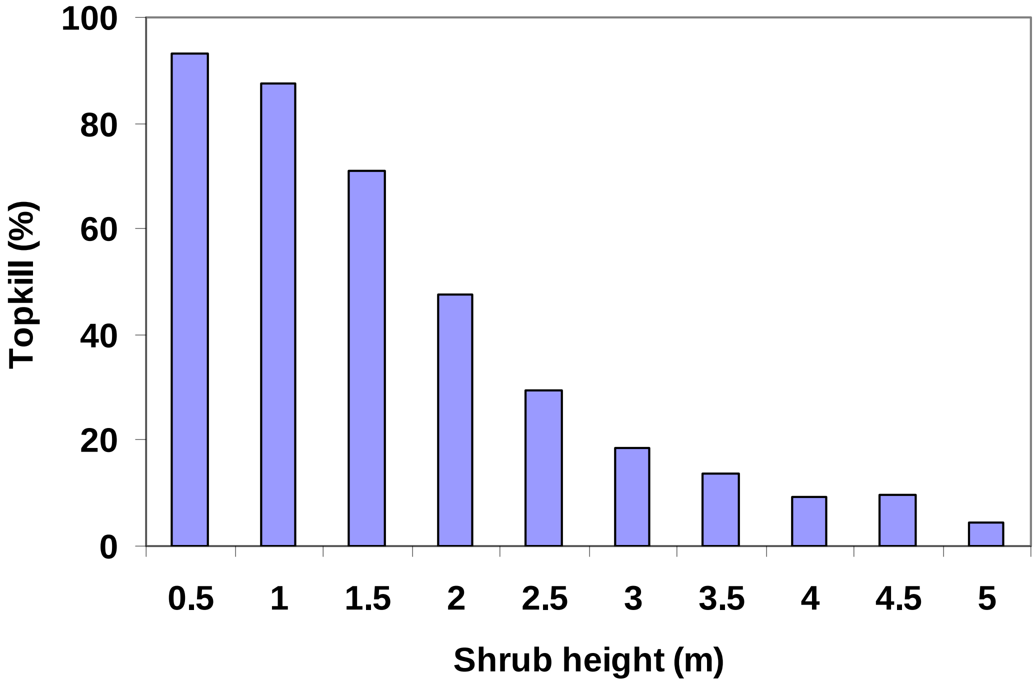

Figure 6.8. Relationship between top-kill and plant height (adapted from Grice and Slatter 1996).

Another aspect of woodlands is that as well as containing a range of species there is a large range of sizes of individuals of any given species (Figure 6.9; Williams *et al.* 1999). Thus, apart from inter-specific differences, the different size classes can vary widely in the proportion that survive fire and some size classes can be very resistant to fire (Figure 6.10; Williams *et al.* 1999).

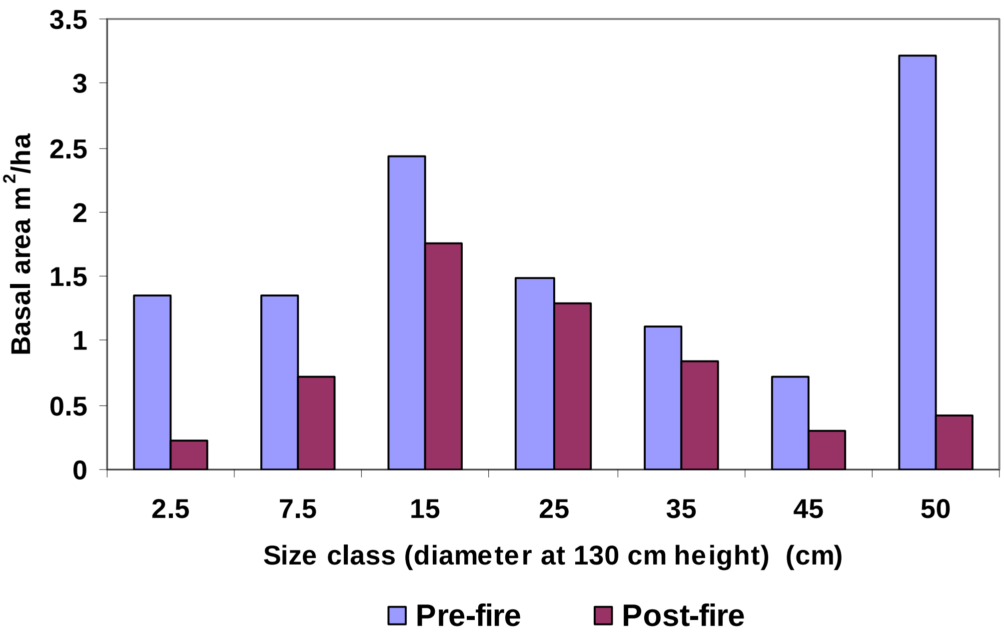

Figure 6.9. The contributions of plants of different diameter at breast height to total basal area of trees in a northern Australian savanna (from Williams *et al.* 1999).

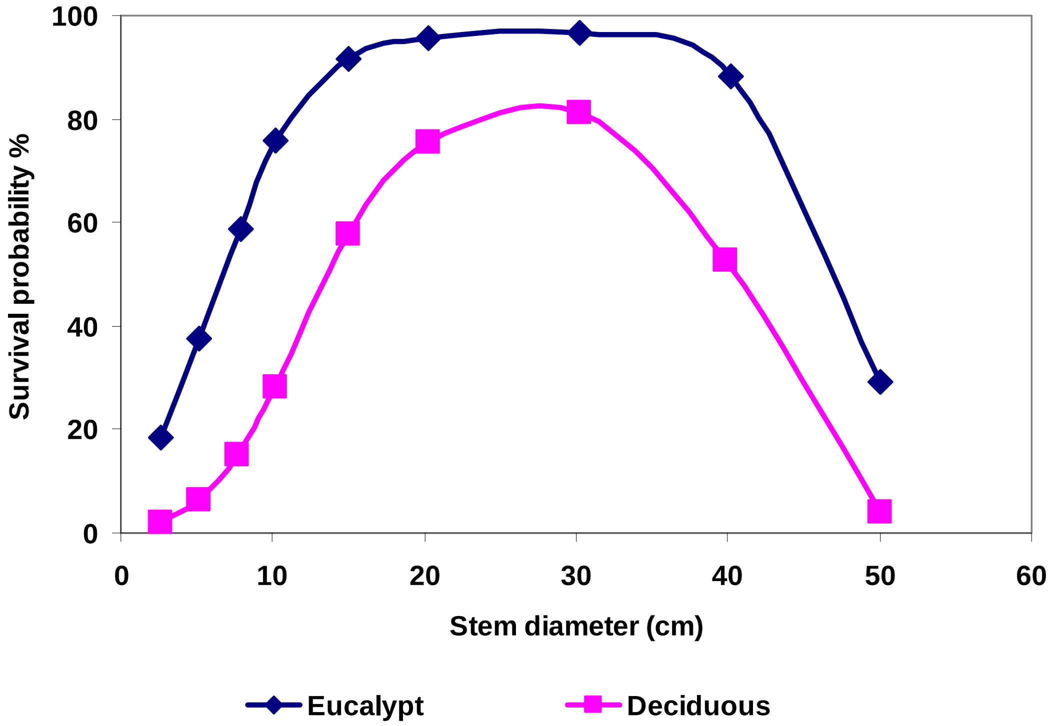

Figure 6.10. The relationship between stem diameter and the probability of surviving fire for various tree species of northern Australian savannas (from Williams *et al.* 1999).

The frequency of fire can have a large impact on the response of woody species. A one-off fire may have little long-term impact on the size or total basal area of the population of woody plants, while a series of two or more fires may have a longer lasting impact (Figure 6.11; Back 2005).

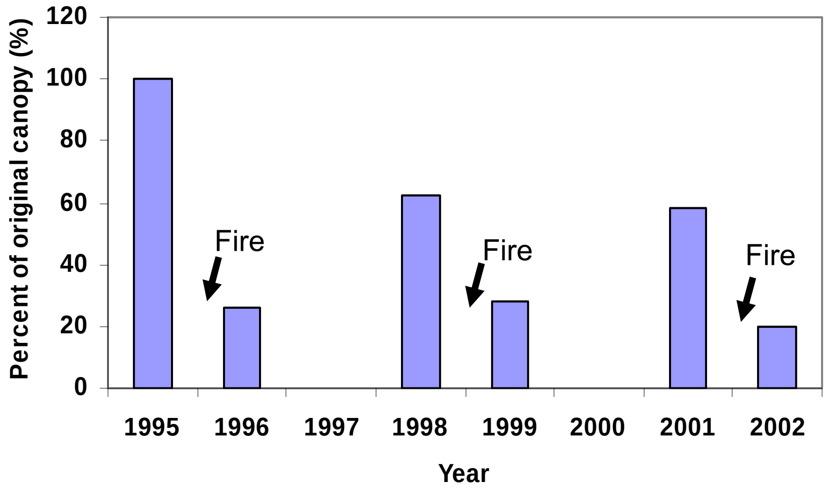

Figure 6.11. The response of currant bush (*Carissa ovata*) to fire (from Back 2005).

6.4. Areas of fire research in northern Australia

The extensive literature on fire in northern Australia reflects the importance of this factor in the ecology of northern ecosystems and in the management of northern pastoral lands. Fire is seen as an environmental phenomenon to be managed and a tool that is available for land management. The research that has been conducted addresses both of these aspects. It has also focused on various aspects of the impacts, uses and management of fire. There is a large literature on various aspects of fire in relation to conservation or ecology of particular communities or species and a somewhat smaller body of work that has expressly explored aspects of particular interest to pastoral land managers. Crucially, fire research effort has been very unevenly spread across northern Australia. Overall, different issues have been explored in different geographical regions, yielding a region-by-issue matrix of research work that has some blanks, an incomplete, but still very useful picture in relation to fire in northern Australian pastoral lands.

We have identified the following general bodies of research work that have been undertaken on fire in northern Australia:

6.4.1. Research on fire in the Top End of the Northern Territory

This work includes what are probably the most long-running research projects on fire in northern Australia, based at two well-known sites in Kakadu National Park, Kapalga and Munmarlary. Here the focus was on changes in the composition and structure of the tree and shrub layers of savanna woodlands with a strong emphasis on the conservation implications of different fire regimes.

In the Top End of the Northern Territory, fire is frequent, a large proportion of the region being burnt annually. Fuel loads reach 2.5-5 t ha^{-1} under such a regime. In any one season, fire intensity increases as the dry season progresses. During the Kapalga study, the intensities of annual early dry season and late dry season fires averaged 2200 kW m^{-1} and 7700 kW m^{-1} respectively. In the absence of fire, fuel loads build rapidly to a maximum of 8-10 t ha^{-1} in 2-4 yr and an unplanned fire in a 7-year unburnt plot had an estimated fire intensity of 20,000 kW m^{-1} (Williams *et al.* 1999).

The results of the Kapalga study that are most relevant to the management of pastoral lands are those relating to changes in the density of woody plants. In unburned and early dry season burned plots, the total live stem basal area increased marginally but it declined substantially under a regime of late dry season fires. Overall, the experiment yielded a linear decline in tree survival (stems and whole plants) with increasing fire intensity but the response varied with tree functional type. Survival was greater for eucalypts and deciduous trees and lower for palms and acacias. Deciduous non-eucalypts (*Terminalia, Erythrophleum*) were more sensitive to fire than dominant eucalypts. Generally, whole-plant survival was significantly higher than stem survival. Fire on a long-unburnt plot caused greater mortality in small and large trees than in trees of intermediate-sized (Williams *et al.* 1999), a result also reported by Lonsdale and Braithwaite (1991). Fire may cause greater mortality in deciduous trees when they are burned during the period of leaf flush in the late dry (Williams *et al.* 1999). Lonsdale and Braithwaite (1991) generalised that, in this type of woodland, about 1% of the canopy trees died each year – one-tenth of these from lightning strike, one-tenth from wind-throw, one-tenth from termite attack or fire and the rest from the interaction between termite-hollowing and fire; more generally, 14.3% of trees and shrubs were killed by the fire. Fire also affects tree dynamics by reducing seed production and seedling survival of some dominant trees (e.g. Darwin woollybutt (*Eucalytpus miniata*)) in Top End savannas, though at least some species develop a capacity to resprout by their first post-fire wet season (Setterfield 2002).

Long-term exclusion of fire leads to a reduction in grass cover in these Top End systems but rainfall is more important than fire in driving grass layer composition. The effects of fire on the grass layer are apparently greater where herbage is in “poor condition” as a result of pastures being heavily grazed (Williams *et al.* 2003c). Annual sorghum is a significant contributor to fuel loads. Wet season fires may be a management option for reducing fuel loads in such native grasslands (Williams *et al.* 1999).

Fire is a key factor in nutrient cycling processes in Top End savannas (Cook 1994). Significant quantities of all macronutrients, copper and zinc were transferred to the atmosphere during the experimental fires conducted during the Kapalga work, but these were subsequently deposited via particulates. Nitrogen losses were significant and may exceed inputs via deposition of particulates and biological nitrogen fixation. Any attempts to manage these processes by reducing fire frequency may be negated by the virtually inevitable more intense fires that occur with the higher fuel loads that result (Cook 1994).

6.4.2. Fire to manage "woody thickening" and the pasture layer (VRD)

Dyer *et al.* (2003) reported 5 years of results from a long-term study at Kidman Springs in the Victoria River District. The research considered the issue of "woody thickening" and the consequences of burning for the 'pasture' layer with emphasis on the implications for pastoral land management. It compared the effects of a range of fire regimes in arid short-grass and ribbon grass (*Chrysopogon fallax*)–blue grass (*Dichanthium* spp.) pasture types. Burning twice with a two-year recovery period between fires or three times in five years significantly reduced standing yield and ground cover but a short period of recovery between fires allowed yield and cover to return to pre-burn levels. In arid short-grass pastures, all burning treatments resulted in significant reductions of perennial grasses, associated with an increase in the annual native couch (*Brachyachne convergens*). In ribbon grass-blue grass pastures, only burning three years in five significantly reduced perennials, in association with a significant increase in the annual Flinders grass (*Iseilema vaginiflorum*). Ribbon grass-blue grass is more stable than arid short-grass under a range of fire regimes. Burning caused changes in species composition in arid short-grass, promoting annuals, but suppressing perennials (Dyer and Mott 1999). Prescribed fire in these systems reduced the incidence of wildfire (Dyer and Stafford Smith 2003). Season of burn had no significant effects on pasture response to fire. It was generally concluded that fire is not a suitable management option for arid short-grass communities in poor condition and that good grazing management must be in place before the use of fire is considered (Dyer and Mott 1999).

Generally, in the Victoria River District, the suppression of fire resulted in increases in tree basal area, lower pasture growth and perennial grass composition, and higher rates of utilisation (Dyer and Stafford Smith 2003). Tree and shrub species examined in this study were bauhinia (*Bauhinia cunninghamii*), conkerberry (*Carissa lanceolata*), silver box (*Eucalyptus pruinosa*), rosewood (*Terminalia volucris*), common hakea (*Hakea arborescens*) and inland bloodwood (*Eucalyptus terminalis = Corymbia terminalis*). Mortality rates were typically below 5%, regardless of the fire regime. Fire intensity and plant height at the time of fire were important in determining the response of woody plants to fire (Dyer *et al.* 2003). While mortality rates were low, fire caused significant reductions in tree canopy cover and plant height (Dyer *et al.* 2003). The only kinds of fire that reduced tree basal area were late dry season fires. Modelling work suggested that it would take 15 years of a burning regime before differences in tree basal area and perennial pasture condition began to emerge. It indicated that prescribed fire was economically attractive over the longer time horizon (tens of years) with relatively little short-term economic benefit. Any long term gains would have to be traded off against the little or negative benefit that would be expected in the short-term (Dyer and Stafford Smith 2003).

Tropical tall grasslands in the Katherine District (which borders the Victoria River District) were also the target of research to test the effects of burning part of a paddock as a means of altering the distribution of grazing pressure (Andrew 1986a). A strategy that involved burning different halves of a paddock in successive years attracted cattle to the burnt half of the paddock, so relieving grazing pressure on the unburnt half. While this increased annual animal gains (in the short-term) by 20 kg/head, it reduced total pasture yield substantially.

6.4.3. Fire to manage herbaceous species composition

The prevalence of wiregrasses is an issue for pastoral land management in certain vegetation types, notably in Mitchell grass (*Astrebla* spp.) and black spear grass communities. Wiregrasses provide less useful forage than the perennial grasses that they replace. At least two studies have tested the usefulness of burning as a means of countering increases in wire grasses. Research focused on the means to reduce the prevalence of wire grasses, and increase more desirable species in Mitchell grass and black spear grass communities.

A series of studies undertaken at Gayndah in south-east Queensland tested the prospects for using fire to alter the composition of black spear grass pastures, in particular to increase the amounts of black spear grass and reduce the amount of wiregrass. Orr *et al.* (1991) found that a single fire, or two fires in successive years, failed to increase the yield of black spear grass unless the treatment area was destocked post-fire. The combination of burning and destocking increased the contribution of black spear grass in the pasture at the expense of wiregrasses. The recommendation stemming from this research was to combine late dry season fires in successive years with a rest from grazing over summer. Campbell (1995) showed that burning can promote recruitment of seedlings of black spear grass but be detrimental to wiregrasses. In a long unburnt system, after three annual burns spear grass had the greatest and increasing basal area, while the basal area of wiregrasses had declined. A partial explanation for this trend was that black spear grass had a seed burial mechanism so the seeds were protected from fire whereas wiregrass was less well adapted in this regard and much of its seed remained on the soil surface during fire and was killed. This is consistent with our knowledge of the general ecology of this species (Grice and McIntyre 1995). Campbell (1995) also demonstrated that fire, through the effects of smoke and heat, stimulated dormant seed of spear grass to germinate. He contended that spear grass had a greatly reduced opportunity to germinate in the absence of fire. Spring burning was suggested as a practical means of restoring spear grass pastures that were degraded by abundant wiregrass.

A study by Orr and Paton (1997) examined the effects of the duration of post-burning spelling of pastures. The burning regime consisted of early wet season fires, that is, burning after the first rains of >25 mm. Pasture yields, which were influenced by both grazing and year, and the yield, frequency and seedling population of black spear grass, were greater after 4 and 6 month deferment and a half stocking rate treatment than after 0 or 2 months deferment. However, early post-fire grazing of small plants of black spear grasses led to plants of increased diameter. Although the yield of wiregrasses declined over time, the effects of treatment were not significant. This experiment did not include an unburned treatment for comparison.

These results are backed by those of Orr *et al.* (1997). In their study, burning and grazing both influenced pasture composition. Burning increased the yield of black spear grasses under exclosure but not under grazing. However, seedling recruitment, plant density and basal area of black spear grasses were similar under grazing and exclosure. Burning reduced the occurrence of wiregrasses. The main mechanism whereby fire influenced black spear grass was through enhanced recruitment: seedlings grew more quickly in burned compared with unburned treatments, arguably because they emerged earlier on burned plots. Burning probably reduced the number and size of segments of wiregrass plants rather than causing death of whole plants. At least two successive fires are necessary to substantially increase the proportion of black spear grass whereas three successive fires may be necessary to reduce the density of wiregrass. Less frequent fires may be sufficient to maintain black spear grass. Reduced stocking rates may reduce the risk that wiregrass populations will increase and also increase the likelihood of fires for manipulating species composition.

The species in the genus *Aristida* have a range of ecological responses and grouping them all together can make recommendations inaccurate (McIntyre and Filet 1996). Spring burning and reduced grazing pressure had no marked effect on the density of black spear grass or wire grasses at Glenwood (Orr 2004) in contrast to the positive results from this strategy at Brian Pastures (Orr *et al.* 1997). The main wire grass species were the "coarse-leaved" taxa (particularly *Aristida ramosa*) at Brian Pastures but there were a number of species including "fine-leaved" types at Glenwood (McIntyre and Filet 1996).

Phelps (1999) concluded that, in Mitchell grasslands, it was the combination of burning and post-fire moisture stress that was important in reducing wiregrass survival.

Dean (1996) argued that burning Mitchell grass country was not desirable because of likely impacts on seeding establishment and survival in an environment with highly variable rainfall. However, Scanlan (1980, 1983) concluded, on the basis of measurements following spring wildfires, that controlled burning may help improve areas with a low density of Mitchell grass through increased seed production and enhancement of tiller numbers.

6.4.4. Fire to control invasive woody species (Burdekin and Fitzroy)

Work in the upper Burdekin catchment and adjacent coastal areas tested the effects of burning on several species of invasive shrubs, specifically rubber vine (*Cryptostegia grandiflora*) and Indian jujube (*Ziziphus mauritiana*) (Grice 1997a), parkinsonia (*Parkinsonia aculeata*) (Grice *et al.* 2004), bellyache bush (*Jatropha gossypiifolia*) (Bebawi and Campbell 2002) and mesquite (*Prosopis pallida)* (Campbell and Setter 1999).

Mid-late dry season fires can kill significant proportions of individuals of rubber vine and parkinsonia (Grice 1997a) even with fuel loads under 2000 kg/ha (Radford *et al.* 2008). However, a regime of multiple fires is necessary to achieve effective control (Grice 1997b). Further work included tests of the effects of burning on non-target components of the riparian elements of Burdekin landscapes (Radford *et al.* 2008). Cooba (*Acacia salicina*) and strap wattle (*A. holosericea*) increased in density after one fire, but declined after two wet season fires. Rubber vine was the only species that showed an unambiguous decrease in numbers after repeated wet or dry season burning. Fire appeared to reduce recruitment and increase mortality of some shrubs. Single fires resulted in increases of some woody species whereas repeated (two) fires led to decreases but had little overall floristic effect on plant communities. Overall, fire reduced density of some tree size-classes, reduced rubber vine and increased some native ruderals. Wet season burning caused less off-target damage compared with dry season burning to control rubber vine although it takes more than one fire to achieve the same result.

The unpalatable native shrub currant bush (*Carissa ovata*) has greatly increased in density in the Burdekin and Fitzroy regions. Experiments show that currant bush continued to increase in unburnt plots but not in plots burnt during the wet season (Back 1998, 2005; Grice *et al.* 2000). Two or more fires were required to maintain the currant bush at a reduced level. Fire has been historically used in the process of clearing the brigalow scrub and poplar box woodlands, minimising regrowth and establishing sown grasses (Cameron and Wildin 1976; Back *et al.* 2008).

6.4.5. "Woody thickening" in the Northern Gulf savannas

Analogous to research in the Burdekin woodlands is a limited amount of work undertaken in the Northern Gulf savannas. This explored the use of fire to manage native tree and shrub species (Grice 2008). It focused on areas in which one of two species in particular, breadfruit (*Gardenia vilhelmii*) and gutta percha (*Excoecaria parviflora*), were assessed by pastoralists to have increased to densities that were problematic. Experimental prescribed fires were of low intensity due to limited fuel loads, but these led to either substantial mortality and/or detectable shifts in population structure. The value of this work is limited by the fact that it was short-term so that results are best interpreted as responses to individual fires, or a small number of fires, rather than to longer-term fire regimes. All experimental prescribed fires were conducted in the mid-late dry season during a period when most wet seasons were drier than long-term averages.

6.4.6. Work on "woody thickening" on Cape York Peninsula

The broad-leaved paperbark tree (*Melaleuca viridiflora*) has invaded 13% of grassland sites on Cape York Peninsula and increased significantly in abundance at 46% of sites where it was recorded in 1966 (Crowley and Garnett 1998). Aerial photography showed a 10% loss of grassland between 1969 and 1988. This encroachment and woodland thickening was attributed by Crowley and Garnett (1998) to a reduction in the use of fire in the region. Woodland thickening is a conservation issue on Cape York Peninsula as it is associated with the loss of open grasslands impacting on the food source and survival of the chicks of the endangered, federally-listed golden-shouldered parrot.

Fire is relatively common on Cape York Peninsula compared with many other regions of northern Australia with 42% of a study area (Artemis Station, Central Cape York) burnt over 4 years (Crowley and Garnett 2000). A survey of land-holders indicated that fire was generally used to improve visibility for mustering, provide firebreaks to avoid too much forage being lost to wildfires, provide green pick and to control cattle movement. Burning to modify vegetation structure was regarded as of secondary importance. Most fires were lit between April and August.

Crowley *et al.* (2009) studied the impact of no fire, burning in one year and burning in two consecutive years on the population dynamics of broad-leaved paperbark over 3 years. They found that numerous suckers of broad-leaved paperbark occurred in the grass layer regardless of burning treatment. The suckers were rapidly recruited to the canopy in the absence of fire, increasing the number of individuals in the canopy/sub-canopy by 51%. Two consecutive fires decreased the number of individuals in the canopy by 24%. Population projections indicated that withholding fire for 20 years could allow a sevenfold increase in broad-leaved paperbark on ti-tree flats. Crowley *et al.* (2009) concluded that annual to triennial storm-burning should be effective at maintaining a stable, open vegetation structure of broad-leaved paperbark on Cape York Peninsula.

6.4.7. Role of fire in the ecology of invasive herbaceous plants

Non-native grasses present a number of important issues for northern Australian landscapes, including pastoral lands. Some species, at least, are a source of considerable conflict between different groups of stakeholders who have an interest in these landscapes (Grice 2004). Species that were introduced as potential forage plants are invasive, whether or not their potential as forage has been fully realised. Perhaps the most notable example of such a species is gamba grass (*Andropogon gayanus*). This species is recognised as a useful pasture grass by sections of the northern grazing industry but perceived as a problem because it is invasive and fuels high intensity fires that can alter savanna systems (Rossiter *et al.* 2003). The emphasis in this research has been on the processes whereby species such as gamba grass alter the grass-fire cycle in these woodlands. Mean fuel loads of gamba grass were up to four times those of native grasses, and gamba grass cures later in the dry season resulting in fires of higher intensity compared with those fuelled by native grasses (Rossiter *et al.* 2003).

The case has been made that buffel grass (*Cenchrus ciliaris*) also contributes to altered fire regimes with negative consequences for native species (Butler and Fairfax 2003). These impacts mainly involve buffel grass carrying fires into remnants of intact brigalow woodlands.

Bray (2004) and Vogler (2002) studied the impact of fire on the exotic pasture weed giant rats tail grass (*Sporobolus pyramidalis*) at three sites in coastal and sub-coastal Queensland. They found that a fire event could reduce the soil seed-bank near the soil surface by a variable 10-90%.

However, a significant soil seed-bank remained (>600 seeds/m^2). Fire had no impact on the number of tussocks. Bray (2004) found a strong interaction between fire and the amount of rainfall on the establishment of seedlings. A fire event in below-average or average rainfall years resulted in few giant rats tail grass seedlings establishing. However, a fire followed by an above-average rainfall season resulted in the establishment of a large number of seedlings (>400 seedlings/m^2), while few seedlings (1-19 seedlings/m^2) established in unburnt plots.

Vogler (pers. com.) is currently assessing the impact of fire in the ecology of grader grass (*Themeda quadrivalvis*), an exotic annual grass that is invading large areas of the Burdekin woodlands and southern Cape York Peninsula. Preliminary findings indicate that burning soon after seed set can reduce the amount of grader grass in the following season.

6.4.8. Fire regimes in an ungrazed, mesic savanna in north Queensland

A PhD project conducted at Cape Cleveland, near Townsville, focused on the biology and ecology of the ground stratum of the vegetation in woodlands dominated by Clarkson's bloodwood (*Corymbia clarksoniana*), Morton Bay ash (*C. tessellaris*) and poplar gum (*Eucalyptus platyphylla*) with giantl spear grass (*Heteropogon triticeus*), kangaroo grass (*Themeda triandra*) and black spear grass prominent in the understorey (Williams *et al.* 2003a, 2003b, 2005a, 2005b). Most seedlings emerged after rains at the start of the wet season and seedling emergence was enhanced by both burning and manual removal of herbage. Burning in the early dry season promoted similar seedling densities to cutting in either season. Burning enhanced germination and emergence of seedlings of one of the dominant grasses, tall spear grass (Williams *et al.* 2005b), and this species declined in the absence of fire (Williams *et al*. 2003a).

In these communities, the germinable seed-bank was dominated by grasses and forbs at densities ranging from 58-792 seeds/m^2 with 53 spp. represented. Native perennial grasses were poorly represented in the seed-bank and there were very few seeds of trees or shrubs. Germinable seed-banks were greatest in the late wet season. Recent fire history affected seed-banks by releasing seeds from dormancy, reducing seed-banks of sub-shrubs and non-grass monocots, and increasing seed-density of hairy indigo (*Indigofera hirsuta*). Seed-banks recovered well in the year following burning. Late dry season fires, through some combination of heat shock and smoke effects, broke dormancy of a number of species (Williams *et al.* 2003b).

Early and late dry season fires produce elevated temperatures in the top soil that are sufficient to promote germination of some species. Elevated temperatures penetrated 30 mm into the soil during late dry season fires but only 10 mm into the soil during early dry season fires. The legumes *Galactia tenuiflora* and hairy indigo germinated from greater depths following late versus early fires. This resulted in higher densities of these species after late dry season fires compared with early dry season fires (Williams *et al.* 2005a).

Species richness was around 30-40 species per 100 m^2 and similar to that of savannas of the Northern Territory (Williams *et al.* 2003a). Fire regimes did not significantly affect species richness at the 100 m^2 scale but it did at the 1 m^2 scale, with richness being lowest in unburnt control plots, intermediate in plots burnt in the early dry season and greatest in plots burnt in the late dry. Differences disappeared by two years. Grasses, twining perennial forbs and ephemeral forbs increased after fire but had declined by two years post-fire. Late dry season fires increased the abundance of exotic plant species. Woodland trees and shrubs and sub-shrubs as a group showed no response to fire regime but coffee bush (*Breynia oblongifolia*), stinking passion fruit (*Passiflora foetida*), *Galactia tenuifolia* and hairy indigo increased. This study pointed to some differences between these north-east Queensland woodlands and those that were the focus of the Kapalga study (see Section 6.4.1, above). In the north-east coastal Queensland woodlands, the total density of trees >2 m high increased in the absence of fire but there was no evidence that fire intensity influenced the release of saplings from suppression through competition from established trees.

6.4.9. Effects of burning on pasture yield and animal performance

Three studies focused on fire in relation to pasture yield, forage quality and animal performance. One was conducted in the Burdekin woodlands, one in the Burnett region of south-east Queensland and one in the Pilbara region of Western Australia. In the Burnett region, the live-weight gain of steers was monitored for 9 months following spring burning of native black spear grass pasture (Ash *et al.* 1982). In the three months following the fire, the live-weight gain of the steers grazing burnt pasture was significantly greater than that of steers grazing unburnt pasture (0.59 vs. 0.20 kg/day). This was associated with higher nitrogen content and green leaf production of the burnt pasture. In the period 4-6 months after burning the steers grazing the unburnt pasture recorded higher weight gains (0.77 vs. 0.58 kg/day). After 9 months the steers grazing the burnt pasture were 8kg heavier. Four months after burning there was little difference in the quality of the pasture as measured by nitrogen concentration. The lower pasture yield and early flowering of the burnt pasture probably prevented further live-weight gains of the steers grazing burnt pasture.

A study carried out at Swan's Lagoon in the lower Burdekin region of north Queensland explored whether early wet season burning increasing animal production (McLennan *et al.* 1986). It measured pasture availability and steer live-weight gains in pastures dominated by black spear grass, comparing five burning treatments grazed at 3 ha/beast. Yields in annually early burn plots were 8% lower than those of unburnt burn plots. Live-weight gains were "slightly but not significantly" greater in the wet season following burning. The assessment of this research was that burning in the early wet is not of great benefit and brings with it a considerable risk if a poor wet season leads to a feed shortage in the subsequent dry season. The authors argue that it would be better to retain the "moribund" material as a "drought reserve" and utilise it with nitrogen supplements.

Research in the Pilbara region examined the effects of burning on the yield and nutrient levels of good condition pastures dominated by kangaroo grass (Bennett *et al.* 2002). Nitrogen and phosphorus levels were higher in burnt than in unburnt areas four months after burning, but similar after the first post-burning wet season. Burning gave no benefit in terms of productivity and forage quality with lower total biomass in burnt compared with unburned areas for three years post-fire. It was predicted that it would take 4-5 years for litter levels and total standing herbage to recover from burning.

Another documented example where burning can significantly impact animal performance is from the Wambiana grazing trial where poor follow-up rainfall after burning resulted in a prolonged period of little pasture recovery so that cattle had to be removed and agisted elsewhere (O'Reagain *et al.* 2007).

6.4.10. Remote sensing to document broad-scale fire regimes

Considerable effort has been put into describing the fire regimes of northern Australia. In order to do this on the broadest of scales, remote sensing techniques have been developed and applied to identify both current 'hotspots' (mapping existing fires in real time) and fire scars. Both temporal and spatial patterns of fire occurrence have been described using these technologies.

6.4.11. Fire issues in the Kimberley region of Western Australia

The literature contains few reports of scientific research on fire in the Kimberley region of northern Western Australia. However, some review work has been done considering the implications of research undertaken elsewhere for the region. On the basis of his review, Craig (1999) recommended a regime of late dry season burning with an inter-fire interval of 3-6 years in spinifex (*Triodia* spp.) country of the low rainfall zone. He argued that these fires should take place just before or just after the first rains of the wet season. He also made the point that post-fire grazing pressure is a key consideration in this environment and that it is preferable to follow a fire with a rest from grazing during the ensuing wet season. Early dry season fires can be used to create fire-breaks in preparation for the more intense fires of the late dry season. However, in this region, fuel is often discontinuous, requiring wind speeds above a threshold in order for fires to carry.

6.4.12. Research on fire in semi-arid woodlands

The considerable body of fire research conducted in the semi-arid woodlands of western New South Wales is relevant to mulga (*Acacia aneura*) and eucalypt (e.g. poplar box, *Eucalyptus populnea*) woodlands of south-western Queensland, including at least some parts of the Maranoa-Balonne region. Fire research in western NSW focused on the effects of fire on native trees and shrubs that contribute to the so-called "woody weed" problems of grazed rangelands of this region (Noble 1997). Shrub species vary greatly in their responses to burning though most species are relatively fire susceptible in the early stages of growth (Hodgkinson 1979, Hodgkinson and Griffin 1982). Low fuel loads are a critical factor restricting the using of fire in many landscapes of the region due to a combination of historical and current livestock grazing regimes and low and erratic rainfall (Noble and Grice 2002). Hodgkinson and Harrington (1985) put the case for prescribed burning as a means of managing shrub populations in these environments. Appropriate alignment of grazing regimes and fire regimes is critical for prescribed burning to be effective.

6.4.13. Role of fire in the management of sown pasture species

Historically, fire has played an important role in the establishment of buffel grass and other sown pastures, creating an ash bed into which the seeds were sown following the clearing of brigalow forest in central and southern Queensland (Cameron and Wildin 1976). Fire has also been used in the establishment of stylos in the northern Territory (Stocker and Sturtz 1966) and prior to surface broadcasting or aerial seeding of legumes over large areas or in hilly terrain in Queensland (Shaw and Ticknell 1993; Cook *et al.* 1993). However, surface broadcasting results in generally unreliable establishment, largely because of root competition from existing plants (Cook 1984).

The widespread establishment of stylos (*Stylosanthes* spp.) in native pasture systems has enabled the stocking rate to increase while still maintaining individual animal production. An unintended consequence has been the overgrazing and degradation of the perennial grass tussocks and subsequent dominance of the pasture by stylos. Stylo dominance is undesirable due to reduction in ground cover, reliance on a single species that could be wiped out by disease and possible soil acidification due to nitrogen fixation. Fire has been used to control increasing Seca stylo dominance in central Queensland, although uncertainty exists over when and how often to burn (McIvor *et al.* 1996; Orr pers. com.).

6.5. Principles for using fire in northern pastoral lands

Research clearly indicates that fire is a key driver of northern Australian ecosystems, including those used for pastoralism. It strongly influences structure and composition of each stratum of the vegetation as well as the interactions between those strata. An overall implication of research on the "fire ecology" of a range of northern systems and, more directly on responses to particular prescribed fires, is that fire has value as a management tool for pastoral systems. However, both individual fires and fire regimes must be tailored to particular purposes. An overall principle relating to the use of fire in northern Australian pastoral lands is:

Principle 4. Devise and apply fire regimes that enhance grazing land condition and animal productivity whilst minimising undesirable impacts

Conclusions from the discussion above lead to four general guidelines for the use of fire to manipulate the composition and structure of woody and herbaceous vegetation on pastoral lands in northern Australia.

6.5.1. Managing woody species

Arguably the primary issue of pastoral land management that might be addressed using a prescribed burning regime is the management of woody plants. This being the case it is critical to recognise that the use of fire as a tool must be integrated into the overall management system of pastoral properties (see Section 6.5.4 Relationship between fire and grazing). In pastoral lands, the use of fire in relation to woody species is mainly to reduce the abundance of woody species but fire can also be used to promote certain woody species under some circumstances.

The density of the woody components of the vegetation is important to successful pastoralism because generally grass production declines with increasing tree basal area (Figure 6.6; Scanlan 2002). Individuals of some woody species can be killed by fire though there is much inter-specific variation in the proportion of plant killed. Inter-specific differences in the responses of trees and shrubs to individual fires and fire regimes mean that composition of the vegetation can be manipulated using fire. The literature gives some indication of how particular species and vegetation types respond to different types and frequencies of burning. Application of this principle depends on the availability of adequate fuel which, in most land types of northern Australian pastoral areas consists predominantly of grass material with varying amounts of tree and shrub litter. Most fires in these systems are, therefore, ground fires, rather than the canopy fires common in many vegetation types in southern Australia.

Some types of fire are more effective that others at reducing the density of the shrubby stratum of northern Australian vegetation types. Managing the shrub stratum with fire does not require that target species are killed by fire – topkill can be useful in at least some circumstances. In these cases, fire is used to alter the structure of shrub populations without necessarily killing a large proportion of individuals. Again, the use of fire for this purpose depends on the availability of adequate grass fuel.

Fire has been used to promote certain woody species. However it is generally recommended that burning is not used to promote recruitment and seedling growth in the valuable forestry species such as spotted gum and ironbark in sub-coastal Queensland (Debuse and Lewis 2007). Fire reduces seed production, increases seed predation by ants, reduces availability of microsites and reduces seedling survival of Darwin woollybutt in the monsoonal region of the Northern Territory (Kakadu National Park) (Setterfield 2002).

As a general rule, mid-late dry season fires of moderate to high intensity are most likely to be effective in regulating the density and biomass of woody plants. Somewhat lower intensity fires may be effective against species that are more fire-susceptible or where the tree and shrub population consists of a large proportion of very small individuals.

Repeated burning will often, perhaps usually, be necessary to keep populations of trees and shrubs in check. Repeated burning can be used to address at least two phenomena.

First, fire can promote the germination of some woody species that maintain soil seed-banks, many *Acacia* spp. falling into this functional group. Large populations of seedlings can emerge following a single fire event because the heat of the fire breaks seed dormancy and so synchronises germination of a large proportion of the seed-bank. Species that exhibit these demographic characteristics tend to be relatively fire susceptible which means that a second prescribed fire conducted before plants reach reproductive size should greatly reduce their populations. One risk associated with this strategy is that the accumulation of grass biomass after an initial fire is inadequate to fuel a second fire before the plants that germinated after the first fire reach a fire resistant size class and/or are able to reproduce. This risk is less likely to be realised in well managed grazing systems that maintain good populations of perennial tussock grasses. Trying to manage woody plants with fire in areas currently with high tree basal area can be difficult, as pasture production is already greatly suppressed. The rate of accumulation of herbaceous biomass post-fire will be strongly influenced by land type, climatic zone and seasonal conditions.

Second, many northern Australian plant communities include woody species whose individuals are relatively resilient to fire, that is, a large proportion of individuals survive being burnt and replace their canopies relatively quickly. A regime of burning appropriate for the management of these systems may need to involve relatively frequent burning but there must be a suitable trade-off between fire frequency, fire intensity and short-term pastoral production. Depending upon the species composition of the woody species, and their density and population structure, a regime of a fire every three to five years may be appropriate. Particularly for the many systems whose "fire ecology" has not been the subject of research, considering local knowledge and taking an adaptive management approach are advisable.

Fuel loads are a critical issue. For individual fires whose purpose is to help reduce populations/biomass of woody species, the research literature suggests that a minimum fuel load for an effective prescribed fire is around 2000 kg/ha. 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 atmospheric temperature is higher, relative humidity is lower and wind speed is greater. A prescribed fire will also be more effective when the fuel load has good spatial continuity. It is especially important when attempting to use fire to manage woody plants that fuel/forage is not wasted by burning when the time (year, season and daily conditions) is not appropriate.

Guideline 4.1. 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-late dry season fires of moderate to high intensity are most likely to be effective in regulating the density and biomass of woody plants. Fuel loads are a critical issue - to reduce populations/biomass of woody species, a minimum fuel load of 2000 kg/ha is suggested.

6.5.2. Managing herbaceous species

Fire can be used to manipulate herbaceous species composition by killing plants, influencing recruitment or altering grazing preferences. It is important to know how different species respond to individual fires and to particular fire regimes. Post-fire spelling/grazing may be critical to maximising any benefits of using fire. Land type and soil type affect outcomes via species composition and land condition will influence capacity for effective fires. There maybe insufficient desirable plants to get a readily detectable positive response in the short- to medium-term. Property size will affect capacity to use prescribed fire by limiting capacity to impose grazing regimes that allow for the accumulation of adequate fuel, thus reducing the window of opportunity for burning.

The manipulation for which there is greatest support in the scientific literature is the control of wiregrasses in Mitchell grasslands and black spear grass pastures. Late dry season fires in successive years appear to be useful in reducing the contribution of wiregrass to the herbaceous layer. Perhaps as important as any inhibitory effects of burning on the abundance of wiregrass is the promotion of species that might replace it. The prime candidate in the systems that have been studied is black spear grass. It benefits from fire because its germination is greater on the open ground that is created by burning. Burning in Mitchell grass is more contentious and at this point in time there is scant scientific evidence to support other specific manipulations of the herbaceous layer to improve its value to the grazing industry. Resting after the burn is often required to gain the greatest benefits as grazing the newly burnt pasture can negate the positive benefits from fire on desirable pasture species.

Guideline 4.2. Use fire to change the composition of the herbaceous layer by killing plants, influencing recruitment or altering grazing preferences. Most research concerns the control of wire grasses in Mitchell grasslands and black spear grass pastures where fire is sometimes (e.g. coarse wire grasses in the Burnett region) but not always effective.

6.5.3. Managing grazing patterns

Grazing pressure tends to be unevenly distributed across paddocks. On some land types, grazing can be concentrated on a small proportion of a paddock. This heterogeneity can involve a positive feed-back such that livestock (or native herbivores) preferentially graze areas where previous grazing and trampling have removed lower quality forage and made higher quality forage more accessible. This uneven grazing pattern within paddocks generates areas of over- and under-utilisation. Pasture resting and infrastructure (e.g. fencing) should be considered in the first instance to manage grazing pressure on the over-utilised areas and encouraging the use of under-utilised areas (see Chapters 4 and 5). Fire can be used to encourage grazing animals to use under-utilised areas by temporarily improving their attractiveness to animals (Andrew 1986a; Dyer *et al.* 2003; Letnic 2004) and possibly at the same time providing some rest to the non-burnt areas. The timing, intensity and frequency of burning are important and grazing management in relation to burning is critical.

Care however is required to ensure the desired outcome is achieved and the significant risks are minimised. Scientific evidence that demonstrates the success of this strategy is limited and restricted to experimental conditions in the monsoon tallgrass region in the Northern Territory (Andrew 1986a). One problem with using fire to change grazing patterns is that animals do not graze exclusively on the burnt areas (Dyer *et al*. 2003) so there will be some grazing (and possibly continuing deterioration) on the non-burnt (over-utilised) areas. Where only small areas are burnt the concentration of grazing on this small area may, on balance, have an overall negative impact, especially if the following season is poor.

Fire intensity to remove ungrazed patches need not be high, although the fire needs to be able to carry across grazed patches. Consideration should also be given to burning for other purposes (e.g. woody plant control) at the same time which may require a more intense fire regime.

Guideline 4.3. Use fire to change grazing patterns by temporarily improving the attractiveness of previously ungrazed areas and providing rest to previously grazed areas.

6.5.4. Relationship between fire and grazing

The application of fire in pastoral land management requires careful consideration of the links between grazing and fire regimes. Both the pre-fire and post-fire grazing regimes are important, the former because it influences fuel accumulation, and the latter because it affects post-fire recovery of pastures.

Destocking in the pre-fire period will facilitate the accumulation of the fuel. It is not possible to be prescriptive about the length of a rest period that is necessary to attain particular biomass levels. The period of rest required will be influenced by the condition of the pastures and seasonal conditions. In particularly favourable seasons adequate fuel may be accumulated without rest period.

Post-fire recovery will also be facilitated by resting of pastures. There is evidence to recommend destocking a burned area for a full wet season after the fire although in very good seasons shorter periods of spelling (6 - 8 weeks) may be sufficient to allow recovery. Attempting to recover the costs of imposing a fire regime by grazing ‘green pick’ does not produce a reliable increase in animal production, increases the risks of feed shortage later in the season, and can damage reshooting perennial grasses. A useful rule of thumb may be rest burnt areas until palatable, perennial grasses have set seed.

7. Technical guide for grazing management in northern Australia

In this chapter, the research results, and the principles and guidelines that were derived from them in earlier chapters, are applied to some general issues of grazing management in northern Australia.

The principles and guidelines are shown in Table 7.1.

Table 7.1. Principles and guidelines for grazing management.

Principle 1. Use fences (paddocks) and water points to manipulate grazing distribution
Guideline 1.1. 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 about 3-4 km** **to strike a balance between improving 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.** **Guideline 1.2. Smaller paddocks and additional water points do not overcome uneven utilisation by cattle at the plant community or patch scales. Other methods (e.g. fire, careful selection of water point locations) are needed to improve evenness of utilisation at these scales.** **Guideline 1.3. 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 better grazing distribution.** **Guideline 1.4. 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.**
Principle 2. Managing stocking rates is vital to meeting animal production and land condition goals

Guideline 2.1. 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 2.2. Regularly assess the need to adjust stocking rates in relation to current and anticipated feed supply and feed quality. Some variation in stocking rates over time is required to manage periods of below-average pasture growth. Capacity to vary numbers over time also 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.

Guideline 2.3. 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 3. Rest pastures to maintain them in good condition or to restore them from poor condition to improve pasture productivity

Guideline 3.1. Rest pastures during the growing season. As a rule of thumb commence the rest period after 38-50 mm of rain or sufficient to initiate pasture growth at the beginning of the growing season. If it is difficult to access country after rain then resting should commence before the wet season starts.

Guideline 3.2. 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 3.3. 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.

Principle 4. Devise and apply fire regimes that enhance grazing land condition and animal productivity whilst minimising undesirable impacts

Guideline 4.1. 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-late dry season fires of moderate to high intensity are most likely to be effective in regulating the density and biomass of woody plants. Fuel loads are a critical issue - to reduce populations/biomass of woody species, a minimum fuel load of 2000 kg/ha is suggested.

Guideline 4.2. Use fire to change the composition of the herbaceous layer by killing plants, influencing recruitment or altering grazing

preferences. Most research concerns the control of wire grasses in Mitchell grasslands and black spear grass pastures where fire is sometimes (e.g. coarse wire grasses in the Burnett region) but not always effective.

Guideline 4.3. Use fire to change grazing patterns by temporarily improving the attractiveness of previously ungrazed areas and providing rest to previously grazed areas.

The management of four major issues that are common in northern grazing lands is considered in this chapter:

1. Matching pasture supply to animal demand (land in generally good condition)
2. Managing pasture in poor (C) condition
3. Managing woody plant problems
4. Utilising ungrazed areas distant from water

The relationships between issues and management factors are shown in the following table and serve as the structure for this chapter.

Table 7.2. Management factors than can be used for management issues in northern grazing lands. Factors with more stars indicate a greater role in managing the issue.

Issue	**Management factor**			
	Infrast-ructure	**Stocking rate**	**Pasture rest**	**Fire**
1. Matching of pasture supply/animal demand		***	*	*
2. Poor pasture condition	(*)	***	***	*
3. Woody plant problems		*	*	***
4. Ungrazed areas distant from water	***			

7.1. Matching pasture supply to animal demand

A major challenge facing managers of grazing land in good condition (generally A/B) is how to optimally use this feed for animal production, while at the same time maintaining land condition. High stocking rates increase pasture utilisation. In good years this can increase animal production per hectare, but in poor years high stocking rates can give poor animal production and degrade pastures.

The amount of feed grown each year can vary widely due to the timing and amount of rainfall so the appropriate number of animals to utilise the feed also varies widely. In theory, it would be desirable to change animal numbers each year so that the feed demand by animals matches the feed supply from the pasture. In this way, overgrazing and subsequent pasture deterioration during periods when pasture growth is low are avoided, and animal production increases in years with high pasture growth. However, this is not simple because the feed supply is not known in advance, and there are practical limits to how much and how often animal numbers can be altered, particularly in a breeding enterprise.

7.1.1. Signs

The pastures in this scenario are generally in A and/or B condition but may have some overgrazed patches in C condition with low ground cover and some less desirable species.

Further grazing of these patches is likely to lead to the patches increasing in size and frequency, and if continued over a period of years it is likely the overall condition of the pastures will decline.

With varying climate, such pastures will change in appearance from having ample forage throughout the year in 'good' years, to having adequate feed right through the year in average seasons, to being somewhat grazed down on by the end of the dry, or winter, season in years with poor summer rain. What are the best stocking management options to ensure the risk of overgrazing in drier years remains low? And are there ways to opportunistically, or perhaps routinely, take advantage of at least some of the extra feed in those wetter years?

7.1.2. Causes

The major cause of mismatches in feed supply and demand is the temporal variability in pasture growth rates. Pasture growth rates can vary widely both between years and during years and on different parts of a property. Additionally, mixes of contrasting land types in a paddock can result in selective grazing that initiates patch formation and subsequent declines in land condition e.g. sandy loam alluvial box flats in a paddock with ironbark hills and ridges.

This is compounded by the production system of beef enterprises, in which most animals stay on the property for more than one year and, in the case of breeders, up to 10-12 years. Changing numbers within or between years will have immediate and ongoing impacts on herd structure and cash flow, as well as exposing the business to risks in the market (which also varies within and between years). Hence, beef enterprises have limited flexibility in changing cattle numbers within and between years and breeder enterprises have the least flexibility of all.

Despite this limited flexibility there is usually some variation in stock numbers on a property either within or between years. Total cattle numbers, and especially the total AEs, will vary within years as a consequence of selling animals (steers, surplus heifers, cull cows), producing calves, perhaps buying animals (bulls, heifers, stores), and due to changes in liveweight and/or physiological status of individual animals over time. For example, on a breeding property AEs may vary by 10-20% during the year.

Total AEs will vary between years due to variations in breeding rate, retention rate, selling rate, and selling time. For example, delaying sale of steers and cull heifers by just a couple of months can increase the average AEs carried in a year by 10%.

7.1.3. Management response

The questions are how best to manage stocking rates over time to reduce the chances of there being:

(1) chronic underuse of pasture, and
(2) chronic, or even periodic, overgrazing of pasture.

The appropriate management response is to improve stocking rate management supplemented by pasture spelling and the use of prescribed fire.

Although changes in growing conditions are a major cause of mismatches between feed supply and demand, they are largely outside the control of managers and the most effective management response is to adjust stocking rate i.e. the demand side of the equation.

There are two broad approaches to the management of stocking rate. The first approach is to stock at a relatively low level year-in-year-out so that the level of pasture utilisation is not excessive in any given year (or at least most years). This approach avoids overgrazing in poor years but forgoes the extra animal production that could be achieved in good years and hence may incur a financial penalty.

The second approach is to adjust animal numbers seasonally so that animal demand is less than or equal to current and/or anticipated future feed supply. This practice should minimise periods of overgrazing and feed deficit while making good use of feed in above-average years. This can result in higher overall utilisation of feed but there are major risks if animal numbers are not reduced quickly enough when pasture supply is declining – pastures may be overgrazed, animals lose condition, additional expenditure on supplements is needed, and there may be forced sales, perhaps at a loss.

Managing stocking rate is the most important management response but pasture resting can also be used to alter the pasture supply and when pasture is consumed, and fire can assist in changing grazing patterns to prevent poor condition patches from increasing.

7.1.4. Management action: Manage stocking rate to carrying capacity

Coping with variability in pasture growth is critical to land condition, animal production, financial returns and sustainability. Since stocking rate is a major driver of animal production and financial returns, and also of land condition it is important that it is matched to long-term carrying capacity for sustainability of grazing enterprises.

7.1.4.1. Evidence

There have been many experiments over more than 50 years examining stocking rate or utilisation responses.

Animal production

There is a large international and Australian literature showing animal production per head declines, and animal production per unit area increases initially to a maximum and then declines, as stocking rate is increased. Most studies with intensively managed sown pastures have shown a linear decline in animal production per head with an increase in stocking rate [Figure 7.1., Jones and Sandland (1974)] but Ash and Stafford Smith (1996) have shown that animal production in rangelands is less sensitive due to the much greater spatial and temporal variability of rangelands.

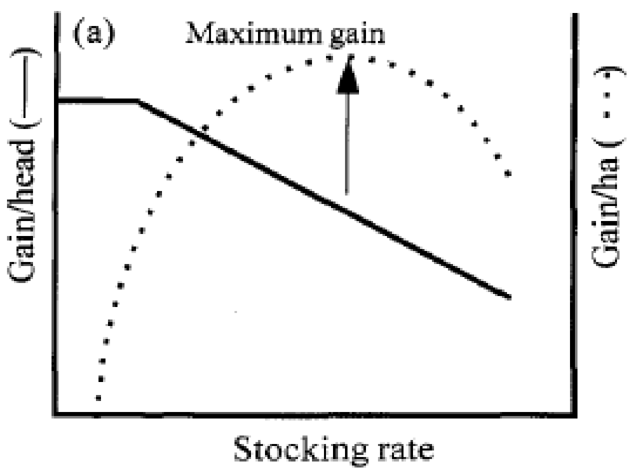

Figure 7.1. Generalised stocking rate-animal production relationships.

Several major trials in northern Australia over the past 20 years provide more local information. Table 7.3 shows how stocking rate has affected animal production.

Table 7.3. Average annual liveweight gain per hectare (kg) in relation to stocking rate for trials in northern Australia. For stocking rate, 1 = lowest stocking rate and 2, 3 , … represent progressively higher stocking rates

Trial	Years	Stocking rate					
		1	2	3	4	5	6
Kangaroo Hills	10	24	42				
Aristida-Bothriochloa - Keilambete	8	43	61	53			
Aristida-Bothriochloa - Glentulloch		37	52	59			
Glenwood	2	26	50	90	95		
Lansdown	3	35	49	46			
Galloway Plains	13	18	28	34	37	53	
Wambiana	10	14	21				
Pigeon Hole	3	13	16	19	20	27	
Mt Sanford	6	15	21	21	25	26	43

These results show that most trials have been conducted on the left hand side of Figure 7.1 with maximum animal production per hectare at the highest stocking rate for most sites. The other two trials had maximum animal production per hectare at an intermediate stocking rate. This may reflect the seasons experienced or the relative insensitivity of animal production on native pasture to stocking rate.

The values in Table 7.3 are mean values over a number of years and results from Wambiana show there can be marked year to year differences. During high rainfall years early in the trial (Years 1 to 4) LWG/ha was 27 kg at moderate stocking rate and 15 kg at low stocking rate. However, during the subsequent six years (Years 5 to 10) when rainfall was much lower, LWG/ha fell to 16 kg at moderate stocking rate and 13 kg at low stocking rate.

It can be difficult to compare results of different studies since a stocking rate of say one steer per five hectares may be light at a productive site, but heavy at a less productive site. Converting stocking rate to average utilisation levels provides a way to overcome some of these difficulties (Figure 7.2). The increase in LWG/ha as stocking rate increases, and thus utilisation increases, remains clear. The relationships for the different sites are similar although not the same. However, further analysis of the Wambiana results shows there is much variation between individual years.

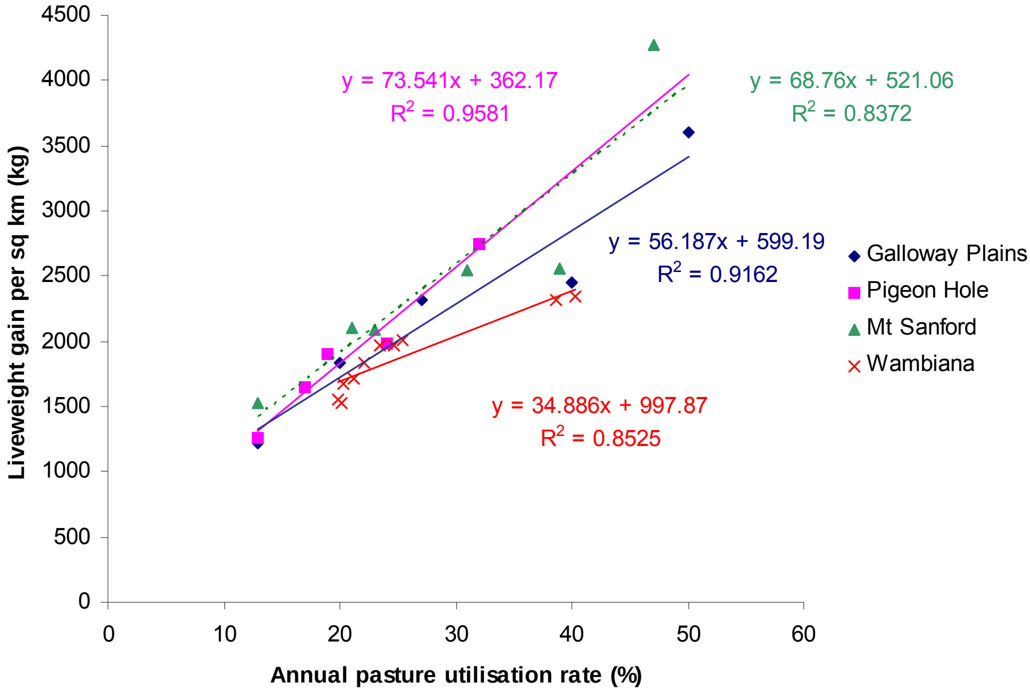

Figure 7.2. LWG/ha versus utilisation rate for four trials in northern Australia

Financial performance

Both Pigeon Hole and Galloway Plains had the best economic performance at the highest stocking rate but at Glenwood and in the *Aristida-Bothriochloa* project financial performance was best at intermediate stocking rates.

As for animal production, financial performance varies widely from year to year. This is illustrated by the Wambiana results in Table 7.4. In the early years with good growing seasons, the larger number of animals at the heavier stocking rate generated much higher gross margins than those at the lower stocking rate. However, in later years with poorer growing seasons the gross margins at the heavier stocking rate were much lower and over the ten years, the lower stocking rate had approximately twice the average gross margin of the heavier stocking rate.

Table 7.4. Gross margins ($/ha) for low and moderate stocking rates at Wambiana.

Stocking rate	Years 1-4	Years 5-10	Years 1-10
Moderate	39	-13	8
Low	23	14	17

Land condition

The general impact of increasing stocking rates on land condition is a decline in condition as shown in Figure 7.3 for the Ecograze project.

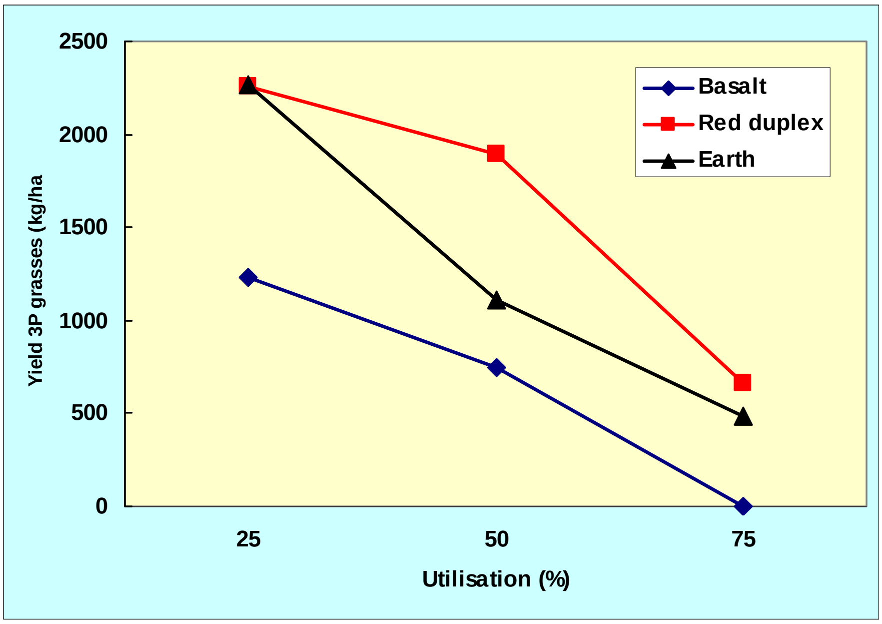

Figure 7.3. Impact of utilisation rate on the yield of 3P grasses in the final year of the Ecograze project.

The concept of safe utilisation rates has been used to estimate long-term carrying capacity. Based on research trials, simulation models and case study properties, most land types have estimated safe utilisation levels of 20-30%. Expert knowledge has been used to develop recommended safe utilisation rates for land types in the GLM program. These provide a guide to setting stocking rates but there is still a need to monitor the performance of individual paddocks to ensure the chosen rates are suitable and to ensure that, when necessary, stocking rates are reduced to cope with low rainfall years.

7.1.4.2. Conclusions

Although most experiments have only examined stocking rates where animal production per area was less than the maximum, it is possible to reach some conclusions on suitable stocking rates. These will involve a balance between high levels to increase animal production and low levels to aid maintenance of land condition (Figure 7.4). This figure shows the general relationships but the specific values for a particular situation are not known.

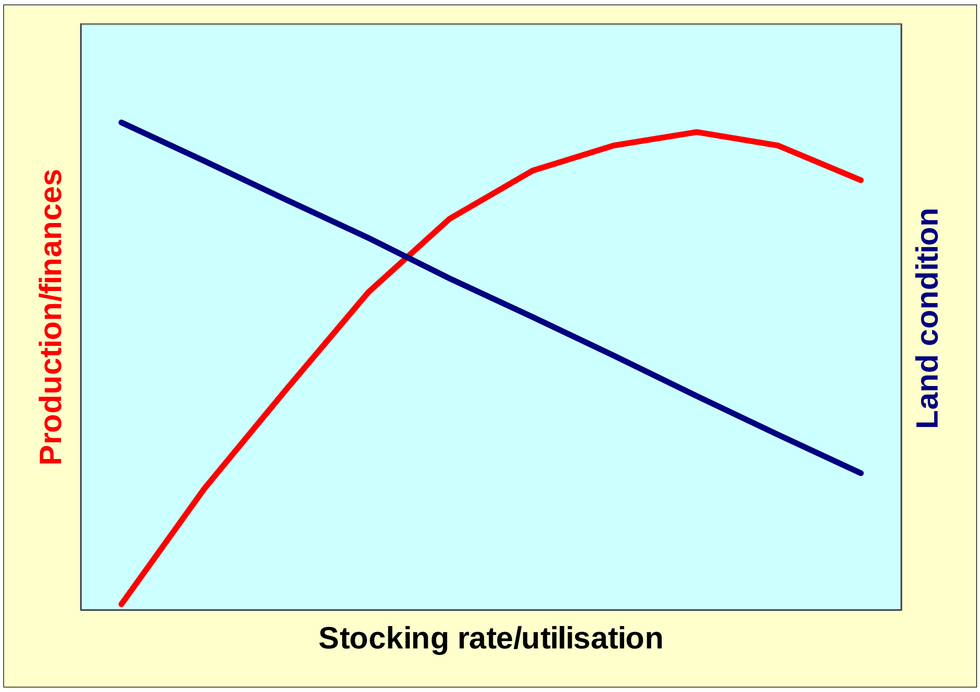

Figure 7.4. Generalised relationships between stocking rate/utilisation and animal production and financial returns (red line), and land condition (blue line). Note that the land condition line is hypothetical and the relationship between stocking rate and land condition is not necessarily linear but could take a number of forms.

The implications from grazing research for stocking rate management for profit and land condition are not consistent. This may be due to most trials running for too short a time (<10-15 years), and pasture systems having a degree of resilience to change, so that some trials did not produce much change in land condition even with their highest level of grazing pressure. In many cases the results are confounded by reduced stocking or hand feeding for periods at the high stocking rates. Several trials have shown the pasture systems to be much more productive and profitable with average rates of utilisation higher than that recommended, although this only tends to hold for trials, or periods of trial, that experienced above-average rainfall in a sequence of years. One exception is Galloway Plains where relatively heavy stocking (50% average annual utilisation) generated the most profit even during a series of below-average years and with only modest declines in pasture and soil condition.

Combining results from a number of studies, a risk-averse approach to stocking rate management has generally proven to be the most successful long-term approach for managing land condition and profitability in rangelands. A 'moderate' stocking rate generally provides the highest financial returns. At low stocking rates there are too few animals so production is low; at high stocking rates there are weight-for-age penalties or high feeding costs. There is a need to limit the amount of pasture that is eaten so that sufficient is left to provide ground cover, support soil organisms, and contribute to soil organic matter. The general trend is for land condition to decline as stocking rate increases but this did not occur in all trials reflecting the short periods of some trials, good growing seasons in others, and limited ranges of utilisation. The responses depend on seasonal conditions; there is little effect of higher stocking rates on animals and pastures in good years, so they perform better.

The Wambiana trial showed that in the long-term, constant low stocking (25% utilisation) gave the best financial returns and maintained pasture condition. Constant moderate stocking (50% utilisation) gave high returns during early wet years but not in the long term when poor seasons were experienced; it also led to poor pasture condition.

Grazing pressure from feral and native herbivores needs to be allowed for when setting stocking rates. Also, the stocking rate needs to be discounted to allow for the area of a paddock that is not accessible from water.

7.1.5. Management action: use more flexible stocking rate strategies

Stocking rates may be increased above the long-term carrying capacity in good seasons to take advantage of above average pasture growth with lower risk of harming the pasture, but prompt action is required to reduce stocking rates as pasture availability and seasonal conditions decline. It is usually the combination of high stocking rates and low pasture availability during periods of poor rainfall that results in major declines in land condition that can persist for decades. It is wise to set an upper stocking rate limit even for very good seasons to avoid excessive pasture utilisation rates.

Stocking rates should be reduced in poor years, especially during poor wet seasons (because of the sensitivity of perennial grasses to grazing at this time). Plans for a progressive reduction in stocking rates during deteriorating seasonal conditions should be developed to avoid crisis management.

Stocking rate decisions should be based on an assessment of current pasture conditions. This should consider patterns of grazing distribution within paddocks. Where they have been developed, use plant and soil indicators to inform decisions about the need to reduce stocking rates to avoid land degradation as pasture availability and seasonal conditions decline. The condition of perennial grass tussocks (such as the amount of residual biomass or stubble height) are important indicators of future plant survival and pasture productivity. Reducing stocking rates late in the wet season may allow seed production by palatable perennial grasses. Maintaining minimum levels of ground cover is important to protect the soil.

In regions where rainfall and pasture growth are particularly unpredictable a tactical approach to setting stocking rates may be useful, whereby adjustments are made on an ongoing basis in response to changing conditions. This approach requires the capacity for a considerable degree of flexibility in stock numbers, but it can allow for best use of forage when it is available and protection of the land when seasonal conditions are poor.

Decisions on adjusting stocking rates should be made at least twice a year (at the start and end of the dry season). Where it is feasible, reducing stocking rates during the wet season if rains are poor can help protect pasture condition.

Seasonal forecasts can be used in areas where they have good reliability to aid in making stocking rate decisions for the coming wet season. However, remember the limitations of seasonal forecasts and be prepared to adjust for different conditions. Estimates of expected pasture production based on historical records can be used where seasonal forecasts are not reliable.

7.1.5.1. Evidence

Most experiments used either set (fixed stocking rate) or variable (fixed utilisation) stocking rates and only the Pigeon Hole and Wambiana projects compared the two approaches.

There was little difference between the two approaches at Pigeon Hole. There was only a small financial benefit (a return on invested capital of. 8.7% versus 8.1%) and no benefit for land condition and pastures (although this may reflect the short duration of the trial).

At Wambiana, animal numbers were changed each year at the end of the growing season. The variable stocking rate strategy did not produce any better financial return than simply set stocking and there was a high risk (both financial and ecological) in the transition between good and poor years.

7.1.5.2. Conclusions

Varying stocking rates can provide an economic benefit in good years but increases ecological and financial risks. The Wambiana results showed there was potential to make more money through taking advantage of a run of better than average seasons. However, there was no indication of how the approach would work when above-average years occur in isolation.

Forage budgeting is an approach to matching short-term animal demand (less than one year) to current (and anticipated) forage supply. A forage budget can be developed at the start of each dry season that allows for adequate pasture residue (800-1000 kg/ha, 40-70% ground cover depending on the region) at the start of the next wet season and for the possibility of a poor wet season.

7.1.6. Management action: implement pasture resting

Resting pastures can both increase the amount of pasture grown and reduce the amount consumed. This can increase the total feed supply or defer when it is consumed. Pasture resting also has a role to play in maintaining and restoring pasture condition.

7.1.6.1. Evidence

While there has been considerable research on using pasture resting to improve land condition (see Chapter 5 and Section 7.2), there has been little study of the effects of pasture resting on land in good condition. One of the few studies was the Ecograze project where resting paddocks in the early growing season each year for 8 weeks combined with 50% utilisation gave similar pasture performance to 25% utilisation without pasture rest. Both these treatments maintained land in good condition.

Pasture resting during the early growing season avoids the grazing of regrowing perennial grasses when there are most sensitive to defoliation. By allowing patches to grow without continual re-grazing, they become more like the remainder of the pasture and animals are less likely to return to these patches (especially if resting is combined with fire).

A general conclusion from South African studies was that pastures in good condition should be rested one year in four (and more often for pastures in poor condition).

7.1.6.2. Conclusions

Where the aim is to grow more feed then resting will need to be during the growing season but if the aim is to reduce consumption then this can be any time during the year.

Although the aim of resting in this case is concerned with the amount of feed available for animals, resting may give additional benefits in terms of maintaining or improving land condition.

7.1.7. Management action: implement a prescribed fire regime

Fire can be used to influence where animals graze and encourage them to leave grazed patches and graze elsewhere.

7.1.7.1. Evidence

There is both experimental evidence (e.g. Andrew 1986a) and a lot of practical experience that animals prefer burnt areas that are regrowing to unburnt areas.

7.1.7.2. Conclusions

Fire can be used to manage the location of grazing but many factors need to be considered when planning a fire regime for a property (see Section 6.5.3).

7.2. Pasture in poor (C) condition

Section 7.1 referred to a situation where a paddock is in good overall condition but there are some patches in poorer condition and the pasture may be commencing to deteriorate. In this section we are dealing with pastures where this process has continued and the paddock is now in poor condition. Section 7.3 deals with land in poor condition due to too many woody plants.

Pastures in C condition may only produce 40-50% of the useful forage produced by pastures in good condition. The challenge for land in poor (C) condition is to both manage animal numbers to minimise periods of feed shortage, while improving land condition.

7.2.1. Signs

Most of the paddock or particular parts of the paddock (e.g. preferred land type) are in C condition. Two common scenarios are:

(a) **the amount of pasture is low; there are some 3P plants but they are small and widely spaced with low vigour**. Less desirable perennials and/or annuals are likely to be the dominant forage. Feed shortages may develop quickly in dry periods although high nutritional quality feed may be available for short periods. Ground cover is poor with deteriorating soil surface condition, with some erosion and significant loss of water through runoff.

(b) the **pasture is dominated by undesirable perennial species** such as unpalatable grasses and forbs. 3P grasses are still present in small amounts and ground cover is good.

7.2.2. Causes

The primary cause of poor land condition is usually chronic and continuing overgrazing which may be exacerbated by drought and/or intense wildfire events. Frequent and severe defoliation can have deleterious effects on both individual plants by reducing their vigour, and on soils and pastures by reducing land condition (lower cover and more bare ground, lower infiltration and more run-off, altered botanical composition, patchiness).

The 3P grasses are often selectively grazed within the pasture leading to them being weakened, resulting in their death or reduction in size and vigour. Seed production of 3P grasses may be prevented and recruitment of new 3P grass seedlings is minimal.

With the decline of 3P grasses other plants increase which have strategies to survive the grazing pressure. This may be quick growing and prolific seeding species (e.g. windmill grasses) or species with unpalatable traits (e.g. wire grasses, rattlepods) which are avoided by livestock. Unpalatable traits may include tough leaf blades and stems, chemical deterrents or physical deterrents (prickles and spines).

The two scenarios present quite different problems and the management responses will be discussed separately.

7.2.3 Management response: a) Little pasture with some 3P grasses

Major objectives in this situation are to encourage the remaining 3P grasses to increase in vigour and number in the pasture and to minimise the loss of soil and water in runoff, while still utilising the pasture for animal production. Animal performance in this scenario is likely to be good for a short period each year and poor for the majority of the year.

The most effective actions will be matching stocking rates to forage available combined with pasture resting.

The less desirable pasture species may still produce useful forage but often for short time periods before setting copious amounts of seed. This useful forage can be nutritious for short periods, although there will probably not be a large bulk. To effectively utilise this forage without causing further land degradation requires flexible grazing strategies which match stocking period and stocking rates (see Chapter 4) to this forage cycle. Care must be taken to prevent further loss of the few remaining 3P grasses and further resource degradation which is likely if the pasture is continuously stocked.

Frequent and severe defoliation can have deleterious effects on both individual plants by reducing their vigour and on soils and pastures by reducing land condition. Pasture rest targets both the health and reproduction of individual plants and the overall land condition.

Installing additional infrastructure may be useful to move stock away from preferentially overgrazed land types or to enable the application of pasture resting. Fire is unlikely to be an important action in this scenario unless a particular species is known to be significantly encouraged by fire (e.g. black spear grass growth and recruitment in the Burnett region) or to encourage grazing of rank patches. Fire can further damage the weakened pasture depending on the situation.

7.2.3.1 Evidence

Evidence relating to managing stocking rates has been presented in Section 7.1.4.1. This section presents the evidence relating to pasture resting under three headings – season of rest, duration of rest period, and number (or frequency) of rest periods.

Season of rest

Grasses are susceptible to heavy grazing when they are regrowing at the start of the growing season. This is illustrated in Table 7.5. Plots that were heavily grazed in the early growing season produced only 60% of the yield of plots that were only lightly grazed at this time. In contrast, level of utilisation during the dry season had no impact while effects of utilisation during the late growing season were intermediate.

A number of studies have shown that resting during the growing season can produce desirable pasture changes. For example, in the Ecograze trial at Charters Towers, resting for 8 weeks at the start of the growing season each year led to higher yields (and proportions in the pasture) of the 3P grasses compared to continuous grazing (Table 7.6). Yields with 50% utilisation and pasture rest were similar to those with 25% utilisation and no rest, and greater than those with 50% utilisation and no rest.

Table 7.5 Influence of season and intensity of utilisation on pasture growth in the following growing season (from Ash and McIvor 1998).

Season	Utilisation	Relative yield
Early growing season	Low	100
	Medium	82
	High	61
Late growing season	Low	100
	Medium	91
	High	68
Dry season	Low	100
	Medium	107
	High	105

Table 7.6. Yields (kg/ha) of 3P grasses on continuously grazed and rested plots in the final year of the Ecograze project for plots grazed to utilise 25 or 50% of the forage. [A]There was no treatment of 25% utilisation and pasture rest for the State I plots.

Pasture condition	Utilisation (%)	Continuous (no rest)	Rest
State I	25	2060	A
	50	1250	1730
State II	25	1910	2010
	50	600	1720

Resting during the dry season will increase the ground cover at the end of the dry season, prevent repeated grazing of regrowing shoots, and prevent the removal of aerial buds on grasses. The only trial in northern Australia comparing wet season rest and dry season rest found little impact of either (Hacker and Tunbridge 1991) and there is no experimental evidence to indicate that the dry season is a priority time for pasture rest to occur.

Duration of the rest period

Most trials have not compared different durations of rest. One of the few that did was the study by Orr and Paton (1997) where 4 and 6 months wet season rest gave a greater response – more spear grass (Table 7.7) and less wire grass – than no rest or 2 months rest. The higher yield of spear grass was also associated with higher seedling recruitment in some years. The 6 month rest treatment had double the black spear grass basal area than no rest after 4 years of rest treatment.

Table 7.7. Impact of duration of the rest period on yield of black spear grass (from Orr and Paton 1997).

Rest period (months)	Spear grass yield (kg/ha)
0	700
2	800
4	1900
6	2400

Number of rest periods

There are no experiments in northern Australia that have examined the number of rest periods needed to achieve a particular goal. However there is a body of evidence from the experiment of Orr and Paton (1997) and short-term and long-term exclosure studies that provides some guidance. An example is given in Figure 7.5 which shows how the growth of plots at Galloway Plains that had been grazed for 13 years at different stocking rates varied during 4 years of exclosure. The 4 years of exclosure improved the productivity of the previously heavy grazed treatments – yields increased from 30 to 80% of those on the previously lightly grazed treatment. The proportion of 3P grasses also increased slowly over time. The limited evidence does indicate that two or more rest periods results in a greater improvement than a single rest period; this may be linked to the time required for previously overgrazed plants to recover, set seed and for those seeds to establish and grow into new tussocks.

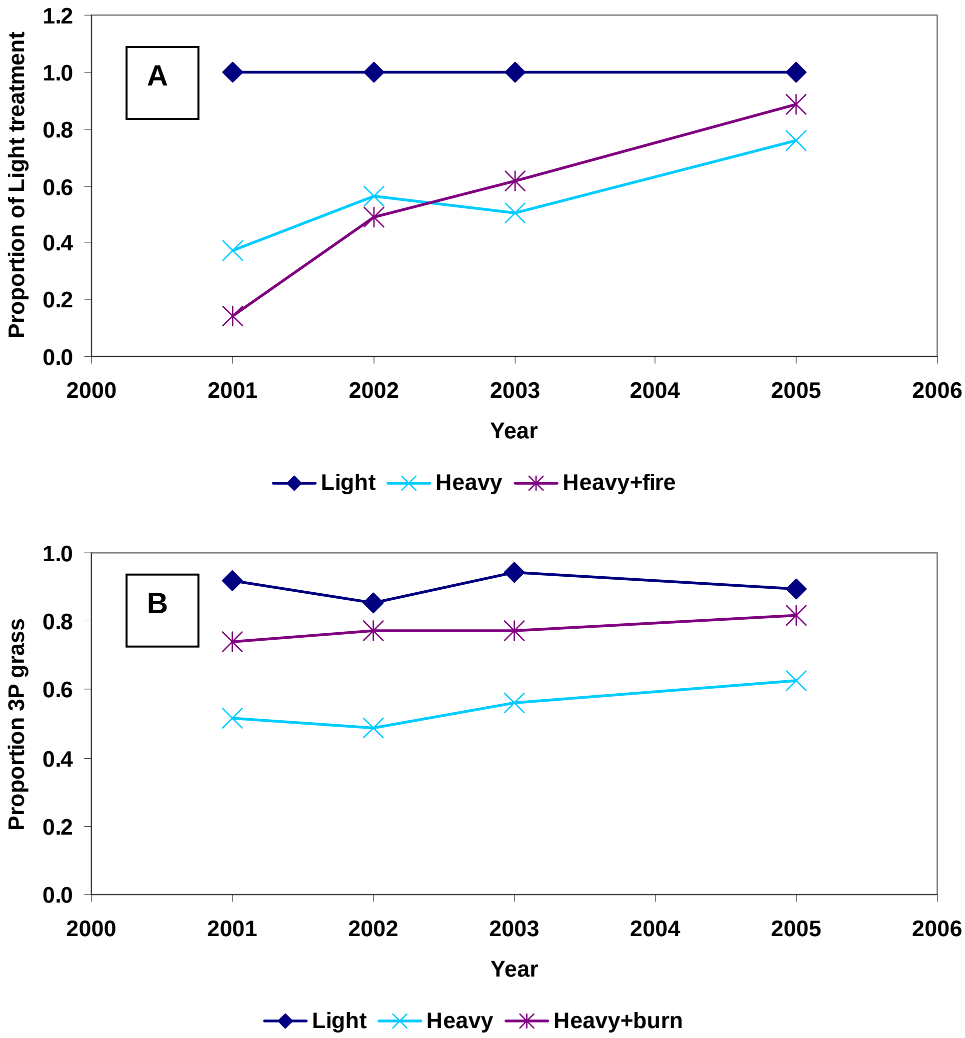

Figure 7.5. Recovery of annual pasture production (A) and proportion of 3P grasses (B) in previously Heavy stocked paddocks (2ha/animal; C/B land condition) compared to a lightly stocked treatment (5.3ha/animal; A land condition) following continuous resting (exclosure) and burning to remove old pasture after the 2001 measurement. The experiment was conducted at the Galloway Plains grazing trial. The exclosures were burnt to remove the previous years pasture growth in late 2001, 2002 and 2004 (Bray pers. com.).

Use of fire to rest areas

Fire has been used to rest parts of paddocks as animals prefer to graze recently burnt areas in preference to non-burnt areas. This will give some resting to the non-burnt areas and has been effective under experimental conditions in a tropical tallgrass pasture near Katherine (Andrew 1986a) but its effectiveness more generally or under commercial conditions is unknown. The animals do not graze exclusively on the burnt areas so there will be some grazing (and possibly continuing deterioration) on the non-burnt areas. Where only small areas are burnt the concentration of grazing on this small area may also do more harm than the benefit derived on the non-burnt area.

Fire can be used to remove old patches of dry mature herbage so that all young material is equally accessible. This can aid even grazing and prevent continued selective grazing of existing poor condition patches. However, burning removes the feed supply and if seasons are poor can lead to heavy grazing and the need for additional rest.

7.2.3.2. Conclusions

The experimental data, although limited, indicate that resting during the wet season and particularly during the early growing season when grasses are most susceptible to heavy defoliation is important for encouraging 3P grasses (see Chapter 5). Rest during the dry season may also be useful for maintaining ground cover and improving rainfall infiltration for the following growing season.

The duration of a rest period is a balance between the benefit to the pasture (greater benefits with longer rests) and the loss of grazing combined with the lower quality of the accumulated herbage (greater losses with longer rests). The benefits of a longer rest period are:

- A long period so it is more likely there will be some good growing conditions
- Rest occurs during the early growing season when grasses are particularly susceptible to grazing, and also later when they are setting seed and accumulating reserves
- Allow new seedlings to establish, grow and set seed, and existing plants to expand
- Includes a range of flowering times to cater for different species
- Allows an increase in the plant’s root reserves (mostly in the late wet season)
- Cattle do not need to be moved during the wet season

Most response to spelling seems to occur in the early part of the growing season, so the duration of rest period for poor condition pastures should be a minimum of 8 weeks from the start of effective growth. However, a full wet season rest may be more practical to manage and, perhaps, more cost-effective in some situations.

Like the duration of rest periods, the number of rest periods is a trade-off between the benefit to the pasture and the amounts of foregone grazing. There is limited experimental evidence but general agreement that as land condition declines pastures need more rest if land condition is to be improved. Responses to rest are much less in below-average rainfall years compared to average or good years, perhaps not unexpectedly, so cost-effectiveness is likely to be better in better years.

There is low confidence in predicting the rate of recovery and cost effectiveness of using resting to improve land in C-condition in many land types. However, our current “best-bet” guide is that pastures need two growing season rests to improve by one ABCD condition class. Thus for pastures in C condition, plan on taking four good growing seasons to recover to A condition. Where growing conditions are poor, more rest periods will be required.

The stocking rate used in conjunction with resting will be critical for success. If stocking rates are not matched to feed supply and ongoing overgrazing occurs, minimal gains will be made with resting. Section 7.1 describes how to match pasture supply and animal demand. Caution is required to ensure that the animals relocated during resting do not exceed the capacity of land where they are placed, potentially causing further degradation.

Success of resting depends on the presence of 3P grass plants and/or soil seed banks. Species composition recovery is likely to be very slow where there is almost a complete lack of 3P grass plants and soil seed bank. Resting is less likely to be useful in this situation as there are no desirable species to encourage, although resting may be useful to build up ground cover. Fire is unlikely to be useful in this situation due to no desirable species to encourage and lack of fuel.

Re-seeding with 3P grasses is generally not an option in most rangeland situations, however re-seeding could be considered on more productive land types where the risk of pasture establishment failure is minimised and the large financial outlay for re-seeding is rewarded through greater future productivity.

7.2.4 Management response: b) undesirable perennial species

The main objective in this situation is to reduce the undesirable species and encourage the 3P grasses to increase in the pasture.

Unpalatable perennial grasses and forbs increase due to preferential grazing of more palatable species which reduces the competitive ability of the palatable species and enables the unpalatable species to access more resources without the “costs” of being grazed.

The most effective action will depend on the undesirable species being targeted and whether or not it is sensitive to fire regimes. The undesirable species are split into three categories based on their response to management actions:

1. Sensitive to fire
2. Sensitive to grazing management and competition from other pasture species.
3. Insensitive to grazing management or fire

Local knowledge may be required to determine which category an individual species belongs in a specific region.

7.2.4.1 Evidence

Species sensitive to fire

For species sensitive to fire (e.g. some wire grasses in the Burnett region), fire can be used in combination with grazing management to manipulate herbaceous species composition by killing plants, influencing recruitment or altering grazing preferences. This is shown in Figure 7.6.

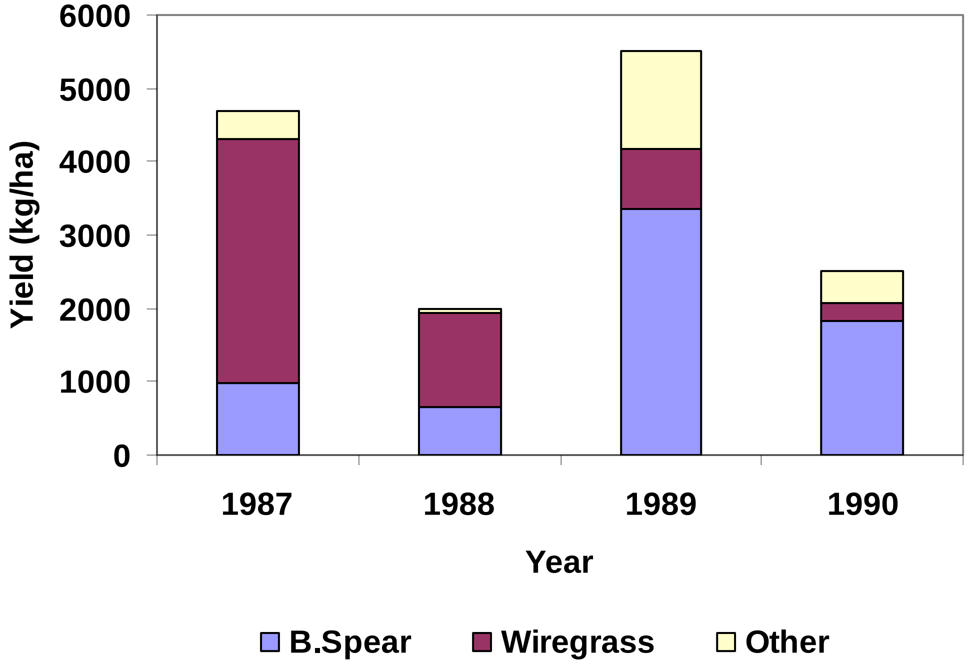

Figure 7.6. Black spear grass increases in proportion of yield and wiregrass declines as a proportion of yield under a regime of annual burning and protection from grazing (from Orr *et al.* 1991). Total yield varies with seasonal rainfall.

Species sensitive to grazing management and competition from other pasture species

Some unpalatable species can not be managed with fire but may be sensitive to grazing management through competition from 3P grasses (e.g. parthenium, blue snake weed).

Overgrazing for long periods and ongoing selective grazing reduces the vigour of 3P grasses and may allow other grasses and forbs to establish and dominate. In this situation matching stocking rates to the 3P grass forage and resting may be useful to allow the 3P grasses to recover and compete successfully with the undesirable species (see Sections 7.1).

Species insensitive to grazing management or fire

Some introduced and native undesirable species are insensitive to grazing management and fire (e.g. weedy Sporobolus grasses, African love grass, some wire grasses in some regions).

In this situation management actions are limited especially in rangeland situations. In more productive land types, herbicides and mechanical removal can be effective and profitable with some species.

The best management action in extensive lower productivity country may be to match stocking rates to palatable feed supply so the desirable species are not further overgrazed and the undesirable species are not further encouraged.

It may be desirable to take steps to prevent the spread of the undesirable species (e.g. weedy Sporobolus grasses) and even take steps to kill the weed even if uneconomic to prevent further spread.

7.2.4.2 Conclusions

The appropriate response for managing pastures dominated by undesirable perennial grasses and forbs depends on the species. For species sensitive to fire a planned fire regime may be an appropriate management response.

Local knowledge should be sought to determine the expected impact of individual fires or particular fire regimes on the specific target unpalatable species (e.g. different types of wiregrasses). Some unpalatable grass species may be encouraged by fire. The fire regime may also encourage other desirable species.

The fire regime required to manage the target species needs to consider the intensity and number of fires required for changing the composition of the herbaceous layer. Fire intensity appears to be less important than for managing woody species. However an important consideration prior to burning is to ensure there are adequate fuel loads and appropriate weather conditions to carry the fire. Land type, soil type and land condition will influence the capacity for effective fires.

Implementation of a fire regime will require planning to ensure adequate fuel is available which may mean adjusting stocking rates or resting to preserve fuel followed by conservative stocking in the post fire period to encourage the recovery of desirable pasture species. Additional infrastructure may be useful for enabling smaller areas to be burnt at one time.

Post-fire resting and setting stocking rates may be critical for maximising any benefits of using fire to manage herbaceous species. Where there are few desirable plants there may be little positive response to prescribed burning in the short- to medium-term.

Utilising fuel accumulation in above-average seasons will minimise the cost of resting prior to burning. Also, look for opportunities to address two or more ‘purposes’ with the same fire regime (e.g. manage a woody plant and an unpalatable grass). Also consider the risk of a low rainfall season and have strategies in place if the season following burning has low rainfall.

7.2.5. General considerations

A general recommendation for using rest to improve pasture condition is to have a planned but flexible regime to rest paddocks for the whole growing season commencing from the first rain event sufficient to initiate new growth (38-50 mm in three days). In effect, a resting regime is applying a number of growing season rest days over a period of years. This raises key questions about how stage of growing season, duration of rest periods, and frequency influence the effectiveness of each rest day applied. Where growing conditions are good, fewer and/or shorter rest periods will achieve a similar benefit to those obtained with longer or more frequent rests under poorer growing conditions.

7.3. Woody plant problem

In northern Australia, many different natural or semi-natural plant communities are used as pastures for the grazing of livestock, mostly cattle. Most of these grazing systems depend on vegetation that includes some woody species, both trees and shrubs. The make up of this woody component varies greatly both within and between vegetation types, in terms of the overall density and biomass of woody plants, the structure of the woody strata and their species composition.

Woody species differ in their growth form, mode of reproduction and reproductive output, mode of dispersal, recruitment patterns and longevity. They also differ in their palatability to different types of herbivores (including livestock) and their responses to different types of disturbance.

Browsing and fire, as well as other kinds of shoot damage, will influence different species, or even different individuals of a species, in different ways. Periodic, severe drought can also have a major impact on some woodland communities (Fensham and Holman 1999). All these factors make for enormous spatial variation in the woody component of northern Australian vegetation. They also contribute to temporal dynamics at various time-scales.

Although the woody components of northern Australian pastoral lands are naturally dynamic, in many areas there is concern that since pastoral settlement there has been a trend to increasing woodiness of the vegetation. This increase comes from three sources: (i) thickening of native understorey species; (ii) increased density of native upper storey species; and (iii) invasion of non-native trees, shrubs and woody vines. Different species are involved in different locations and often there are multiple species involved.

Why is the proliferation of native or non-native woody species a problem in pastoral lands? The following are the major issues, though their absolute and relative importance certainly varies from one situation to another:

- Woody plants can compete with more palatable or more nutritious forage and so reduce the carrying capacity of the vegetation
- Some woody plants are toxic to livestock
- Dense stands of woody plants can inhibit the access of livestock to water
- Dense stands of shrubs can make it difficult to find livestock in large paddocks
- Dense woody vegetation can interfere with efficient animal husbandry e.g. mustering
- Woody vegetation may provide harbour for pest animals such as feral pigs

It is also true that some species of woody plants, both native and non-native can provide both useful browse which may contribute significantly to livestock diets, and shade.

7.3.1. Signs

The relationship between woody and herbaceous plants is a critical one. In general, the biomasses of woody and herbaceous components of the vegetation are inversely related to one another: all else being equal, higher woody plant basal area is associated with lower herbaceous biomass (Figure 7.7). The size, number and distribution of woody plants can all be useful indicators of the impact that woody plants are having on the herbaceous layer. A low density of large scattered trees and shrubs is likely to have little deleterious effect on a pastoral production system and may, in fact, be beneficial. Memories of previous vegetation states (lower tree and shrub densities, for example) can be unreliable. Importantly, the change in woody plant biomass may be gradual and imperceptible so photographic records, including aerial photographs, and satellite imagery provide useful and, perhaps, more reliable information. Another important sign of current or impending problems can come from an examination of tree and shrub population structures. A large proportion of small plants (seedlings, saplings) may indicate a growing population though caution is necessary when making such interpretations. The presence of species such as rubber vine (*Cryptostegia grandiflora*), chinee apple (*Ziziphus mauritiana*), prickly acacia (*Acacia nilotica*), mesquite (*Prosopis* spp.) and parkinsonia (*Parkinsonia aculeata*), which are known invasives, indicates a threat of increasing non-native woody weeds.

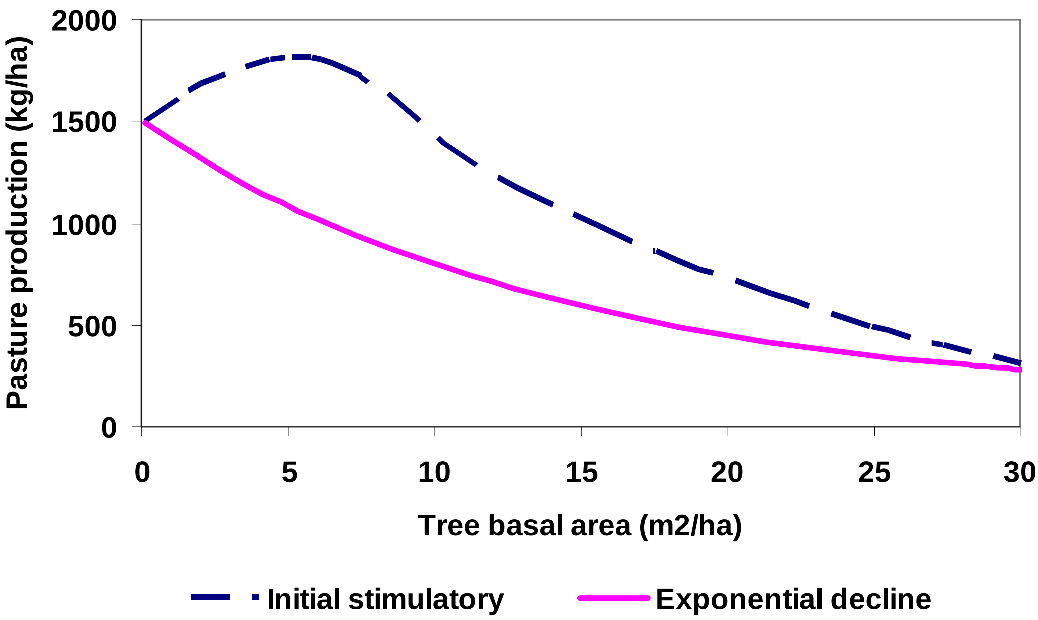

Figure 7.7. Relationship between tree basal area and pasture production (from Scanlan 2002). Some communities may show a stimulatory effect of tree cover at low tree basal area, whereas other communities compete with the pasture even at low tree basal area.

7.3.2. Causes

Many factors drive tree and shrub populations. Some of the important ones are indicated in Figure 7.8 which portrays the dynamic balance between woody and herbaceous (mainly grasses) components of the vegetation. The main drivers of the dynamic are rainfall as a promoter of germination and growth, drought as a cause of mortality, competition between grasses and woody species (for water, light and/or nutrients), grazing and browsing differentially affecting biomass and possibly survival, and fire as a remover of herbaceous biomass and a cause of top-kill and mortality of woody species. Some of these factors can be managed; some cannot. Among the factors driving observed or quantified increases in populations of woody plants are: sequences of very wet years, reduced competition from grasses due to heavy grazing, reduced frequency and/or intensity of fire because of lack of fuel or active fire suppression or, as suggested in some literature, rising CO_2 levels. The significance of these factors is likely to vary from place to place. One important relationship is that between plant size and susceptibility to fire. For many species, small plants are more susceptible to fire than large plants. This means that increasing “woodiness” associated with a lack of fire can create a positive feedback in which effective fire becomes less likely. This feedback loop is exacerbated by the negative effect of increasing woodiness on fuel loads.

7.3.3. Management response: fire and grazing

Fire and grazing/browsing are the principal manageable factors that influence the woody components of northern Australian vegetation. Critically, these two manageable factors interact with one another (Figure 7.8) as herbivores and fire, in effect, compete for herbaceous material. Prescribed burning, then, constitutes a management response to increasing woodiness of northern Australian vegetation.

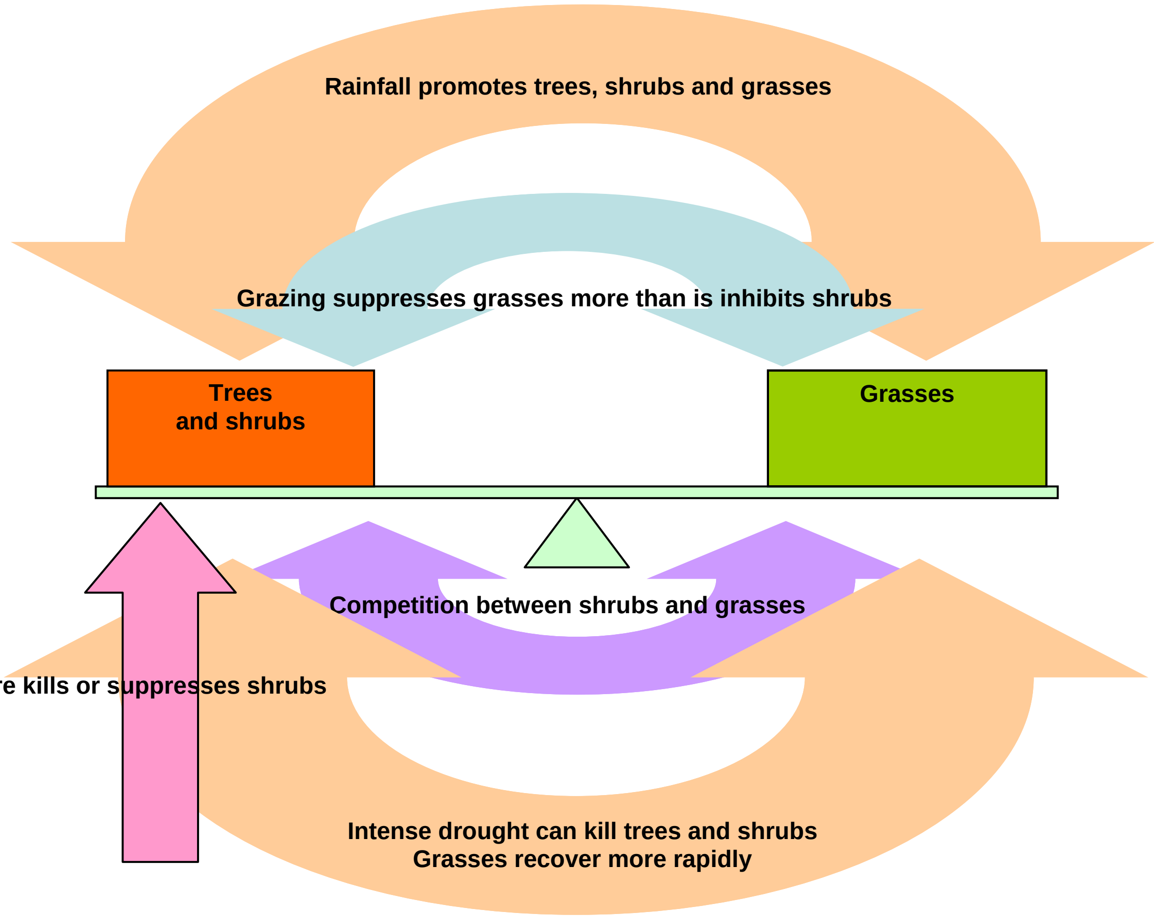

Figure 7.8. Factors affecting tree and shrub populations.

7.3.4. Management action: Use prescribed fire

If it is judged that woody plants are reaching densities, biomasses or total basal area that is deleterious, prescribed burning is one of the options open to land managers. The action would involve instituting a regime of mid-late dry season burning, the most effective regime depending on the woody species present, their density and the size class structure of their populations. More intense fires may be useful for species that are more tolerant of fire, where tree and shrub densities are high and where plants are large (Figure 7.9). Less intense fires may be suitable for fire-susceptible species or where the purpose is to reduce or suppress a cohort of recently-established (i.e. small) shrubs. Heavy grazing over long periods may facilitate an increase in woody plants by reducing the competition that woody seedlings face from palatable herbaceous perennials. It would also reduce the opportunity for conducting prescribed fires. Matching stocking rate to long-term carrying capacity increases the window of opportunity for incorporating effective fire into the management system.

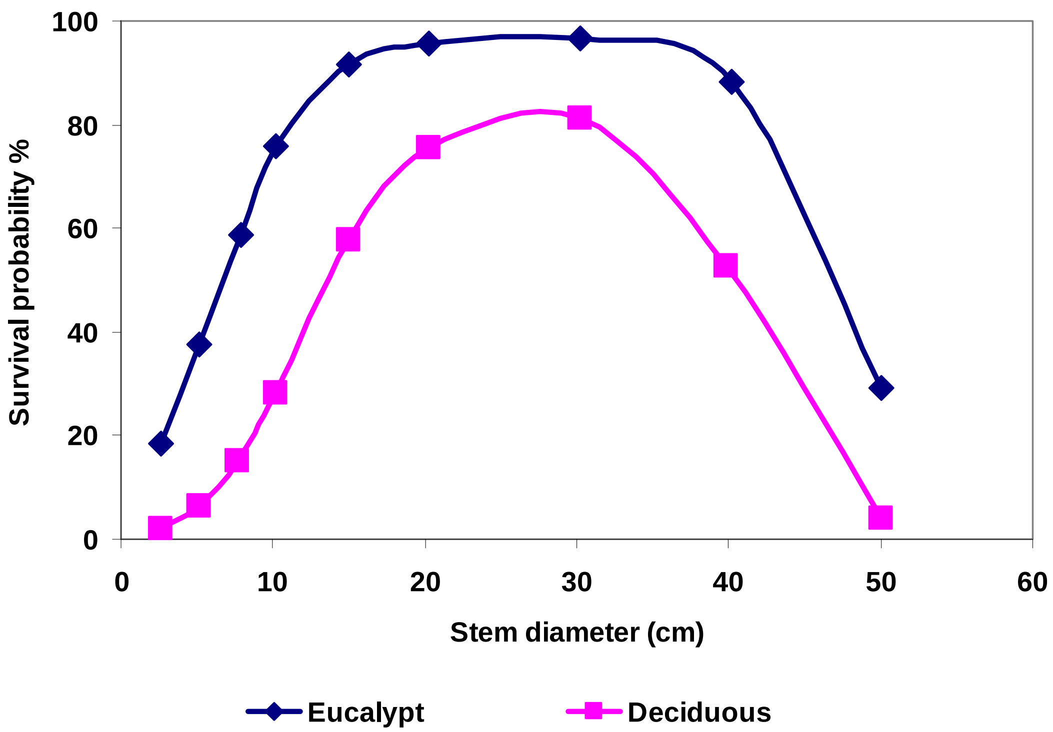

Figure 7.9. The relationship between stem diameter and the probability of surviving fire for various tree species of northern Australian savannas (from Williams *et al.* 1999).

7.3.4.1. Evidence

A lot of the fire research that has been conducted in northern Australia has focused on the ecology and management of the woody plant strata of the vegetation. This work has included research on native communities in the Top End and Victoria River District of the Northern Territory and the Northern Gulf savannas and Cape York Peninsula woodlands in Queensland, as well as on invasive woody species in the Burdekin woodlands of north-east Queensland. Research is lacking for many regions and vegetation communities.

Research at Kapalga demonstrated that a regime of late dry season fires reduced total basal area of live stems of woody plants. Overall, there was a linear decline in tree survival (stems and whole plants) with increasing fire intensity but the response varied with tree functional type. Survival was greater for eucalypts and deciduous trees and lower for palms and acacias. Deciduous non-eucalypts (*Terminalia, Erythrophleum*) were more sensitive to fire than dominant eucalypts. Work in the Top End also quantified relationships between tree size and mortality due to fire. Work in the northern Gulf region of Queensland demonstrated the potential for using fire to reduce the density and biomass of the understorey of at least some types of savanna woodland (Figure 7.10).

Figure 7.10. A fire-induced contrast in the density of the shrubby understorey of a Gulf savanna woodland. The area to the right of the road had been burnt; the area to the left of the road had not. The main understorey species at this site is breadfruit (*Gardenia vilhelmii*).

A fire regime requires the parallel implementation of a stocking strategy that allows for fuel build up before burning and for pasture recovery afterwards. For individual fires whose purpose is to help reduce populations/biomass of woody species, research suggests that a minimum fuel load for an effective prescribed fire is around 2000 kg/ha. 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 atmospheric temperature is higher, relative humidity is lower and wind speed is greater. A prescribed fire will also be more effective when the fuel load has good spatial continuity. Lower intensity, or just slower moving fires, with long residence times may actually lead to higher mortality rates in some trees and shrubs. An example of such a species may be parkinsonia (*Parkinsonia aculeata*).

Fires should be timed to suit the purpose for which they are intended rather than following a simple schedule. This will generally mean waiting for those years in which fuel loads are adequate and may involve pasture resting to accumulate sufficient fuel loads. The length of a pre-fire rest period necessary to facilitate fuel accumulation depends on seasonal forage growth. In poorer growing seasons and in lower rainfall zones a longer period of spelling would be required in order for a particular threshold of herbaceous biomass to be reached. Thus there will be great temporal and spatial variation in what constitutes appropriate pre-fire and post-fire rest periods. In highly favourable seasons, it will be possible to conduct an effective prescribed fire without a pre-fire rest period as herbaceous production will exceed off-take by livestock.

There is no established formula for deciding the most appropriate fire regime (temporal pattern of burning over a sequence of years). The fire interval should be set in response to what is happening in the woody plant populations. This is largely determined by rainfall patterns. For management of *Acacia* spp. that are reaching higher densities than desired, the aim should be to burn before the most recent cohort reaches reproductive sizes. As a general rule the aim should be to burn before the species of concern reach sizes at which they are relatively resilient to fire.

7.3.4.2. Conclusions

There is sufficient scientific evidence to conclude that fire is a useful tool for managing woody plants in at least some northern Australian pastoral systems. Significant gaps do remain in our knowledge of how fire can best be used for different purposes and in different systems. Caution should be applied in extrapolating form one system to another. It is unwise, given current knowledge, to advocate woody plant management practices that are applicable to the enormous variety of situations that exist in northern Australia. In applying prescribed burning for the control of woody plants land managers must be cognisant of any state and local regulations relating to either burning or the management of native vegetation.

With these things in mind, there are some important considerations when contemplating the use of fire to manage woody plant populations. The first is that prescribed burning comes at a cost. Costs will be associated with any resting of pastures that is required in order to build up fuel loads so that an effective fire can be achieved. Burning when fuel loads are inadequate to achieve the purpose of the fire is obviously counter-productive. Likewise, it is important that pastures are not grazed too soon after the fire. Grazing in the immediate post-fire period would hinder the recovery of desirable pasture species. In particular, it is ideal that palatable, perennial grasses are allowed to set seed in the post-fire period and this may require destocking or, at least, very low stocking densities. If pre- or post-fire destocking is necessary, forage must be available for livestock on other parts of the property or off-property or they would have to be sold. Also, fire can promote germination of some woody species, notably *Acacia* spp. It is important to monitor the area in the post-fire period in order to be able to respond appropriately to large-scale germination events. If large recruitment events are triggered by a fire, a second fire will likely be useful. Conducting a second prescribed fire before recruits set seed could reduce the build-up of seed-banks of species such as *Acacia* spp.

7.4. Ungrazed areas distant from water

In large paddocks considerable areas of ungrazed or poorly utilised palatable forage often occur, whilst areas near water often become degraded through overgrazing. This unused pasture represents livestock production that is forgone by the pastoral business. Management options that create the opportunity for cattle to use this pasture have the potential to increase returns to the livestock enterprise by allowing more cattle to be carried where paddocks are currently stocked below the carrying capacity of the land. Improvements in individual livestock production are likely to be small, but there is no evidence available to support this suggestion. If an undeveloped paddock is already stocked at the long-term carrying capacity of the land, paddock development may improve the sustainability of grazing through better grazing distribution.

Developing water point and fencing infrastructure on a property to improve grazing distribution is the primary management option to address this issue, although fire may sometimes have a role (to remove accumulations of old forage and improve grazing distribution) and resting may aid the recovery of previously overgrazed areas.

7.4.1. Signs

In large paddocks, significant areas of the paddock distant from water points that contain palatable forage receive little or no grazing and accumulate masses of ungrazed herbage. The areas near the water points that are subject to very high utilisation are also likely to be large and/or expanding quickly.

7.4.2. Causes

The problem of having ungrazed areas distant from water principally arises in large (i.e. >40-50 km^2) paddocks with few water points where animals are unable to reach the distant parts of the paddock during daily foraging activities. Cattle need to drink regularly (usually once a day) under the hot conditions experienced in northern Australia. Since there is a limit to how far they can walk between drinks they can only travel a limited distance from water to forage, meaning grazing use declines with distance from water and areas of pasture beyond the usual foraging distance from water are little used. In addition to having insufficient water points, poorly located water points (in relation to factors that influence grazing distribution such as topography, shade or favoured areas) can also contribute to this problem.

If stocking rates for a paddock are based on paddock size but there are too few water points for the size of the paddock, there will be an excessive number of cattle per water point. This will contribute to the development of large, expanding areas of overgrazed country and land degradation around water points.

7.4.3. Management response: water point and paddock infrastructure

The most important management response involves making the areas of palatable forage readily accessible to cattle (i.e. all areas are within 'easy' walking distance of water for the cattle so there is a high likelihood of grazing) by establishing more water points. Improving the control of cattle grazing distribution by reducing paddock size is also an important response. This helps minimise the extent to which large numbers of cattle congregate in favoured areas of pasture or use favoured water points. If developing new water points and reducing paddock size makes the areas of ungrazed or poorly utilised pasture available to cattle it may be possible to increase the number of stock carried (providing the long-term carrying capacity of a paddock is not exceeded). If a paddock is already stocked above its long-term carrying capacity (taking distance to water into account), installing additional water points may not allow any significant increase in the number of stock that can be carried in the paddock, but should help distribute grazing pressure more evenly within the paddock.

7.4.4. Management Action: install more water points in large paddocks

Establishing additional watering points in or near areas of unused palatable forage will increase the extent to which cattle graze those areas. It is the most important management action to implement. For the more extensive regions it is preferable that the distance from water to palatable forage should be less than 3 km, and should not exceed 4-5 km. Thus, to ensure reasonable levels of use of an entire large paddock water points should not be separated by more than about 5 to 6 km. A good rule of thumb is to allow one water point per 20-25 km^2 of land area.

7.4.4.1. Evidence

The notion that establishing more water points in ungrazed areas will increase use of those areas is self-evident. Practical experience bears this out. However, understanding the optimum number and distribution of water points to make best use of available forage and the associated response of livestock, productivity and land condition for a region can be informed by research. Most research on these issues has occurred in the more extensive regions (e.g. central Australia and the VRD). There is limited evidence from formal research studies for other regions. However, research in rangelands in the US has also demonstrated that establishing new water points in under-utilised areas can increase grazing in those areas and reduce pressure on previously frequently used areas.

Although a number of studies have reported the maximum distance cattle will walk from water to forage in northern Australia (e.g. up to 11 km on the Barkly Tableland and usually no further than 5-8 km from water in central Australia), most grazing by cattle occurs much closer to water. Grazing pressure usually declines markedly beyond about 3 km from water, although where water points are sparse cattle will use areas further from water. For example, on the Barkly Tableland (where waters were separated by as much as 10 km or more) an assessment over a number of properties showed that about 55-60% of cattle activity occurred within 3 km of water (see Figure 7.11). Although some cattle activity occurred further from water this was low, particularly at the extreme distances. It is this uneven grazing that contributes to the problem of forage not being used effectively at distant sites.

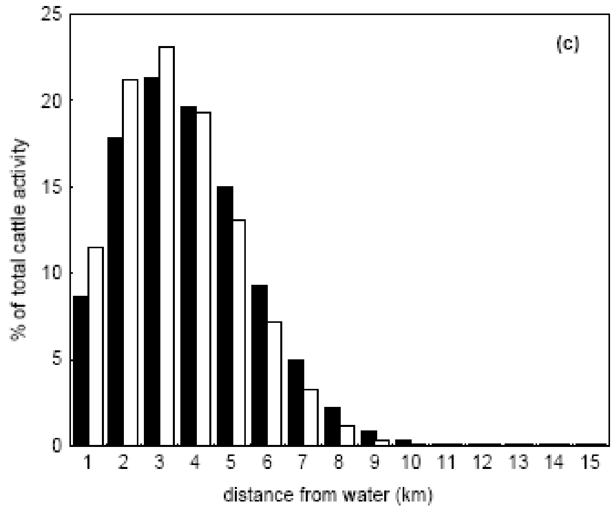

Figure 7.21. The percentage of total cattle activity at various distances from water on two cattle stations (black and white bars) in the Barkly Tableland, NT. Approximately 55-60% of cattle activity occurred within 3 km of water. (From Fisher 2001 and based on hoof print, dung and defoliation data at a number of water points).

At Pigeon Hole in the VRD, where additional waters were established in a large paddock approximately 90% of cattle activity (assessed using GPS cattle collars) occurred within 3 km of water (Figure 7.12). This was because a large proportion of the paddock was within 3 km of water and the areas beyond this distance were generally small (the average distance to water in this paddock was 2.1 km). As a result there were fewer areas where ungrazed forage accumulated. Establishing new water points in large paddocks at Pigeon Hole allowed more cattle to be carried because more of the country was accessible for grazing. Thus, a general recommendation to improve the effective use of available pasture and minimise the size of areas of ungrazed pasture in the more extensive grazing regions is for the majority of a paddock to be within 3 km of water and the distance between water points not to exceed approximately 6 km.

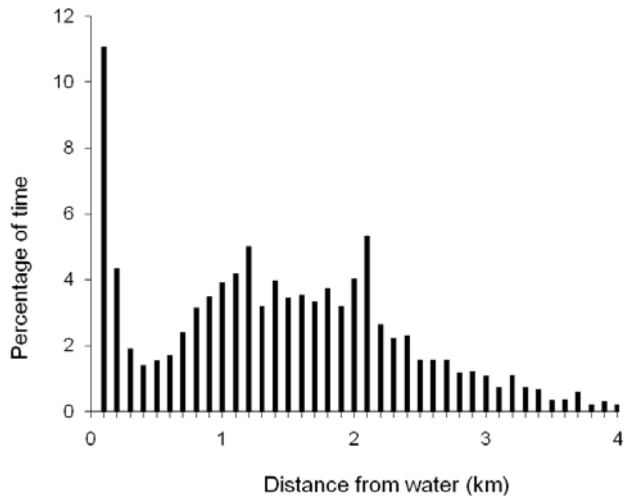

Figure 7.12. The percentage of time cattle spent at various distances from water in a 57 km^2 paddock with five water points at Pigeon Hole (from Hunt *et al*. 2010).

One study of cattle grazing distribution in a commercial-sized paddock (1500 ha) in north-east Queensland (using GPS collars) showed that the majority of cattle activity occurred within approximately 2.5 km of water and the average distance cattle were from water was approximately 1500 m (see Chapter 3). In this case, preferred pasture/land types were generally within 2.5 km of water.

Although the evidence from research is minimal, and there is often considerable variation in cattle grazing behaviour, we are reasonably confident with the recommendation to establish water points in paddocks so that most of a paddock is within 3 km of water in order to maximise the amount of forage that is accessible to cattle.

Waters should be sited away from fence lines and areas that cattle favour (e.g. creek lines, riparian areas, shady sites) whenever possible as this may help reduce the extent to which cattle congregate and loiter around the water for lengthy periods and reduce the possibility these areas will be overgrazed. They should also be sited away from sensitive parts of the landscape, such as soils that are highly erodible. Studies in semi-arid rangelands in SA and WA have shown that grazing use within paddocks is more evenly distributed if water points are located away from fences.

If existing water sources (bores or dams) have sufficient capacity, it may be possible to establish new water points in underutilised areas simply by piping water to tanks and troughs in these locations.

7.4.4.2. Conclusions

There will be regional differences in how many water points are needed and how far apart they should be placed. These differences will be influenced by the productivity and heterogeneity of the land and by other management considerations. In the more developed regions water points are usually already closer than the recommendations.

Obviously the cost of developing new water points must be considered. Where installing new water points ‘opens up’ new country to grazing the investment is more likely to be worthwhile. The quality of the land in ungrazed areas should also be considered prior to installing additional water points. Some land may be ungrazed because of low value pastures rather than because it is too far from water, and installing a new water point to make this area more readily accessible to cattle may not be financially worthwhile.

In a paddock that has multiple water points cattle will not necessarily distribute themselves evenly amongst the different waters. In very large paddocks carrying many animals this can result in large congregations of cattle on certain water points. The number of animals using a water point should be limited to approximately 300 head (see Chapter 4).

It is also important to note that despite having improved access to water, cattle will continue to graze paddocks unevenly to some extent. Other techniques to attract cattle to under-utilised areas should also be implemented. For example, the strategic location and regular relocation of supplements, and strategically burning patch grazed areas or areas with an accumulation of old senescent pasture may help.

If fire is used to remove accumulations of old feed careful management is required after burning. It is generally considered important that perennial grasses in burnt areas be allowed to re-grow so there is a reasonable body of feed before they are grazed again after burning. Burnt areas are best rested from grazing for an entire growing season before being grazed again (Chapter 5). Burning in the early dry season will effectively mean the paddock cannot be used for the remainder of the dry season since the cattle will concentrate on these areas and potentially kill the regrowing perennial grasses (Chapter 6).

Resting may also be required to allow the recovery of overgrazed areas once new water points are established (Chapter 5).

The effect of installing additional waters on the natural biodiversity of an area should also be considered. Many grazing-sensitive species of native fauna and flora now only exist in areas that are remote from water. Installing additional waters so that few water-remote areas remain may pose a risk to the persistence of this biodiversity. Where important biodiversity resources exist, some areas should remain remote from water (or fenced to exclude grazing) to protect these resources. For large properties where undeveloped areas of land still exist, a general recommendation is that up to 10% of a property should be set aside to protect biodiversity.

7.4.5. Management Action: reduce paddock size

Subdividing large paddocks to create smaller paddocks will provide better control over where cattle graze and can thus improve the use of previously ungrazed areas and help reduce overgrazing of favoured areas. This is a much more effective way of managing and improving grazing distribution than simply adding more water points to a paddock. However, because the financial cost involved can be substantial, it might be considered to be less attractive than establishing additional water points.

7.4.5.1. Evidence

Although installing more water points to make ungrazed areas in a paddock more readily accessible to cattle can increase the use of these areas, some areas in large paddocks may still not be grazed much because the cattle prefer other areas. Some water points may also be preferred so a large proportion of the herd may graze in areas near those water points. Reducing the size of large paddocks provides better control over where cattle graze and improves the effective use of available forage, potentially allowing an increase in the number of stock carried with reduced risk of land degradation due to large concentrations of livestock occurring in favoured areas.

Again, there is limited evidence from formal research on the effect of paddock size on grazing distribution and pasture use. The Pigeon Hole project is the only project to have specifically investigated the effect of different paddock sizes. Using GPS collars to record cattle distribution in paddocks over periods of six months, the research at Pigeon Hole indicated that individual cattle (and the mob as a whole) generally use a greater proportion of a paddock if paddock size is reduced. Confining cattle to smaller paddocks appears to have some effect in ‘forcing’ them to use areas they may not use if paddocks were larger (although they still may not use areas that contain few palatable plants). This effect means that having more smaller paddocks results in grazing being distributed more widely across the landscape as a whole, and should improve the effective use of available forage. It is also obvious that fences control where cattle can go at the landscape scale, thus preventing too many animals congregating on preferred parts of the landscape.

The greater effectiveness of reducing paddock size in getting better use of the landscape compared with establishing more waters in large paddocks is shown in Table 7.8, where the area within a paddock that gets little use reduces with declining paddock size.

Table 7.8. The area of within paddocks that receives little use by cattle for paddocks with a range of sizes and number of water points. The composite home range is the combined home ranges of several GPS collared cattle. The area receiving little use is that area not encompassed by the composite home range. These data are for three developed paddocks at Pigeon Hole station and an undeveloped commercial paddock at Mt Sanford in the VRD, NT.

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

Using a paddock size that approximates the usual grazing radius of cattle (i.e. the distance from water that encompasses the majority of cattle grazing) could be considered the ideal for many of the more extensive regions as it will mean most areas in a paddock are accessible to cattle. Assuming a grazing radius of 3 km this would translate to a paddock size of about 36 km^2. In paddocks of this size at Pigeon Hole the herd generally used 80% or more of the paddock area compared to approximately 70% in larger paddocks where additional watering points had been established. The research showed that reducing paddock size did not substantially improve the uniformity of grazing at smaller scales (e.g. patch scales) within paddocks. This suggests there is little value in reducing paddock size below that where all parts are accessible to cattle (i.e. 30-40 km^2) in the more extensive regions of northern Australia, from the perspective of improving grazing distribution. There are unlikely to be increases in total livestock production as a result of further reductions in paddock size.

However, there will be regional differences in what is a suitable paddock size to aim for. A study of grazing patterns in smaller paddocks (500-2000 ha) typical of the Burdekin region of north-eastern Queensland found that the level of pasture defoliation varied little up to 2 km from water (see Chapter 3). The small paddock size is likely to have contributed to evening out grazing use, although other environmental factors such as the degree of spatial variability in land type would also have been important. This evidence suggests that paddocks of 15-20 km^2 are sufficient from the perspective of optimising grazing distribution in this region (although there are no readily available data on grazing patterns for larger paddocks in this region). Other aspects of management (for example the ease of resting pastures or the variability in the landscape) are likely to dictate that paddocks be smaller than this. Also, for more productive areas with higher carrying capacities smaller paddock sizes are likely to be warranted in order to better manage stocking rates and minimise the occurrence of high concentrations of livestock within paddocks.

To better manage grazing impacts paddocks should be designed to separate minor land types that are sensitive to grazing (e.g. riparian zones, frontage country) where possible. Paddocks that contain relatively uniform land types and pasture are likely to be grazed more uniformly. In many situations this will not be practical due to relatively small size or irregular shapes of such areas. However, an understanding of how cattle use the landscape (e.g. their tendency to avoid steep or rugged country; see Chapter 3 for additional details) should be used to inform paddock design.

Creating smaller paddocks will often also require the establishment of additional water points to provide water in all paddocks. Where possible it is recommended that the smaller paddocks contain at least two water points (particularly if they are around 30-40 km^2) since this would further increase the extent of the area grazed in paddocks, reduce the potential for excessive overgrazing around water points (by reducing the number of cattle per water point), and provide some safety and flexibility should one water point fail. Allowing one water point per 20-25 km^2 of land area is recommended to ensure all areas are accessible to cattle.

7.4.5.2. Conclusions

Cost is a major consideration when reducing paddock size. Fencing costs escalate rapidly for paddocks smaller than about 30-40 km^2 (see Figure 7.13), and paddocks smaller than this may be hard to justify solely on the grounds of improving grazing management. The development of new paddocks should occur first on the most productive land where increased returns from development are most likely, or to protect the most sensitive areas.

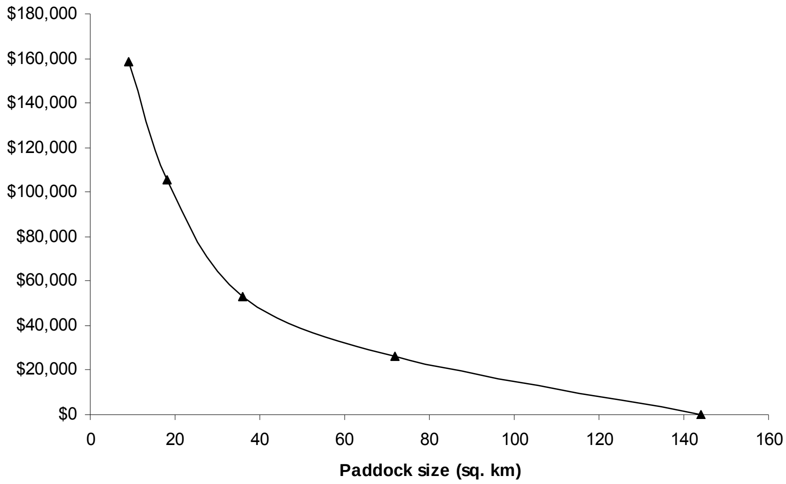

Figure 7.13. The cost for subdividing a large (144 km^2) paddock into smaller paddocks of varying size in the VRD (based on costs in 2007).

For more productive areas with higher carrying capacities, smaller paddock sizes are likely to be warranted in order to better manage stocking rates, have mobs of a manageable size and minimise the occurrence of high concentrations of livestock within paddocks. Smaller paddocks facilitate the use of other management options and in some circumstances may reduce operating costs. For example, having a greater number of smaller paddocks will increase the opportunities for pasture resting, can make mustering easier and can facilitate the use of prescribed fire.

As mentioned earlier, smaller paddocks do not result in completely even use within a paddock. Some areas may still not receive much use, and some areas will be heavily used. However, the rate at which overgrazed areas grow will be slower. As well as reducing paddock size, the use other of tools such as the strategic placement of supplements or prescribed fire should also be considered to improve grazing distribution in paddocks.

8. Extension opportunities

Extension programmes are best designed at the local level where specific local conditions cane given appropriate weighting. However it is possible to make some suggestions that will be generally applicable.

- Brochures, pamphlets, booklets, etc that make information available in an attractive and easy to read format. These should include the latest information but there is also value in "re-issuing" past information that is still relevant but has not had exposure in recent times.

- Follow-up courses to complement activities already undertaken by producers e.g. to target specific areas of interest after GLM courses.

- Build on the bio-economic modelling results to develop locally relevant long-term biological implications of management practices, and also assessments of financial costs and benefits. Relating model outputs to the actual performance of systems and enterprises would increase the confidence in models.

- Case studies of properties already using best-bet management. These provide the most relevant local information, and if combined with producers groups are ideal for focussing discussion of issues. They also provide an opportunity to examine large scale effects e.g. large herds of cattle.

- Producer Demonstration Sites (PDS) provide highly visible locations for demonstrations. Like case studies, they provide commercially relevant information and if they are combined with local producers groups, they can be valuable for stimulating discussion about the costs, benefits, problems, etc. of management practices. They may also be able to be modified if new research results become available suggesting a change of management. Some possible topics for demonstration sites are:

  - Comparison of set stocking with variable stocking rates. A two paddock comparison would enable a discussion group to consider the many factors involved in using these two systems, and demonstrate the outcomes of their management choices.
  - Practical aspects of matching stocking rate to carrying capacity.
  - Comparison of periods of resting during the growing season. This would complement any new research related to pasture spelling and provide a focus for local groups interested in this topic.
  - Best bet combinations for improving land in C condition. This would involve managing stocking rate, pasture resting, fire and possibly fencing and how all these are combined together. The practical information derived from such studies would complement information from more detailed research studies recommended in Chapter 9.
  - Use of fire for the management of locally important woody species. This would provide valuable information on the impacts of fire on different species and this could be incorporated in property management plans.

- The construction of decision trees to aid decision making would help producers considering some change of management e.g. how to consider all the factors that need to be included when planning to install new fences and water points.

9. Research gaps

Based on the results of past research and an assessment of information needs, the following topics have been identified for possible future research.

9.1. Infrastructure

1. How to improve within-paddock uniformity of grazing (top priority for infrastructure)

For example:

- How to manage grazing distribution with fire
- How to use strategic supplement location to improve grazing distribution
- Effectiveness of these approaches.

2. Determine if there is an effect of paddock size/grazing radius on livestock production

There is some ambiguity regarding the effect of paddock and water point development on livestock production. Since the cost of these developments is high we require an understanding of the financial costs and benefits to justify development. This will be critical in determining the optimum level of development for specific region, given their productivity and alternative development options. Improved grazing distribution is expected to allow more stock to be carried in some circumstances, but it is not known how greater development might affect the production per animal vs. production per hectare relationship.

3. Behavioural aspects of the use of waters when multiple waters are available: fidelity to a water point, how to improve fidelity, or how to improve adoption of alternative water points

Where it is not feasible to reduce the size of large paddocks to improve grazing distribution, an alternative is to install additional water points. However, there is no guarantee that cattle will share themselves equally amongst water points so preferred areas within paddocks could be subject to high grazing pressure. Better understanding how to manage the use of water points by cattle should allow improvements in grazing distribution without the need for fences. It might also offer the opportunity for spelling areas within a paddock by rotating access to water points.

4. Develop aids to help guide development plans for subdivision and new water points.

Develop a decision tree on paddock and water development with case study examples. Combine with exploratory modelling of the effects of paddocks and fences on livestock production and land condition.

9.2. Managing stocking rate

1. Better pasture and soil based indicators to guide stocking rate decisions (top priority for stocking rate research)

A key requirement in managing stocking rates is knowing when a reduction in stocking rates or destocking is needed to avoid causing serious damage to pastures or to allow critical life cycle processes such as seeding to occur. Indicators that are based on the condition of pasture plants (especially palatable perennial grasses) and soils will be most useful in protecting the future productivity of the land. This study possibly could be combined with studies on spelling. It is also linked to the previous and next items.

2. Modelling of variable versus set stocking rate strategies

Past studies have shown that the use of variable stocking rate strategies can be more profitable than set stocking but that the risks of making mistakes (and causing pasture damage) are greater. Set stocking at conservative stocking rates is ecologically safer but in some regions may not be as productive or profitable. Modelling of a range of stocking rate strategies for different regions under various seasonal scenarios should improve our understanding of the benefits and risks of different options, and allow best-bet options to be developed.

3. Modelling perennial grass populations (Orr's data) under climate/grazing/utilisation scenarios

The future productivity of perennial grass pastures depends on grasses being able to complete vital lifecycle processes. However, grazing and seasonal conditions can both affect these processes, and some studies have suggested that grazing prevents recruitment of new perennial grasses. Over the long-term, there is likely to be a loss of perennial grasses as established plants die (due to drought and grazing). An understanding of how grazing pressure (utilisation) and seasonal conditions interact to affect grass population dynamics is required to devise spelling and stocking rate strategies. A large body of population dynamics data has already been collected and scenario modelling using these data should improve our understanding of the grazing management needed to promote perennial grass populations.

9.3. Pasture resting

1. Predict response (top priority for resting research)

A major requirement in designing spelling regimes is the ability to predict what response will be obtained. A small plot experiment using matched exclosures and grazed areas at multiple sites across northern Australia (range of land/vegetation types) for three years (to give a variety of growing conditions) on land in different initial condition could examine how all these factors influence the response to rest. The use of common methods and approaches at all sites would enable the data to be analysed and more firm conclusions drawn than is currently possible.

As part of predicting responses it will be necessary to develop some index of the growing conditions during the rest period so that the duration of the rest period can be expressed as "effective rest days" or something similar. The daily values for growth index from GRASP are suggested as a possible starting point.

2. Detailed growth

How do pastures improve during the rest period? What is the contribution of seedlings versus growth of existing plants? This could be studied in conjunction with the research outlined in 1. by detailed charting of individual grass plants over the growing season and seedling establishment counts. It would provide valuable data to calibrate the changes added to GRASP.

3. When is a pasture adequately rested?

How do we know when a pasture is adequately rested and grazing can commence without damage to the pasture? This would need to be based on detailed physiology. It would also be combined with observations of the grass plants to detect practical indicators that could be used for management. This information would enable managers to make objective decisions on the necessary duration of resting.

4. Existing data

There is some value in analysing existing data to extract the most value from it but differences in methods will limit the value to be obtained.

5. Season of rest

Compare rest during the early growing season, the late growing season, and the non-growing season.

6. Definitions

As part of studies of responses to pasture resting it would be useful to define terms and measurements that adequately and informatively describe what is or is not a response in land condition. For instance, an increase in pasture yield may simply reflect the period of no grazing but not indicate any change in land condition. The basal area of perennial grasses and the proportion of 3P grasses in the herbage are likely to be suitable but there are also likely to be other suitable measurements.

It would be good to have a better definition of C condition in the ABCD continuum. At present a number of factors contribute and the characteristics of land in C condition can vary widely. This can hinder communication and also leads to needing to qualify statements as they may or may not apply depending and what aspect of C condition is relevant e.g. low ground cover versus the proportion of undesirable species. The PATCHKEY approach (Corfield *et al.* 2006) offers some promise and should be examined more widely.

9.4. Prescribed burning

1. Grazing-fire-rainfall interactions (top priority for fire research)

Past research has often looked at pairs of these factors independently. There is a need to understand the three-way interactions in pre- and post-fire stages of the fire cycle. Part of the cost of fire will be in lost production in the pre- and post-fire periods. Also, for different regions, what are the best pre- and post-fire management schedules under different seasonal circumstances.

2. Fire and soil condition

Fire affects ground cover and ground cover is important in affecting run-off and so soil erosion. Fire can affect the amount of organic matter on the soil surface and what happens to that organic matter. Fire both releases nutrients from plant material and releases nutrients to the atmosphere. Little is know of these processes in detail or how fire regimes might affect nutrient availability in the short-, medium- and long-terms.

3. Economics of fire compared with other management options

It is important to know the economic costs and benefits of burning versus other strategies for achieving the purposes for which fire is used. There will be major inter-regional differences.

4. Post-fire spelling vs fire for livestock redistribution

See Topic 1 under infrastructure.

5. Unstudied systems/species

There are many of these and there is always uncertainty associated with inter-regional and inter-specific extrapolation. Some woodland types in north Queensland where fire is a common phenomenon are among these. For species it would be worth refining the current “sprouter” versus “obligate seeder” functional grouping.

6. Eucalypt versus non-eucalypts in thickening?

There is a need to understand the dynamics of the tree and shrub layers of woodlands and savannas. Fire is only one of the factors but we have tended to look at its effects in isolation from other drivers of tree and shrub dynamics.

10. References

Alcock MB (1964) The physiological significance of defoliation on the subsequent regrowth of grass-clover mixtures and cereals. In 'Grazing in terrestrial and marine environments'. (Ed. DJ Crisp) pp. 25-41. (Blackwell Scientific Publications: Oxford).

Allan G, Johnson A, Cridland S, Fitzgerald N (2003) Application of NDVI for predicting fuel curing at landscape scales in northern Australia: can remotely sensed data help schedule. *International Journal of Wildland Fire* **12**, 299-308.

Andrew MH (1986a) Use of fire for spelling monsoon tallgrass pasture grazed by cattle. *Tropical Grasslands* **20**, 69-78.

Andrew MH (1986b) Selection of plant species by cattle grazing native monsoon tallgrass pasture at Katherine, N.T. *Tropical Grasslands* **20**, 120-127.

Anon. (2004) Stocktake – balancing supply and demand. Queensland Department of Primary Industries Agdex 320/27.

Arnold GW (1964) Factors within plant associations affecting the behaviour and performance of gazing animals. In 'Grazing in Terrestrial and Marine Environments'. (Ed. DJ Crisp) pp. 133-154. (Blackwell Scientific Publications: Oxford).

Arnold GW, Dudzinski ML (1978) 'Ethology of Free-ranging Domestic Animals.' (Elsevier Scientific Publishing Company: Amsterdam).

Ash AJ, Corfield JP (1998) Influence of pasture condition on plant selection patterns by cattle: its implications for vegetation change in a monsoon tallgrass rangeland. *Tropical Grasslands* **32**, 178-187.

Ash A, Corfield J, Ksiksi T (2001) The Ecograze Project – developing guidelines to better manage grazing country. (CSIRO: Townsville)

Ash AJ, Corfield JP, McIvor JG, Ksiksi TS (2010) Grazing management in tropical savannas: utilization and rest strategies to manipulate rangeland condition. *Rangeland Ecology and Management* (submitted)

Ash, AJ, McIvor JG, Corfield JP, Winter WH (1995) How land condition alters plant-animal relationships in Australia's tropical rangelands. *Agriculture Ecosystems* & *Environment* **56**: 77-92.

Ash A, McIvor J, Mott J, Andrew M (1997) Building grass castles: Integrating ecology and management of Australia's tropical tallgrass rangelands. *The Rangeland Journal* **19**, 123-144.

Ash AJ, McIvor JG (1998) How season of grazing and herbivore selectivity influence monsoon tall-grass communities of northern Australia. *Journal of Vegetation Science* **9**, 123-132.

Ash AJ, Prinsen JH, Myles DJ, Hendricksen RE (1982) Short-term effects of burning native pasture in spring on herbage and animal production in south-east Queensland. In 'Proceedings of the Australian Society of Animal Production Vol 14'. Brisbane, Queensland pp. 377-380. (Pergamon Press)

Ash AJ, Stafford Smith DM (1996) Evaluating stocking rate impacts in rangelands: animals don't practice what we preach. *The Rangeland Journal* **18**, 216-243.

Augustine DJ, McNaughton SJ, Frank DA (2003) Feedbacks between soil nutrients and large herbivores in a managed savanna ecosystem. *Ecological Applications* **13**, 1325-1337.

Baars RMT (1999) The effect of rangeland fires on cattle tick infestation in western Zambia. *Tropical Animal Health and Production* **31**, 275-278.

Back PV (1998) Control of currant bush (*Carissa ovata*) in developed brigalow (*Acacia harpophylla*) country. *Tropical Grasslands* **32**, 259-263.

Back PV (2005) The impact of fire on population density and canopy area of currant bush (*Carissa ovata*) in central Queensland and its implications for grazed woodland management. *Tropical Grasslands* **39**, 65-74.

Back PV, Anderson ER, Burrows WH, Playford C (2008) Woody plant responses to various clearing strategies imposed on a poplar box (*Eucalyptus populnea*) community at Dingo in central Queensland. *Tropical Grasslands* **43**, 37-52.

Bailey DW (2005) Identification and creation of optimum habitat conditions for livestock. *Rangeland Ecology and Management* **58**, 109–118.

Bailey DW, Dumont B, Wallis DeVries MF (1998) Utilization of heterogeneous grasslands by domestic herbivores: theory to management. *Annales de Zootechnie* **47**, 321–333.

Bailey DW, Gross JE, Laca EA, Rittenhouse LR, Coughenour MB, Swift DM, Sims PL (1996) Mechanisms that result in large herbivore grazing distribution patterns. *Journal of Range Management* **49**, 386–400.

Bailey DW, Keil MR, Rittenhouse LR (2004) Research observation: daily movement patterns of hill climbing and bottom dwelling cows. *Journal of Range Management* **57**, 20-28.

Bailey DW, Welling GR (2007) Evaluation of low-moisture blocks and conventional dry mixes for supplementing minerals and modifying cattle grazing patterns. *Rangeland Ecology and Management* **60**, 54–64.

Barnes MK, Norton BE, Maeno M, Malechek JC (2008) Paddock size and stocking density affect spatial heterogeneity of grazing. *Rangeland Ecology and Management* **61**, 380-388.

Barthram GT, Grant SA (1984) Defoliation of ryegrass-dominated swards by sheep. *Grass and Forage Science* **39**, 211-219.

Bartley R, Corfield JP, Hawdon A, Abbott BN, Keen R, Gordon IJ (2007) Grazing impacts on cover, water, sediment and nutrient loss in the Upper Burdekin catchment (2006/07). Meat and Livestock Australia Final Report B.NBP.0321.

Bartley R, Corfield J, Hawdon A, Abbott B, Wilkinson S, Nelson B (2009) Can improved grazing land management reduce sediment yields delivered to the Great Barrier Reef? Meat and Livestock Australia Final Report Project B.NBP.473.

Bastin G, Ludwig J, Eager R, Liedloff A, Andison R, Cobiac M (2003) Vegetation changes in a semiarid tropical savanna, northern Australia: 1973-2002. *The Rangeland Journal* **25**, 3-19.

Bebawi F, Campbell S (2002) Impact of fire on bellyache bush (*Jatropha gossypiifolia*) mortality and seedling recruitment. *Tropical Grasslands* **36**, 129-137.

Bennett LT, Judd TS, Adams MA (2002) Growth and nutrient content of perennial grasslands following burning in semi-arid, sub-tropical Australia. *Plant Ecology* **164**, 185-199.

Biograze (2000) Biograze: water points and wildlife. CSIRO, Alice Springs. 13 pp.

Birkill A (1985) Termite ecology in a tropical savanna grazed by cattle. Honours thesis, School of Biological Sciences, Flinders University, South Australia.

Bishop-Hurley GJ, Swain DL, Potin S, Wark T, Crossman C (2008) Understanding cattle behaviour in riparian areas with and without access to off-stream watering points. Proceedings of the Fifteenth Australian Rangeland Conference, Charters Towers Qld. pp. 60-63

Bosch OJH, Tainton NM (1988) Ecological principles and their application to rangeland management practice in South Africa. In 'Vegetation Science Applications for Rangeland Analysis and Management'. (Ed. PT Tueller) pp. 363-397 (Kluwer Academic Publishers: Dordrecht).

Braunack MV, Walker J (1985) Recovery of some surface soil properties of ecological interest after sheep grazing in a semi-arid woodland. *Australian Journal of Ecology* **10**, 451-460.

Bray SG (2004) The successful lifecycle of the pasture weed giant rats tail grass (*Sporobolus pyramidalis*). PhD Thesis. School of Agronomy and Horticulture, The University of Queensland.

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

Butler DW, Fairfax RJ (2003) Buffel grass and fire in a gidgee and brigalow woodland: a case study from central Queensland. *Ecological Management and Restoration* **4**, 120-125.

Buxton R, Stafford Smith M (1996) Managing drought in Australia's rangelands: four weddings and a funeral. *Rangeland Journal* **18**, 292-308.

Cameron DG, Wildin JH (1976) Brigalow pasture establishment and maintenance. *Queensland Agricultural Journal* **102**, 57-72.

Campbell SD (1995) Plant mechanisms that influence the balance between *Heteropogon contortus* and *Aristida ramosa* in spring burnt pastures. PhD Thesis, University of Queensland.

Campbell SD, Setter, CL (1999) Mortality of *Prosopis pallida* following burning. In 'People and rangelands: building the future. Proceedings of the VI International Rangeland Congress, Townsville, Queensland, Australia, 19-23 July, 1999. Volumes 1 and 2.' (Eds D Eldridge and D Freudenberger) pp. 596-597. (VI International Rangeland Congress, Inc.: Aitkenvale, Qld)

Clark DA, Chapman DF, Land C, Dymock N (1984) Defoliation of *Lolium perenne* and *Agrostis* spp. tillers and *Trifolium repens* stolons in set-stocked and rotationally grazed hill pastures. *New Zealand Journal of Agricultural Research* **27**, 289-301.

Coates DB (1996) Diet selection by cattle grazing *Stylosanthes*-grass pastures in the seasonally dry tropics: effect of year, season, stylo species and botanical composition. *Australian Journal of Experimental Agriculture* **36**, 781-789.

Cook GD (1994) The fate of nutrients during fires in a tropical savanna. *Austral Ecology* **19**, 359-365.

Cook SJ (1984) Establishment of four pasture grasses and siratro from seed oversown into dense and open speargrass pastures. *Australian Journal of Experimental Agriculture and Animal Husbandry* **24**, 360-369.

Cook SJ, Clem RL, MacLeod ND, Walsh, P.A. (1993) Tropical pasture establishment. 7. Sowing methods for pasture establishment in northern Australia. *Tropical Grasslands* **27**, 335-343.

Cooksley DG (2003) Managing native pastures and stylo. MLA Final Report Project NAP3.221.

Corfield JP, Abbott BN, Hawdon A, Berthelsen S (2006) PATCHKEY: a patch classification framework for the upper Burdekin and beyond. Proceedings of the 14th Biennial Conference of the Australian Rangeland Society. (Ed. P Erkelenz) pp. 114-118.

Corfield JP, Nelson B (2008) Scaling up from Ecograze - the Virginia Park experience. Proceedings of the 15th Biennial Conference of the Australian Rangeland Society, Charter Towers, 2008.

Coughenour MB (1991) Spatial components of plant-herbivore interactions in pastoral, ranching, and native undulate ecosystems. *Journal of Range Management* **44**, 530-542.

Cowley RA (2001) The Effect Of Changing Water Distribution From Linear To Point Source On Vegetation And Soil Following Piping Of An Artesian Bore In A Semi-Arid Mulga Paddock. PhD thesis. The University of Queensland, Brisbane.

Cowley RA, McCosker KD, MacDonald RN, Hearnden MN (2007) Optimal pasture utilisation rates for sustainable cattle production with a commercial Brahman herd in the Victoria River Downs region of the Northern Territory. In: ‘Proceedings of the Northern Beef Research Update Conference’. Townsville, Qld. (Eds B. Pattie and B. Restall.) pp. 34–44. (North Australia Beef Research Council.)

Craig AB (1999) Fire management of rangelands in the Kimberley low-rainfall zone: a review. *The Rangeland Journal* **21**, 39-70.

Crawley MJ (1983) *Herbivory: the Dynamics of Animal-Plant Interactions*. Blackwell Scientific Publications, Oxford, UK.

Crowley GM, Garnett, S.T. (1998) Vegetation change in the grasslands and grassy woodlands of east-central Cape York Peninsula, Australia. *Pacific Conservation Biology* **4**, 132-148.

Crowley GM, Garnett, S.T. (2000) Changing fire management in the pastoral lands of Cape York Peninsula of northeast Australia, 1623 to 1996. *Australian Geographical Studies* **38**, 10-26.

Crowley G, Garnett S, Shephard S (2009) Impact of storm-burning on *Melaleuca viridiflora* invasion of grasslands and grassy woodlands on Cape York Peninsula, Australia. *Austral Ecology* **34**, 196-209.

Daines TJ (1980) The use of grazing patterns in the management of Dohne sourveld. *Proceedings of the Grassland Society of Southern Africa* **15**, 185-188.

Danckwerts JE (1991) Veld management in the smaldeel of the eastern cape: future research priorities. *Bulletin of the Grassland Society of Southern Africa Supplement* **1,** 31-48.

Danckwerts JE, Aucamp AJ, Barnard HJ (1983) Herbaceous species preferred by cattle in the false thornveld of the eastern Cape. *Proceedings of the Grassland Society of Southern Africa* **18**, 89-94.

Danckwerts JE, Aucamp AJ (1985) The rate of leaf emergence and decay as criteria for optimising the grazing rotation in semi-arid grassveld. *Journal of the Grassland Society of Southern Africa* **2**, 28-34.

Dean FH (1996) Why burn Mitchell grass? In 'Fire in the Management of Northern Australian Pastoral Lands. Tropical Grassland Society of Australia, Occasional Publication No. 8'. Townsville, Australia. (Eds AC Grice and SM Slatter). (Tropical Grassland Society of Australia)

Debuse V, Lewis T (2007). Using fire in spotted gum-ironbark forests for production and biodiversity outcomes: Guidelines for Landholders. Department of Primary Industries and Fisheries, Queensland.

Dyer R (2000) The role of fire on pastoral lands in northern Australia. In 'Fire and sustainable agricultural and forestry development in eastern Indonesia and northern Australia : proceedings of an International Workshop held at Northern Territory University, Darwin, Australia, 13-15 April 1999'. (Eds J Russell-Smith, G Hill, S Djoeroemana and B Myers) pp. 13-15. (ACIAR: Canberra)

Dyer R, Café L, Cobiac M, Cowley R (2003) Developing sustainable grazing management systems for the semi-arid tropics of the Northern Territory. Meat and Livestock Australia Final Report Project NAP3.211.

Dyer RM, Jacklyn P, Partridge I, Russell-Smith J, Williams R (2001) ‘Savanna Burning: understanding and using fire in northern Australia’. (Tropical Savannas Cooperative Research Centre, Darwin).

Dyer RM, Mott JJ (1999) The impact of fire on two grazed savanna communities in northern Australia. In 'People and rangelands: building the future. Proceedings of the VI International Rangeland Congress, Townsville, Queensland, Australia, 19-23 July, 1999. Volumes 1 and 2.' (Eds D Eldridge and D Freudenberger) pp. 268-269. (VI International Rangeland Congress, Inc: Aitkenvale, Qld.)

Dyer R, Stafford Smith M (2003) Ecological and economic assessment of prescribed burning impacts in semi-arid pastoral lands of northern Australia. *International Journal of Wildland Fire* **12,** 403-413.

Fensham RJ, Fairfax RJ, Dwyer JM (2010) Vegetation responses to the first 20 years of cattle grazing in an Australian desert. *Ecology* **91**, 681–692.

Fensham RJ, Holman JE (1999) Temporal and spatial patterns in drought-related tree dieback in Australian savanna. *Journal of Applied Ecology* **36**, 1035-1050.

Fisher A (2001) Biogeography and conservation of Mitchell grasslands in northern Australia. PhD Thesis, Charles Darwin University, Darwin.

Foran BD (1980) Change in range condition with distance from watering point and its implications for field survey. *Australian Rangeland Journal* **2**, 59-66.

Foran BD, Bastin G, Hill B (1985) The pasture dynamics and management of two rangeland communities in the Victoria River District of the Northern Territory. *The Rangeland Journal* **7**, 107-113.

Fuls ER (1992) Ecosystem modification created by patch-overgrazing in semi-arid grassland. *Journal of Arid Environments* **23**, 59-69.

Gammon DM (1984) An appraisal of short duration grazing as a method of veld management. *Zimbabwe Agriculture Journal* **81**, 59-64.

Gammon DM, Roberts BR (1978a) Patterns of defoliation under continuous and rotational grazing of the Matopos sandveld of Rhodesia 1. Selectivity of grazing. *Rhodesian Journal of Agricultural Research* **16**, 117-131.

Gammon DM, Roberts BR (1978b) Patterns of defoliation under continuous and rotational grazing of the Matopos sandveld of Rhodesia 2. Severity of defoliation. *Rhodesian Journal of Agricultural Research* **16**, 133-145.

Ganskopp D (2001). Manipulating cattle distribution with salt and water in large arid-land pastures: a GPS/GIS assessment. *Applied Animal Behaviour Science* **73**, 251–262.

Ganskopp D and Bohnert D (2006) Do pasture-scale nutritional patterns affect cattle distribution on rangelands? *Rangeland Ecology and Management* **59**, 189–196.

Ganskopp D and Bohnert D (2009) Landscape nutritional patterns and cattle distribution in rangeland pastures. *Applied Animal Behaviour Science* **116**, 110–119.

Gardener CJ (1980) Diet selection and liveweight performance of steers on *Stylosanthes hamata*-native grass pastures. *Australian Journal of Agricultural Research* **31**, 379-392.

Gardener CJ, Ash AJ (1994) Diet selection in six *Stylosanthes*-grass pastures and its implications for pasture stability. *Tropical Grasslands* **28**, 109-119.

Gardener CJ, McIvor JG, Williams J (1990) Dry tropical rangelands: solving one problem and creating another. *Proceedings of the Ecological Society of Australia* **16**, 279-286.

Gibb K, Beard J, O'Reagain P, Christiana K, Torok V, Ophel-Kellerd K (2008) Assessing the relationship between patch type and soil mites: A molecular approach. *Pedobiologia* **51,** 445-461.

Gillard P (1979) Improvement of native pasture with Townsville stylo in the dry tropics of sub-coastal northern Queensland. *Australian Journal of Experimental Agriculture and Animal Husbandry* **19**, 325-336.

Grice AC (1997a) Post-fire regrowth and survival of the invasive tropical shrubs *Cryptostegia grandiflora* and *Ziziphus mauritiana*. *Australian Journal of Ecology* **22**, 49-55.

Grice AC (1997b) Fire for the strategic management of rubbervine *Cryptostegia grandiflora*, an invasive shrub. In 'Bushfire '97 Proceedings, Australian Bushfire Conference'. Darwin. (Eds BJ McKaige, RJ Williams and WM Waggitt) pp. 239-244. (CSIRO Tropical Ecosystems Research Centre)

Grice AC (2004) Weeds and the monitoring of biodiversity in Australian rangelands. *Austral Ecology* **29**, 51-58.

Grice AC (2008) Developing, implementing and evaluating fire management of woody vegetation in the Gulf region. Report to Meat and Livestock Australia on Project NBP.319.

Grice AC, McIntyre S (1995) Spear grass (*Heteropogon contortus*) in Australia: dynamics of species and community. *The Rangeland Journal* **17**, 3-25.

Grice AC, McKenzie JR, Nicholas DM, Pattison M, Whiteman LV, Steele KE, Campbell SD (2004) Will fire help control *Parkinsonia aculeata* L.? Proceedings of the 14th Australian Weeds Conference.,(Eds BM Sindel, SB Johnson) pp. 61- 63. (Weed Society of New South Wales, Sydney).

Grice AC, Radford IJ, Abbott BN (2000) Regional and landscape-scale patterns of shrub invasion in tropical savannas. *Biological Invasions* **2**, 187-205.

Grice TC, Slatter SM (1996) Fire in the management of northern Australian pastoral lands. *Tropical Grassland Society of Australia. Occasional Publication* **8**.

Hacker R (1988) Grazing of crested wheatgrass, with particular reference to effects of pasture size. *Journal of Range Management* **41**, 73-78.

Hacker RB, Hodgkinson KC, Melville GJ, Bean J, Clipperton SP (2006) Death model for tussock perennial grasses: thresholds for grazing-induced mortality of mulga Mitchell grass (*Thyridolepis mitchelliana*). *The Rangeland Journal* **28,** 105-114.

Hacker RB, Tunbridge SB (1991) Grazing management strategies for reseeded rangelands in the East Kimberley region of Western Australia. *The Rangeland Journal* **13**, 14-35.

Hall WB, McKeon GM, Carter JO, Day KA, Howden SM, Scanlan JC, Johnston PW, Burrows WH (1998) Climate change in Queensland's grazing lands: II. An assessment of the impact on animal production from native pastures. *Rangeland Journal* **20**, 177-205.

Harris W (1978) Defoliation as a determinant of the growth, persistence and composition of pasture. In 'Plant Relations in Pastures'. (Ed. JR Wilson) pp. 67-85. (CSIRO: Melbourne).

Hart RH, Bissio J, Samuel MJ, Waggoner JW (1993) Grazing systems, pasture size, and cattle grazing behaviour, distribution and gains. *Journal of Range Management* **46**, 81–87.

Hassall AC (1976) Native pasture management. *Tropical Grasslands* **10**, 53-54.

Hatch GP, Tainton NM (1993) Effect of veld condition and stocking intensity on species selection patterns by cattle in the southern tallgrasslands of Natal. *African Journal of Range and Forage Science* **10**, 11-20.

Heady HF (1975) 'Rangeland management.' (McGraw-Hill Book Company: New York).

Heitschmidt RK, Briske DD, Price DL (1990) Pattern of interspecific tiller defoliation in mixed-grass prairie grazed by cattle. *Grass and Forage Science* **45**, 215-222.

Heitschmidt RK, Taylor CA (1991) Livestock production. In 'Grazing Management An Ecological Perspective'. (Eds RK Heitschmidt, JW Stuth) pp. 161-177. (Timber Press: Portland).

Hendricksen RE, Miller, CP, Punter LD (1999) Diet selection by cattle grazing tropical tallgrass pasture. Proceedings of the VI International Rangeland Congress, Townsville, Queensland, Australia, 19-23 July, 1999. Volumes 1 and 2.' (Eds D Eldridge and D Freudenberger) pp. 222-223. (VI International Rangeland Congress, Inc.: Aitkenvale, Qld)

Hodder RM, Low WA (1978) Grazing distribution of free-ranging cattle at three sites in the Alice Springs District, Central Australia. *Australian Rangeland Journal* **1**, 98–105.

Hodgkinson KC (1979) The shrubs of poplar box (*Eucalyptus populnea*) lands and their biology. *Australian Rangeland Journal* **1**, 280-293.

Hodgkinson KC (1991) Identification of critical thresholds for opportunistic management of rangeland vegetation. *Proceedings of the Fourth International Rangeland Congress* (eds A. Gaston, M. Kernick & H. Le Houeroa), pp. 127–129. Service Central d'Information Scientifique et Technique Montpellier, France.

Hodgkinson KC, Griffin GF (1982) Adaptation of shrub species to fires in the arid zone. In 'Evolution of the Flora and Fauna of Arid Australia.' (Eds WR Barker and PJM Greenslade) pp. 145-152. (Peacock Publications: Adelaide)

Hodgkinson KC, Harrington GN (1985) The case for prescribed burning to control shrubs in eastern semi-arid woodlands. *Australian Rangeland Journal* **7**, 64-74.

Hodgkinson KC, Ludlow MM, Mott JJ, Baruch Z (1989) Comparative responses of the savanna grasses *Cenchrus ciliaris* and *Themeda triandra* to defoliation. *Oecologia* **79**, 45-52.

Hodgkinson KC, Muller WJ (2005a) Death model for tussock perennial grasses: a rainfall threshold for survival and evidence for landscape control of death in drought. *The Rangeland Journal* **27,** 105-115.

Hodgkinson KC, Muller WJ (2005b) Mortality model for a perennial grass in Australian semi-arid wooded grasslands grazed by sheep. In *Pastoral Systems in Marginal Environments.* (Ed. J.A. Milne). p. 108. (Wageningen Academic Publishers, The Netherlands).

Hodgson J, Wade MH (1978) Grazing management and herbage production. In 'Proceedings of the 1978 Winter Meeting of the British Grassland Society' pp. 1.1-1.12. (British Grassland Society: Hurley, UK).

Hodgson J (1966) The frequency of defoliation of individual tillers in a set-stocked sward. *Journal of the British Grassland Society* **21**, 258-263.

Holechek JL, Pieper RD, Herbel CH (2004) 'Range Management: Principles and Practices.' 5th edn (Pearson Prentice Hall: New Jersey.).

Holt JA (1997) Grazing pressure and soil carbon, microbial biomass and enzyme activities in semi-arid northeastern Australia. *Applied Soil Ecology* **5,** 143-149.

Holt JA, Bristow KL, McIvor JG. (1996a) The effects of grazing pressure on soil animals and hydraulic properties of two soils in semi-arid tropical Queensland. *Australian Journal of Soil Research* **34,** 69-79.

Holt JA, Coventry RJ (1988) The effects of tree clearing and pasture establishment on the population of mound-building termites (Isoptera) in north Queensland. *Australian Journal of Ecology* **13,** 321-325.

Holt JA, Grice AC, Brown JR (1996b) Patchiness in herbaceous vegetation: Relationships with soil microbial biomass. Proceedings of the 9th Biennial Conference of the Australian Rangeland Society, Port Augusta, 1996. (Eds L. P. Hunt and R. Sinclair) pp. 143-144.

Horadagoda A, Fulkerson WJ, Nandra KS, Barchia IM (2009) Grazing preferences by dairy cows for 14 forage species. *Animal Production Science* **49**, 586-594.

Howery LD, Provenza FD, Banner RE, Scott CB (1996) Differences in home range and habitat use among individuals in a cattle herd. *Applied Animal Behaviour Science* **49**, 305–320.

Howery LD, Provenza FD, Banner RE, Scott CB (1998). Social and environmental factors influence cattle distribution on rangeland. *Applied Animal Behaviour Science* **55**, 231–244.

Howery LD, Sprinkle JE, Bowns JE (2000) A summary of livestock grazing systems used on rangelands in the western United States and Canada. ag.arizona.edu/pubs/natresources/az1184.pdf.

Hunt LP (2001) Heterogeneous grazing causes local extinction of edible perennial shrubs: a matrix analysis. *Journal of Applied Ecology* **38**, 238–252.

Hunt LP (2008) Safe pasture utilisation rates as a grazing management tool in extensively grazed tropical savannas of northern Australia. *Rangeland Journal* **30**, 305-315.

Hunt LP, Petty S, Cowley R, Fisher A, Ash AJ, MacDonald N (2007) Factors affecting the management of cattle grazing distribution in northern Australia: preliminary observations on the effect of paddock size and water points. *The Rangeland Journal* **29**, 169–179.

Hunt L, Petty S, Cowley R, Fisher A, White A, MacDonald N, Pryor M, Ash A, McCosker K, McIvor J, MacLeod N (2010) Sustainable development of VRD grazing lands. Final report to MLA. Project B.NBP.0375 (submitted for review)

James CD, Landsberg J, Morton SR (1999) Provision of watering points in the Australian arid zone: a review of effects on biota. *Journal of Arid Environments* **41**, 87–121.

Jameson DA (1963) Response of individual plants to harvesting. *Botanical Review* **29**, 532-594.

Johnston PW, McKeon GM, Day KA (1996) Objective 'safe' grazing capacities for south-west Queensland Australia: development of a model for individual properties. *The Rangeland Journal* **18**, 244–258.

Jones RJ (1997) Steer gains, pasture yield and pasture composition on native pasture and on native pasture oversown with Indian couch (*Bothriochloa pertusa*) at three stocking rates. *Australian Journal of Experimental Agriculture* **37**, 755-765.

Jones RJ, Hu FD (2006) Diet selection of steers grazing *Stylosanthes hamata* cv. Verano-grass pastures in north Queensland and its influence on botanical composition. *Tropical Grasslands* **40,** 65-69.

Jones RJ, Sandland RL (1974) The relation between animal gain and stocking rate: Derivation of the relation from the results of grazing trials. *Journal of Agricultural Science, Cambridge* **83**, 335-342.

Kain AJ, Cowley RA (2008) Comparison of rotational grazing and continuous grazing on a buffel grass (*Cenchrus ciliaris*) dominated pasture: preliminary results from Mt Riddock station. Northern Territory Department of Primary Industry, Fisheries and Mines Report.

Kirkman KP (2002a) The influence of various types and frequencies of rest on the production and condition of sourveld grazed by sheep or cattle. 1. Proportional species composition. *African Journal of Range and Forage Science* **19**, 55-62.

Kirkman KP (2002b) The influence of various types and frequencies of rest on the production and condition of sourveld grazed by sheep or cattle. 2. Vigour. *African Journal of Range and Forage Science* **19**, 93-105.

Landsberg RG, Ash AJ, Shepherd RK, McKeon GM (1998) Learning from history to survive in he future: management evolution on Trafalgar Station, north-east Queensland. *The Rangeland Journal* **20**, 104-118.

Lange RT (1969) The piosphere: sheep track and dung patterns. *Journal of Range Management* **22**, 396–400.

Lange RT, Nicolson AD, Nicolson DA (1984) Vegetation management of chenopod rangelands in South Australia. *Australian Rangeland Journal* **6**, 46–54.

Lauder AR, Price NR (2008) Is pasture rest time or timing. Proceedings of the 15th Biennial Conference of the Australian Rangeland Society.

Lemaire G, Agnusdei M (2000) Leaf tissue turnover and efficiency of herbage utilisation. In 'Grassland Ecophysiology and Grazing Ecology'. (Eds G Lemaire, J Hodgson, A de Moraes, C Nabinger, PC de F. Carvalho) pp. 265-287. (CAB International Publishing: Wallingford).

Lemaire G, Chapman D (1996) Tissue flows in grazed plant communities. In 'The Ecology and Management of Grazing Systems'. (Eds J Hodgson, AW Illius) pp. 3-36. (CAB International Publishing: Wallingford).

Letnic M (2004) Cattle grazing in a hummock grassland regenerating after fire: the short-term effects of cattle exclusion on vegetation in south-western Queensland. *The Rangeland Journal* **26**, 34-48.

Leys D (1977) Pasture utilisation by free-ranging cattle in central Australia. Thesis, Australian National University, Canberra.

Lonsdale WM, Braithwaite RW (1991) Assessing the effects of fire on vegetation in tropical savannas. *Australian Journal of Ecology* **16**, 363-374.

Low WA, Hodder RM, Abel DE (1978) Watering behaviour of British breed cattle in central Australia. In 'Studies of the Australian Arid Zone. Vol. III. Water in rangelands'. (Ed. KMW Howes) pp. 165-177. CSIRO, Melbourne.

Low WA, Tweedie RL, Edwards CBH, Hodder RM, Malafant KWJ, Cunningham RB (1981a). The influence of environment on daily maintenance behaviour of free-ranging Shorthorn cows in central Australia. I. General introduction and descriptive analysis of day-long activities. *Applied Animal Ethology* **7**, 11-26.

Low WA, Dudziński ML, Müller WJ (1981b) The influence of forage and climatic conditions on range community preference of shorthorn cattle in central Australia. *Journal of Applied Ecology* **18**, 11–26.

MacLeod ND, Ash AJ, McIvor JG (2004) An economic assessment of the impact of grazing land condition on livestock performance in tropical woodlands. *Rangeland Journal* **29**, 49-71.

MacLeod ND, McIntyre S (1997) Stocking rate impacts on the production and economic performance of steers grazing black spear grass pastures. *Rangeland Journal* **19**, 174-189.

MacLeod ND, Nelson BS, McIvor JG, Corfield JP (2009) Wet season resting - economic insights from scenario modelling. *The Rangeland Journal* **31**, 143-150.

Mazzanti A, Lemaire G (1994) Effect of nitrogen fertilization upon herbage production of tall fescue swards continuously grazed by sheep. 2. Consumption and efficiency of herbage utilisation. *Grass and Forage Science* **49**, 352-359.

McIntyre S, Filet P (1997) Choosing appropriate taxonomic units for ecological survey and experimentation: the response of *Aristida* to management and landscape factors as an example.

The Rangeland Journal **19**, 26-39.

McIvor JG (2001) Pasture management in semi-arid tropical woodlands: regeneration of degraded pastures protected from grazing. *Australian Journal of Experimental Agriculture* **41**, 487-496.

McIvor JG (2002) Pasture management in semi-arid tropical woodlands: effects on ground cover levels. *Tropical Grasslands* **36,** 218-226.

McIvor JG, Ash AJ, Cook GD (1995a) Land condition in the tropical tallgrass pasture lands: 1. Effects on herbage production. *The Rangelands Journal* **17**, 69-85.

McIvor JG, Gardener CJ (1990) Soil and vegetation characteristics of dry tropical rangelands for predicting pasture regeneration in exclosures. *Proceedings of the Ecological Society of Australia* **16**, 273-277.

McIvor JG, McIntyre S, Saeli I, Hodgkinson JJ (2005) Patch dynamics in grazed sub-tropical native pastures in south-east Queensland. *Austral Ecology* **30**, 445-464.

McIvor JG, Noble AD, Orr, D.M. (1996) Review of stability and productivity of native pasture oversown with tropical legumes. North Australia Program Occasional Publication No.1. (Meat Research Corporation: Australia).

McIvor JG, Orr DM (1991) Sustaining productive pastures in the tropics. 3. Managing native grasslands. *Tropical Grasslands* **25**, 91-97.

McIvor JG, Singh V, Corfield JP, Jones RJ (1996) Seed production by native and naturalised grasses in north-east Queensland: effects of stocking rate and season. *Tropical Grasslands* **30**, 262-269.

McIvor JG, Williams J, Gardener CJ (1995b) Pasture management influences runoff and soil loss in the semi-arid tropics. *Australian Journal of Experimental Agriculture* **35**, 55-65.

McKeon GM, Brook KD, Carter JO, Day KA, Howden SM, Johnston PW, Scanlan JC, Scattini W J (1994) Modelling utilisation rates in the black speargrass zone of Queensland. In ‘Clean Country, Clean Product, Clear Profit. Working Papers. 8th Biennial Australian Rangelands Conference’. Katherine, NT. pp. 128–132. (Australian Rangeland Society: Cottesloe, WA.)

McKeon GM, Day KA, Howden SM, Mott JJ, Orr DM, Scattini WJ, Weston EJ (1990) Northern Australian savannas: management for pastoral production. *Journal of Biogeography* **17**, 355–372.

McKeon GM, Stone GS, Syktus JI, Carter JO, Flood NR, Ahrens DG, Bruget DN, Chilcott CR, Cobon DH, Cowley RA, Crimp SJ, Fraser GW, Howden SM, Johnston PW, Ryan JG, Stokes CJ, Day KA (2009) Climate change impacts on northern Australian rangeland livestock carrying capacity: a review of issues *The Rangeland Journal* **31**, 1–29.

McLennan SR, Clem RL, Mullins TJ, Shepherd RK (1986) The effects of burning on pasture yield and animal performance in the sub-coastal spear grass region of north Queensland. In 'Rangelands: A Resource Under Siege - Proceedings of the Second International Rangeland Congress.' Adelaide. (Eds PJ Joss, PW Lynch and OB Williams) pp. 605-606. (Australian Academy of Science)

McNaughton SJ (1984) Grazing lawns: animals in herds, plant forms, and coevolution. *American Naturalist* **124**, 863-886.

Mott JJ (1987) Patch grazing and degradation in native pastures of the tropical savannas in northern Australia. In 'Grazing-lands research at the plant-animal interface'. (Eds FP Horn, J Hodgson, JJ Mott, RW Brougham) pp. 153-161. (Winrock International: Morrilton).

Mott JJ, Bridge BJ, Arndt W (1979) Soil seals in tropical tall grass pastures of northern Australia. *Australian Journal of Soil research* **30**, 483-494.

Mott JJ, Ludlow MM, Richards JH, Parsons AD (1992) Effects of moisture supply in the dry season and subsequent defoliation on persistence of the savanna grasses *Themeda triandra*, *Heteropogon contortus* and *Panicum maximum*. *Australian Journal of Agricultural Research* **43**, 241-260.

Noble J (1997) 'The delicate and noxious scrub.' (CSIRO: Melbourne).

Noble JC, Grice AC (2002) Fire regimes in semi-arid and tropical pastoral lands: managing biological diversity and ecosystem function. In 'Flammable Australia: the fire regimes and biodiversity of a continent'. (Eds RA Bradstock, JE Williams and AM Gill) pp. 373-400. (Cambridge University Press: Cambridge)

Norman MJT (1960) Grazing and feeding trials with beef cattle at Katherine, N.T. Technical Paper No. 12. CSIRO Division of Land Research and Regional Survey, Melbourne.

Norman MJT (1965) Post-establishment grazing management of Townsville lucerne on uncleared land at Katherine, N.T. *Journal of the Australian Institute of Agricultural Science* **31**, 311-313.

Norton BE (1998) The application of grazing management to increase sustainable livestock production. *Animal Production in Australia* **22**, 15-26.

Northup BK, Brown JR, Ash AJ (2003) Using variability to identify potential state and transition stages of tropical tallgrass sites in northeast Australia. In 'Proceedings of the 7th International Rangeland Congress, Durban, South Africa' pp. 2045-2047.

Northup BK, Brown JR, Holt JA (1999) Grazing impacts on the spatial distribution of soil microbial biomass around tussock grasses in a tropical grassland. *Applied Soil Ecology* **13**, 259-270.

O'Connor TG (1991) Local extinction in perennial grasslands: a life-history approach. *American Naturalist* **137**, 753-773.

O'Connor TG (1994) Composition and population responses of an African savanna grassland to rainfall and grazing. *Journal of Applied Ecology* **31,** 155-171.

O'Connor TG (1996) Hierarchical control over seedling recruitment of the bunch-grass *Themeda triandra* in a semi-arid savanna *Journal of Applied Ecology* **33**, 1094-1106.

O'Connor TG, Pickett GA (1992) The influence of grazing on seed production and seed banks of some African savanna grasslands. *Journal of Applied Ecology* **29**, 247-260.

O’Reagain P, Bushell J, Holloway C (2007) Testing and developing principles and management guidelines for the sustainable management of the seasonably variable tropical savannas. Meat and Livestock Australia Final Report Project NBP.318.

O'Reagain P, Bushell J, Holloway C, Reid A (2009) Managing for rainfall variability: effect of grazing strategy on cattle production in a dry tropical savanna. *Animal Production Science* **49**, 85-99.

O'Reagain PJ, Mentis MT (1989a) The effect of plant structure on the acceptability of different grass species to cattle. *Journal of the Grassland Society of Southern Africa* **7**, 163-170.

O'Reagain PJ, Mentis MT (1989b) Sequence and process of species selection by cattle in relation to optimal foraging theory on an old land in the Natal sour sandveld. *Journal of the Grassland Society of Southern Africa* **7**, 71-76.

O'Reagain PJ, Turner JR (1992) An evaluation of the empirical basis for grazing management recommendations for rangeland in southern Africa. *Journal of the Grassland Society of Southern Africa* **9,** 38-49.

Orr DM (1980) Efects of sheep grazing Astrebla grassland in central western Queensland. II. Effects of season rainfall. *Australian Journal of Agricultural Research* **31**, 807-820.

Orr DM (1991) Trends in the recruitment of *Astrebla* spp. in relation to seasonal rainfall. *Rangeland Journa1* **13,** 107-117.

Orr DM (2004) Dynamics of plant populations in *Heteropogon contortus* (black speargrass) pastures on a granite landscape in southern Queensland. 4. The effects of burning on *H. contortus* and *Aristida* spp. populations. *Tropical Grasslands* **38**, 77-87.

Orr DM (2005) Effects of stocking rate, legume augmentation, supplements and fire on animal production and stability of native pastures. Meat and Livestock Australia Final Report NAP3.207.

Orr DM (2010) Managing the grass-legume balance in *Stylosanthes scabra* cv. Seca pastures in central Queensland *Tropical Grasslands* **44,** (in press).

Orr DM, Evenson CJ (1991) Effects of sheep grazing *Astrebla* grasslands in central western Queensland. III. Dynamics of *Astrebla* spp. under grazing and exclosure between 1975 and 1986. *The Rangeland Journal* **13**, 36-46.

Orr DM, McKeon GM, Day, K.A. (1991) Burning and exclosure can rehabilitate degraded black speargrass (*Heteropogon contortus*) pastures. *Tropical Grasslands* **25**, 333-336.

Orr DM, Paton CJ (1997) Using fire to manage species composition in *Heteropogon contortus* (black speargrass) pastures 2. Enhancing the effects of fire with grazing management. *Australian Journal of Agricultural Research* **48**, 803-810.

Orr DM, Paton CJ, Lisle AT (1997) Using fire to manage species composition in *Heteropogon contortus* (black speargrass) pastures 1. Burning regimes. *Australian Journal of Agricultural Research* **48**, 795-802.

Orr DM, Phelps DG (2003) Plant species diversity in *Astrebla* spp. grassland following 18 years of sheep grazing. Proceedings of the VIIth International Rangeland Congress, Durban. (Eds N Allsopp, AR Palmer, SJ Milton, KP Kirkman, GIH Kerley, CR Hurt, CJ Brown) pp. 256-258.

Orr DM, Phelps DG (in preparation) Ecosystem process in northern Mitchell grass pastures as affected by sheep grazing management over 25 years *The Rangeland Journal*

Orr DM, Yee MC, Myles DJ (2006) Impact of short-term exclosure from grazing on pasture recovery from drought in six Queensland pasture communities. *Tropical Grasslands* **40**, 202-212.

Parsons AJ, Johnson IR, Harvey A (1988) Use of a model to optimise the interaction between frequency and severity of intermittent defoliation and to provide a fundamental comparison of the continuous and intermittent defoliation of grass. *Grass and Forage Science* **43**, 49-59.

Parsons AJ, Penning PD (1988) The effect of the duration of regrowth on photosynthesis, leaf death and the average rate of growth in a rotationally grazed sward. *Grass and Forage Science* **43**, 15-27.

Paton CJ (2004) Restoring the condition of degraded black speargrass pastures in southern speargrass zone SWAMP: Speargrass, Wiregrass, Animal Management Project. Meat and Livestock Australia Final Report NAP3.209.

Paton CJ, Rickert KG (1989) Burning, then resting, reduces wiregrass (*Aristida* spp.) in black speargrass pastures. *Tropical Grasslands* **23**, 211-218.

Phelps DG (1999) The combined stresses of spring burning and low summer rainfall can reduce *Aristida latifolia* infestations. In 'People and rangelands: building the future. Proceedings of the VI International Rangeland Congress, Townsville, Queensland, Australia, 19-23 July, 1999. Volumes 1 and 2.' (Eds D Eldridge and D Freudenberger) pp. 253-254. (VI International Rangeland Congress, Inc: Aitkenvale, Qld.)

Phelps D, Orr D, Houston I (2007) Mitchell grass death in Queensland: extent, economic impact and potential for recovery. MLA Final Report Project NBP.348.

Post DA, Bartley R, Corfield J, Nelson B, Kinsey-Henderson A, Hawdon A, Gordon I, Abbott B, Berthelsen S, Hodgen M, Keen R, Kemei J, Vleeshouwer J, MacLeod N, Webb M (2006) Sustainable grazing for a healthy Burdekin catchment. Meat and Livestock Australia Final Report NBP.314.

Pratchett D, Gardiner G (1993) Does reducing stocking rate necessarily mean reducing income? *In* ‘Proceedings of the Fourth International Rangeland Conference’. (Eds A. Gaston, M. Kernick and H. Le Houérou). pp. 714-716. Association Française de Pastoralisme, Montpellier.

Pratt DJ, Gwynne MD (1977) 'Rangeland Management and Ecology.' (Robert E. Krieger Publishing: Huntington, New York).

Pratt DW (1993) Principles of controlled grazing. http://www1.foragebeef.ca/$foragebeef/frgebeef.nsf/all/frg37/$FILE/grazingprinciples.pdf.

Provenza FD, Villalba JJ, Dziba LE, Atwood SB, Banner RE (2003) Linking herbivore experience, varied diets, and plant biochemical diversity. *Small Ruminant Research* **49**, 257–274.

Purvis JR (1986) Nurture the land: my philosophies of pastoral management in central Australia. *Australian Rangeland Journal* **8**, 110-117.

Quirk M, McIvor J (2003) ‘Grazing Land Management: Technical Manual.’ (Meat and Livestock Australia: Sydney).

Radford IJ, Grice AC, Abbott BN, Nicholas DM, Whiteman L (2008) Impacts of changed fire regimes on tropical riparian vegetation invaded by an exotic vine. *Austral Ecology* **33**, 151-167.

Richards JH (1993) Physiology of plants recovering from defoliation. Proceedings of the XVII International Grassland Congress, Palmerston North. pp. 85-94.

Ridley PER, Schatz T (2006) Meeting post weaning market specifications for the live cattle export trade to South East Asia. MLA Project NAP 3.111 Final Report.

Rittenhouse LR, Bailey DW (1996) Spatial and temporal distribution of nutrients. In: M. B. Judkins and F. T. McCollum, III [eds.]. Proceedings of the 3rd Grazing Livestock Nutrition Conference. Proceedings, Western Section, American Society of Animal Science **47**(Suppl 1), 51–61.

Roe R, Allen GH (1945) Studies on the Mitchell grass association in south-western Queensland. 2. The effect of grazing on the Mitchell grass pasture. Bulletin No. 185, Council for Scientific and Industrial Research, Melbourne.

Roe R, Allen GH (1993) Studies on the Mitchell Grass Association in South-Western Queensland. 3. Pasture and wool production under different rates of stocking and continuous or rotational grazing. *The Rangeland Journal* **15**, 302-319.

Rossiter NA, Setterfield SA, Douglas MM, Hutley LB (2003) Testing the grass-fire cycle: alien grass invasion in the tropical savannas of northern Australia. *Diversity and Distributions* **9**, 169-176.

Roth CH (2004) A framework relating soil surface condition to infiltration and sediment and nutrient mobilization in grazed rangelands of northeastern Queensland, Australia. *Earth Surface Processes and Landforms* **29**, 1093-1104.

Roth CH, Prosser IP, Post DA, Gross JE, Webb MJ (2003) Reducing sediment export from the Burdekin catchment project. CSIRO Land and Water, Meat and Livestock Australia Final Report NAP3.224 (MLA, North Sydney.)

Russell-Smith J, Edwards AC, Cook GD, Schatz J, Brocklehurst P (2006) Estimating greenhouse gas emissions from savanna burning in northern Australia. *Forest Ecology and Management* **234**, S152.

Russell-Smith J, Stanton P (2002) Fire regimes and fire management of rainforest communities across northern Australia. In 'Flammable Australia: the fire regimes and biodiversity of a continent'. (Eds RA Bradstock, JE Williams and AM Gill) pp. 329-350. (Cambridge University Press: Cambridge)

Savory A, Butterfield J (1999) 'Holistic management A new framework for decision making.' (Island Press: Washington, D.C.).

Scanlan JC (1980) Effects of spring wildfires on *Astrebla* (Mitchell grass) grasslands in north-west Queensland under varying levels of growing season rainfall. *The Rangeland Journal* **2**, 162-168.

Scanlan JC (1983) Changes in tiller and tussock characteristics of *Astrebla lappacea* (curly Mitchell grass) after burning. *The Rangeland Journal* **5**, 13-19.

Scanlan JC (2002) Some aspects of tree-grass dynamics in Queensland's grazing lands. *The Rangeland Journal* **24**, 56-82.

Scanlan JC, Hinton AW, McKeon GM, Day KA, Mott JJ (1994) Estimating safe carrying capacities of extensive cattle-grazing properties within tropical, semi-arid woodlands of north-eastern Australia. *Rangeland Journal* **16**, 64-76.

Scanlan JC, McIvor JG (1993) Pasture composition influences soil erosion in *Eucalyptus* woodlands of northern Queensland. Proceedings of the XVII International Grasslands Congress, Palmerston North, Hamilton and Lincoln, New Zealand and Rockhampton. Australia. pp. 65-66.

Scanlan JC, Pressland AJ, Myles DJ (1996a) Run-off and soil movement on mid-slopes in north-east Queensland grazed woodlands. *The Rangeland Journal* **18,** 33-46.

Scanlan JC, Pressland AJ, Myles DJ (1996b) Grazing modifies woody and herbaceous components of north Queensland woodlands. *The Rangeland Journal* **18**, 47-57.

Scattini WJ (1973) A model for beef cattle production from rangeland and sown pasture in south-eastern Queensland. PhD Thesis, University of California, Berkeley, USA.

Schmidt PJ (1969) Observations on the behaviour of cattle in a hot dry region of the Northern Territory of Australia, with particular reference to walking, watering and grazing. M.Rur.Sc. thesis, The University of New England, Armidale.

Setterfield SA (2002) Seedling establishment in an Australian tropical savanna: effects of seed supply, soil disturbance and fire. *Journal of Applied Ecology* **39**, 949-959.

Shaw KA, Tincknell IW (1993) Producer establishment practises and experiences in north Queensland. *Tropical Grasslands* **27,** 367-372.

Shaw K, Rolfe J, English B, Matthews R, Kernot J (2009) Ecobeef demonstration. QDPIF report.

Silcock RG, Beale IF (1986) Complete destocking will not reclaim some Australian rangelands. Proceedings of the Australian Rangeland Society 4th Biennial Conference, Armidale. pp. 150-153.

Silcock RG, Hall TJ (1996) Tactical pasture management: Enhancing profits from poplar pox country. International Wool Secretariat Final Report Project DAQ.076

Silcock RG, Jones P, Hall TJ, Waters DK (2005) Enhancing pasture stability and profitability for producers in Poplar Box and Silver-leaved Ironbark woodlands. MLA Final Report NAP3.208.

Singh VP, Hall LP (1976) Responses of *Andropogon pumilus* Roxb. to various heights and intervals of clipping. *Journal of Range Management* **44**, 135-137.

Smith EL (1960) Effects of burning and clipping at various times during the wet season on tropical tall grass range in northern Australia. *Journal of Range Management* **13**, 197-203.

Squires, V. 1981. Livestock Management in the Arid Zone. Inkata Press, Melbourne.

Stafford Smith DM (1988) 'Modelling: three approaches to predicting how herbivore impact is distributed in rangelands.' Report 628. (New Mexico Agriculture and Experimental Station Regional Resources: Las Cruces.)

Stafford Smith DM (1990) Waters and the patterns of animal use. Proceedings of the Sixth Australian Rangeland Conference, Carnarvon WA. pp. 35-44.

Stobbs TH (1973) The effect of plant structure on the intake of tropical pastures II. Differences in sward structure, nutritive value, and bite size of animals grazing *Setaria anceps* and *Chloris gayana* at various stages of growth. *Australian Journal of Agricultural Research* **24**, 821-829.

Stobbs TH (1977) Seasonal changes in the preference by cattle for *Macroptilium atropurpureum* cv. Siratro. *Tropical Grasslands* **11**, 87-91.

Stocker GC, Sturtz JD (1966). The use of fire to establish Townsville lucerne in the Northern Territory. *Australian Journal of Experimental Agriculture and Animal Husbandry* **6**, 277-279.

Stoddart LA, Smith AD, Box TW (1975) *Range Management.* McGraw-Hill, New York.

Stoltsz CW, Danckwerts JE (1990) Grass species selection patterns on rotationally-grazed Dohne sourveld during autumn and early winter. *Journal of the Grassland Society of Southern Africa* **7**, 92-96.

Stuth JW (1991) Foraging behaviour. In 'Grazing Management An Ecological Perspective'. (Eds RK Heitschmidt, JW Stuth) pp. 65-83. (Timber Press: Portland).

Tainton NM (1981) 'Veld and pasture management in South Africa.' (Shuter and Shooter: Pietermaritzburg).

Tainton NM (1999) 'Veld management in South Africa.' (University of Natal Press: Pietermaritzburg).

Tainton NM, Groves RH, Nash R (1977) Time of mowing and burning veld: short term effects on production and tiller development. *Proceedings of the Grassland Society of Southern Africa* **12**, 59-64.

Teague WR, Dowhower SL (2003) Patch dynamics under rotational and continuous grazing management in large, heterogeneous paddocks. *Journal of Arid Environments* **53**, 211–229.

Teague WR, Dowhower SL, Waggoner JA (2004) Drought and grazing patch dynamics under different grazing management. *Journal of Arid Environments* **58**, 97-117.

Tomkins N (2008) Managing grazing by alternating water points – determining the effect of grazing patterns, Rockhampton Downs. Final report to MLA, B NBP.0376.

Tomkins NW, O'Reagain PJ (2007) Global positioning systems indicate landscape preferences of cattle in the subtropical savannas. *Rangeland Journal* **29**, 217-222.

Tomkins NW, O'Reagain PJ, Swain D, Bishop-Hurley G, Charmley E (2009). Determining the effect of stocking rate on the spatial distribution of cattle for the subtropical savannas. *Rangeland Journal* **31,** 267-276.

Tothill JC, Gillies C (1992) The pasture lands of northern Australia. Tropical Grassland Society of Australia Occasional Publication No. 5.

Tothill JC, McDonald CK, McHarg GW (2009) Effect of wet season rotational grazing on pasture and animal production in buffel (*Cenchrus ciliaris*) - siratro (*Macroptilium atropurpureum*) pastures in south-east Queensland. *Tropical Grasslands* **43**, 162-170.

Townsend S (1997) The impact of fire management on stream water quality in the wet/dry tropics of northern Australia. In 'Bushfire '97: Proceedings 6th Australian Bushfire Conference, Plaza Hotel, Darwin, Northern Territory, Australia'. (Eds B McKaige, RJ Williams and WM Waggitt) pp. 60-65. (CSIRO Tropical Ecosystems Research Centre: Winnellie, N.T.)

Townsend SA, Douglas MM (2000) The effect of three fire regimes on stream water quality, water yield and export coefficients in a tropical savanna (northern Australia). *Journal of Hydrology (Amsterdam)* **229**, 118-137.

Veira DM (2007) Meeting water requirements of cattle on the Canadian prairies. *Rangeland Journal* **29**, 79-86.

Vogler WD (2002) Autecology of *Sporobolus pyramidalis* with emphasis on seed ecology. PhD Thesis. School of Agronomy and Horticulture, University of Queensland, Brisbane.

Walburger KJ, Wells M, Vavra M, Del Curto T, Johnson B, Coe P (2009) Influence of cow age on grazing distribution in a mixed-conifer forest. *Rangeland Ecology and Management* **62**, 290–296.

Wallis de Vries MF, Daleboudt C (1994) Foraging strategy of cattle in patchy grassland. *Oecologia* **100**, 98–106.

White DH (1987) Stocking rate. In 'Ecosystems of the World. 17B. Managed Grasslands: Analytical Studies'. (Ed. RW Snaydon) pp. 227-238. (Elsevier: Amsterdam).

Williams PR, Congdon RA, Grice AC, Clarke, P.J. (2003a) Effect of fire regime on plant abundance in a tropical eucalypt savanna of north-eastern Australia. *Austral Ecology* **28**, 327-338.

Williams PR, Congdon RA, Grice AC, Clarke PJ (2003b) Fire-related cues break seed dormancy of six legumes of tropical eucalypt savannas in north-eastern Australia. *Austral Ecology* **28**, 507-514.

Williams PR, Congdon RA, Grice AC, Clarke PJ (2005a) Germinable soil banks in a tropical savanna: seasonal dynamics and effects of fire. *Austral Ecology* **30**, 79-90.

Williams PR, Congdon RA, Grice AC, Clarke PJ (2005b) Effect of season of burning and removal of herbaceous cover on seedling emergence in a eucalypt savanna of north-eastern Australia. *Austral Ecology* **30**, 491-496.

Williams RJ, Cook GD, Gill AM, Moore PHR (1999c) Fire regime, fire intensity and tree survival in a tropical savanna in northern Australia. *Australian Journal of Ecology* **24**, 50-59.

Williams RJ, Woinarski JCZ, Andersen AN (2003) Fire experiments in northern Australia: contributions to ecological understanding and biodiversity conservation in tropical savannas. *International Journal of Wildland Fire* **12**, 391-402.

Winter WH, Mott JJ, McLean RW, Ratcliff D (1989) Evaluation of management options for increasing the productivity of tropical savanna pastures 1. Fertiliser. *Australian Journal of Experimental Agriculture* **29**, 613-622.

Wright DM, Jordan GJ, Lee WG, Duncan RP, Forsyth DM, Coomes DA (2010) Do leaves of plants on phosphorus-impoverished soils contain high concentrations of phenolic defence compounds? *Functional Ecology* **24**, 52–61.