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Catchment management, water quality and nutrient flows as they relate to the Northern Australian beef industry

An overview of literature and current research

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This overview would not have been possible without the willing and generous assistance of very many people. I had originally intended to put with the review a list of the people who were contacted and provided information, but so many people have helped this was not considered feasible. To all those people who gave me, and those on the review team, so much of their time, often at such very short notice, I express my sincere thanks. I also wish to thank those who helped with the component reviews — I know that for most, this involved many hours outside the normal working day. Their commitment and interest have been keenly felt and very much appreciated. I also thank Heather Hunter (Queensland Department of Natural Resources) for the written sections on Queensland monitoring programs that have been incorporated in Review 5.

The workshop convened by the Meat Research Corporation to review the draft report, held in Brisbane on August 7th, 1997, provided invaluable feedback. This final report incorporates many of the suggestions and comments made at the workshop and the time and input of those attending the workshop is acknowledged with gratitude. In particular, I would like to thank Barry Walker (NAP3 program coordinator) and Annemarie Watt (Environment Australia) for written comments on the draft report. It has not been possible to include all changes suggested at the workshop and others have no doubt been inadvertently overlooked. I apologize for these omissions. John Aldrick (CSIRO Land and Water) kindly reviewed several chapters in the final report and his many helpful suggestions are gratefully acknowledged. Finally, I wish to thank the project steering committee for their guidance, advice and assistance throughout the project.

EXECUTIVE SUMMARY

Extended dry seasons over several years combined with changed cattle production systems have placed increased pressure on native pastures across northern Australia. Over the past twenty years stocking rates in some areas have begun to exceed 'safe' carrying capacities resulting in undesirable changes in pasture composition, and soil degradation. The increases in grazing pressure have coincided with an increasing awareness that the changed processes in the land that lead to pasture and soil degradation, can also affect water quality of the catchment. There is particular concern about the off-shore effects that changes in river water quality may be having. Such effects may involve, for example, increased sediment and nutrient inputs degrading the estuarine breeding grounds of commercial fisheries or changing the ecology of coral reefs. This concern is illustrated by the several conferences and workshops that have been held to discuss the changes in, and effects of, terrigenous inputs to the Great Barrier Reef lagoon, and by the formation in Queensland of the Downstream Effects of Agricultural Practices (DEAP) committee.

There is also increasing awareness of the need for Australian industries to be productive and economically viable, but not at the expense of degrading our natural resources so as to impair their capacity for use, including use by future generations. This need has been enunciated in the principles of ecologically sustainable development. As a result of the increased awareness within the community of the need to maintain the productivity of our natural environment, there are increasing requirements for agricultural commodities to be produced so as not to cause degradation of our biota, and land and water resources. It is becoming more and more incumbent on agricultural industries to demonstrate that their management practices are not degrading the environment.

It is now well understood that catchment water quality and its implications for downstream biota and water use, are the result of all activities within a catchment. This has lead to the concept of Integrated or Whole Catchment Management and the development of catchment management groups. The aim of these groups is to develop catchment management strategies and plans to ensure that management is integrated and that the different land uses are not detrimentally affecting other industries. While the management of grazing lands must take place within a whole catchment framework, it is also essential that the off-site effects attributable to particular grazing practices be separated from those caused by other industries, or which occur naturally. By being in possession of the facts, the industry can take proper and realistic responsibility, and develop a strategic position for the future which will enhance its competitiveness, particularly internationally.

These issues are of concern to the Meat Research Corporation and the Land and Water Resources Research and Development Corporation and are being addressed in Phase 3 of the North Australia Program (NAP3). Phase 3 follows Phases 1 and 2, and extends from mid 1996 to mid 2001. The North Australia Program, which is jointly funded by the Meat Research Corporation and the Land and Water Resources Research and Development Corporation, seeks to "improve the profitability, international competitiveness and ecological sustainability of beef production in northern Australia".

International competitiveness has been addressed by examining the determinants of competitiveness and concluding, among other things, that adoption of acceptable environmental standards will be fundamental to the future of the industry. Subprogram 2 of NAP3, Improving Resource Management, aims to increase international competitiveness and hence profitability, by improving the development and adoption of ecologically sustainable resource management systems and their profitable utilization by the northern Australian beef industry.

To assist in developing a relevant program of research for NAP3, the Meat Research Corporation and the Land and Water Resources Research and Development Corporation jointly commissioned a broad overview of current information on the effects of catchment use and management in the grazing lands of northern Australia, on water and nutrient cycles and the downstream fluxes of water, sediment and nutrients. Interactions between grazing management (primarily stocking rates and their variation in time and space), drought, clearing and pasture improvement in producing these effects, were regarded as particularly important. Also important were the effects of these changes on the ecological status of riverine, estuarine and marine ecosystems, although the review was not concerned with impacts upon biological diversity more generally as this has been the focus of another project within NAP3. As well as reviewing current knowledge, the commissioned review was also required to recommend work which might appropriately be funded by NAP3 and to prepare a draft report for review by a forum of northern Australian beef producers and others with responsibilities in natural resource management.

A large amount of research relevant to this topic has been undertaken and it was not possible in the time-frame available to comprehensively review all material. The aim has been to identify major gaps in understanding and knowledge. Most research to date has involved understanding the effects of particular stocking regimes on pasture composition and water, sediment and sometimes nutrient fluxes. Generally, this work has been for plots or small catchments. There has also been some work identifying the effect of clearing and pasture improvement on components of the water balance. The terrestrial inputs from catchments flowing into the Great Barrier Reef lagoon, the fate and effect of these inputs, has also received some attention. Estimations of terrestrial inputs and their change following the introduction of grazing, have been based on fluxes measured for plots or small catchments or on extrapolations from rivers and streams for which sediment concentration and flow data are available. A very limited amount of work is currently underway using coral and sediment cores to investigate temporal changes in terrestrial inputs from catchments on the east coast of Queensland. The issue of the degree to which the introduction of grazing has increased sediment and nutrient fluxes to the marine environment over and above natural inputs, and the effect of this increase, particularly on the Great Barrier Reef, remains equivocal.

Despite the large amount of research that has been undertaken, major gaps in knowledge remain, which is not surprising given the vast area covered by the northern Australian beef industry. Areas of particular concern are:

- the paucity of research investigating the effects of grazing and grazing land management on wetlands and riparian areas; qualitative subjective assessments based on observation are numerous but there are few data that quantify the changes that have occurred;
- the major gaps in our knowledge of the interactions between the various components of the grazing system, their variation for different land types, and in time and space within a given land unit — past work has focussed predominantly on pasture—animal interactions; in future, consideration also needs to be given to vegetation—nutrient—soil biota interactions and soil—pasture condition—water inter-relationships;
- the scant research in processes for areas larger than plot and small catchment — this reflects the 'grazing trial' nature of much research carried out to date; for example, apart from studies of the effect of the distribution of watering points, there has been little investigation of animal behaviour and its effect within paddocks, or of the time it takes for local changes in the flux of water, sediments and nutrients as a result of grazing management practices to have an effect on fluxes from the whole catchment;
- the lack of information on components of the water balance and changes in the flux of water, sediment and nutrient, relating to particular landscapes (land with similar climate, geology, topography, regolith and soil, and vegetation); also of concern is the fact that relatively little use seems to be being made of land system data although land information is critical to assessments of land productivity and its inherent susceptibility to degradation; and
- the apparent non-awareness within the grazing industry as a whole, of the need to adjust stocking rates, both in space and time, to match pasture productivity, and of the degradational consequences of not doing so both on the land on which the pastoral enterprise depends, and on the water resources downstream.

Given the large gaps in knowledge in many areas relevant to understanding the effects of the northern Australian beef industry, there are several recommendations which could be made for appropriate work. The following specific recommendations reflect the outcome of discussions arising at the workshop held in Brisbane, to review the draft report.

Recommendations

The first two recommendations are for more preliminary work to be undertaken before development of the final research proposal. The third recommendation relates to the type of research to be undertaken.

Further information on current projects

Current projects related to water and nutrient movement, and catchment management more generally, need to be assessed to identify more specifically the knowledge that is being obtained and any deficiencies of the work. This will require the collection of further details on the problems being addressed, project objectives, methods being used, where the work is being undertaken, the organization that is doing it, the timescale and the sources of funding. NAP2 projects that are being extended into NAP3 need to be included.

Identification of appropriate catchment(s) for research

Given that major research will need to be limited to one or two catchments as a result of funding constraints, an important issue is the catchment(s) in which the research should be done. A scoping study that considers all catchments across northern Australia needs to be undertaken as a matter of priority. As a starting point, the study needs to establish the criteria against which catchments would be ranked and grouped. Some of the suggested criteria are:

- a perceived high potential for the grazing industry to affect land and water quality;
- a catchment community that wants the sort of information that will be generated by the research;
- a catchment that is considered to be important from the point of view of the grazing industry; and
- an effective extension process already in place to pick up research results and incorporate them into catchment planning.

The first criterion requires characterisation of catchments in terms of biophysical attributes, including geomorphology, climate and land use, in an attempt to identify potential vulnerability to degradation and risk of off-site effects. Also important are whether catchments are coastal or inland and whether rivers are regulated or unregulated. It is also recommended that this scoping project assess the land system and other resource mapping information available across northern Australia. Note should also be made of catchments in which NAP3 projects arising from NAP2 projects, are being undertaken.

Recommended research

The third recommendation is to establish a project or projects to identify and measure the significant effects that the north Australian beef industry is having on the movement of water and nutrients within the catchment and the effect of this movement on water quality and the sustainable use of other resources.

It is recommended that the research involve:

- an analysis of the surface hydrology, landforms and patterns of sediment generation, transport and deposition, and the delineation of geomorphic provinces;
- an interpretation of the inherent capacity of the geomorphic provinces to supply sediment and nutrients to the major river systems and the susceptibility of the land within them to degradational processes as a result of specific grazing practices;
- establishing budgets for water and key nutrients at paddock to catchment scales, using the provinces as a guide to major landscapes for which budgets are required;
- examining the extent to which grazing and grazing management practices enhance loss (as distinct from redistribution) of water, sediment, nutrient or organic matter, from local areas (ie, catchment divide to water course); and
- determining the effect any such losses are having on land functioning and productivity, both on and off site.

It was recognized that this project needs to be linked with the biodiversity research that will be funded in NAP3.

1. INTRODUCTION

1.1. Background

Extended dry seasons over several years combined with changed cattle production systems have placed increased pressure on native pastures across northern Australia over the past twenty or so years [see, for example, Tothill and Gillies (1992) and Williams *et al.* (1993)]. Until the 1970s, the rangelands were grazed at low stocking rates by British breeds of cattle which were poorly adapted to the tropics. In drought years with low pasture production, animals died if stock numbers were not reduced, with the result that cattle herds tended to naturally readjust to the prevailing conditions (Figure 1.1). During the 1970s, *Bos indicus* cross-breeds which were better adapted to dry conditions, were introduced. The greater capacity of these breeds to survive dry periods, aided by diet supplementation with non-protein nitrogen and minerals, resulted in large increases in herd sizes by the late 1970s (Figure 1.2). In addition to increased herd numbers, improved transportation allowed cattle to remain on properties for longer during droughts and to return from agistment sooner. As a consequence, stocking rates began to exceed 'safe' stocking rates and this has resulted in undesirable changes in pasture composition and soil degradation (Tothill and Gillies, 1992).

The increases in grazing pressure have coincided with an increasing awareness that activities in one part of a catchment not only affect land condition and processes where they occur, but that the changed processes on land can also lead to changes in waterways and downstream waterbodies. There is growing concern that high grazing pressures and grazing land management are having detrimental effects not only on pastures and land condition but also on water quality. There is particular concern about the off-site effects that may result from inappropriate grazing management in catchments draining to the coast. Such effects may involve, for example, increased fluxes of sediments and nutrients degrading the estuarine breeding grounds of commercial fisheries and altering the ecology of off-shore reefs. The effect of terrigenous inputs of sediment and nutrients on the Great Barrier Reef, classified as a World Heritage Area, has received particular attention [see, for example, papers in the proceedings of recent conferences such as Downstream Effects of Land Use (Hunter *et al.* 1996); Great Barrier Reef: Terrigenous Sediment Flux and Human Impacts (Larcombe, P., Woolfe, K. and Purdon, R. 1996); The Great Barrier Reef: Science, Use and Management (Turia, N. and Dalliston, C., 1997)].

There is also increasing awareness of the need for Australian industries to be productive but not at the expense of degrading our natural resources so as to impair their capacity for use, including use by future generations. This need has been enunciated in the principles of ecologically sustainable development. Bringing together the knowledge of scientists, primary producers and others who use and manage the different catchment resources, will play an important role in ensuring that the development of our industries takes place within the bounds of the productive potential and susceptibility to deterioration of our land and water resources.

In moving to define 'best practice' within the northern Australian beef industry, account must be taken of the whole range of environmental effects of the industry. This includes both the direct effects on land (including the biota) as well as the indirect effects on waterways, such as chemical contamination or the stimulation of algal and microbial proliferation. In many instances, other primary industries and land uses located within a catchment can have similar effects on catchment resources. For this reason, management strategies are needed for whole catchments to ensure that there is integrated management of land, water and the associated biological resources, and that the different land uses are not detrimentally affecting other industries. While whole or integrated catchment management is essential, it is also necessary that the off-site effects due to grazing be separated from those caused by other industries, as well as from the changes which occur naturally. It is only in this way that the grazing industry can take proper but at the same time realistic responsibility for its actions. By being in possession of the facts, the industry will be able to adopt a strategic position for the future.

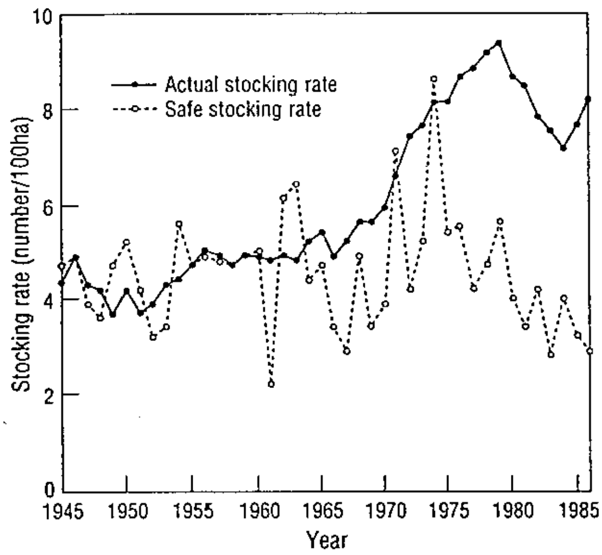

Figure 1.1. Actual and safe stocking rates for the period 1945-1985, Dalrymple shire, Qld. (from Pressland and McKeon 1990)

Safe stocking rate = summer pasture growth (kg/ha Dec-May) x 30% utilization / 6 months animal intake x shire index (accounts for effect trees)

Pasture growth: calculated using the GRASP model

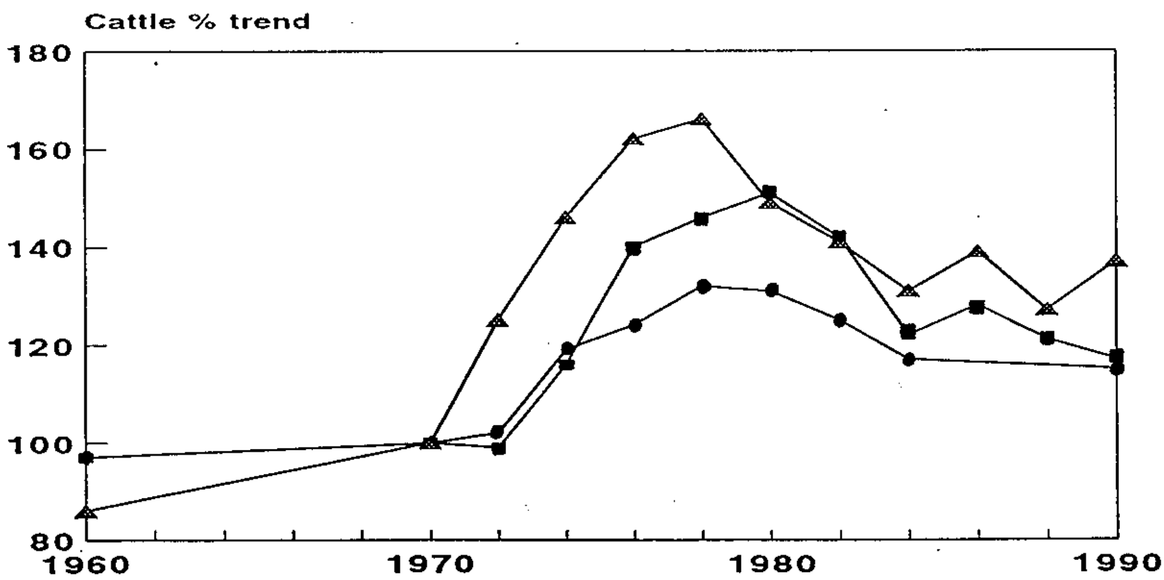

Figure 1.2. Relative changes in cattle populations from 1970-1990, using 1970 as a base. (From Tothill and Gillies, 1992)

▲ Queensland ■ Northern Territory ● Western Australia

These issues are of concern to the Meat Research Corporation (MRC) and the Land and Water Resources Research and Development Corporation (LWRRDC) and are being addressed in Phase 3 of the North Australia Program (NAP3). Phase 3 follows Phases 1 and 2, and extends from mid 1996 to mid 2001. The North Australia Program, which is jointly funded by the MRC and the LWRRDC, seeks to "improve the profitability, international competitiveness and ecological sustainability of beef production in northern Australia". This is to be achieved through the operation of four sub-programs:

1. Meeting Market Requirements;
2. Improving Resource Management;
3. Improving Property Management; and
4. Improving Program Delivery.

International competitiveness has been addressed by examining the determinants of competitiveness and concluding, among other things, that adoption of acceptable environmental standards will be fundamental to the future of the industry. Subprogram 2, Improving Resource Management, aims to increase international competitiveness and hence profitability, by improving the development and adoption of ecologically sustainable resource management systems and their profitable utilization by the northern Australian beef industry. The key issues to be addressed by the subprogram are:

- the need to understand and more effectively apply existing principles and indicators of ecologically sustainable grazing systems;
- the need to continue and expand core investigations of the effects of grazing management strategies and to integrate them with activities promoting preferred strategies;
- the need to strategically position the northern Australian beef production sector to identify and deal with environmental threats and opportunities, including consideration of alternative resource management systems, should existing systems not be ecologically sustainable and profitable.

The principal strategies to address the key issues are:

- to identify and act on constraints and opportunities to improve the adoption of ecologically sustainable grazing systems;
- to apply and further develop ecological sustainability principles for profitable systems in particular agro-ecological regions; and
- to define and monitor the state of the soil, water and biological resources used or affected by the northern Australian beef industry.

2. Overview of catchment management, water quality and nutrient flows, and ecological effects as they relate to the northern Australian beef industry

In this context, the Meat Research Corporation and the Land and Water Resources Research and Development Corporation jointly commissioned a broad overview of current information on the effects of catchment management in the grazing lands of northern Australia, on water and nutrient cycles and the downstream fluxes of water, sediment and nutrients. Interactions between grazing management (primarily stocking rates and their variation in time and space), drought, clearing and pasture improvement in producing these effects, are particularly important. Also important are the effects of these changes on the ecological status of riverine, estuarine and marine ecosystems. Appendix 1 provides full details of the Terms of Reference for this review.

2.1. Scope of the review

2.1.1. Geographic area and regional variation

For the purposes of this overview, the effects of extensive grazing only are considered, not the effects of beef production from feed-lots. Grazing lands in northern Australia include those of Queensland, the Northern Territory and the north-west part of Western Australia (Figure 1.3.).

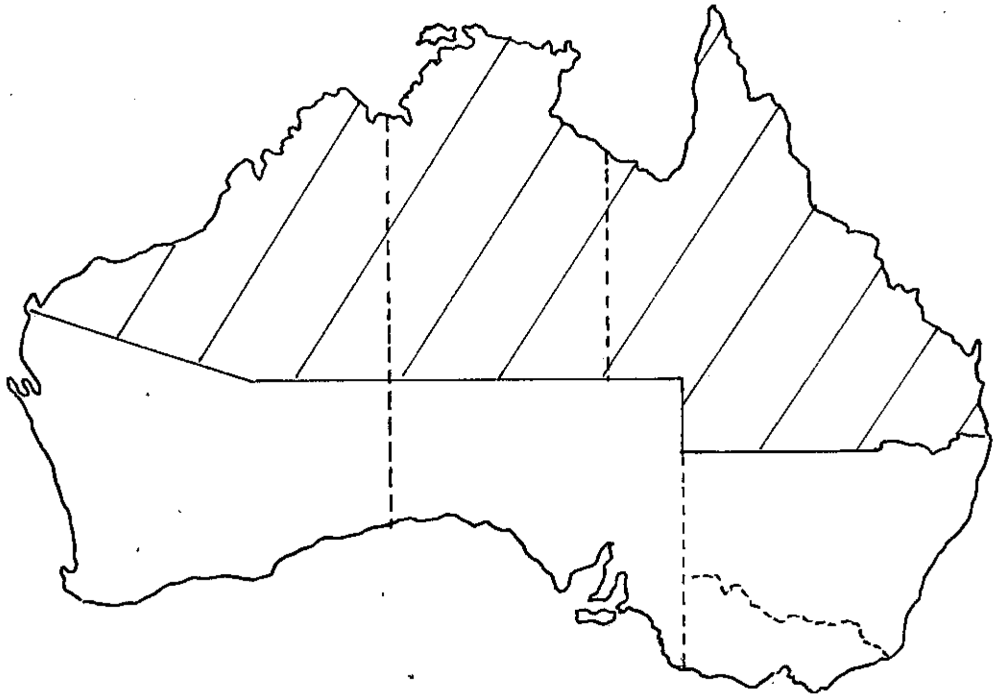

Figure 1.3. The area of northern Australia encompassed by this review

Encompassing such a large part of Australia, a wide variation in climate and landscape characteristics occurs throughout the region. The low latitude tropics have a more clearly defined summer rainfall pattern and rainfall declines from the coastal areas to the more arid inland. The variation in climate has a large influence on the hydrology of northern Australian catchments. Catchments draining to the coast occur in the more humid areas of northern Australia and mostly have pronounced high volume late summer flows that decline to low or zero flow over the winter, spring and early summer months. In contrast, the internally draining river systems, such as those of the Cooper, Diamantina and Georgina, are characterised by high flow variability which increases downstream. Discharge volumes also tend to decrease downstream. This pattern reflects the variable and erratic rainfall with increasing aridity inland, and the immense dispersal system of the floodplains (Morrish, R.B. 1996).

There is also enormous variation in geology and landform, and corresponding diversity in soils, vegetation and associated fauna. Clearly the effect of grazing management will vary considerably throughout northern Australia. Ideally an understanding of the effects of grazing management on the land and its biota, and the downstream ramifications, should consider the variation in catchment characteristics and landscapes. This has not been possible in this review due to the time constraints. Principles only are discussed, while the need for these to be translated with respect to specific catchments and landscapes is noted.

2.1.2. Biological diversity

"Biological diversity (often shortened to biodiversity) encompasses the variation that exists between individuals within a species, between populations of species, between species themselves, between communities, landscapes and ecosystems" (Lambeck, 1997). Retaining the natural biological diversity within a region is another issue that is being increasingly recognized as important. The importance derives from philosophic considerations and the view that human societies should not cause the decline and extinction of other organisms, as well as from practical and economic perspectives — we simply do not know the future needs and problems of society and the hitherto unknown benefits that particular biota, communities or ecosystems may provide for them.

The effect of grazing on the northern Australian native fauna and flora (which is taken as including all levels of biological organization from species variety through to ecosystems) is of increasing concern, as much of the biological diversity of northern Australia is not included in formal reserves. The lack of representation within reserves means that maintenance of a considerable proportion of the northern Australian biota will very often depend on the management of grazing and grazing lands. Management of grazing and grazing lands so as to conserve the biological diversity within northern Australia is a major issue for the Improving Resource Management subprogram and is the focus of a separate project to identify appropriate research for funding under NAP3. Consequently the effect of grazing on biological diversity generally was not a component of this review. The effects of grazing on riparian and wetland biota, however, are considered in the context of the off-site effects of grazing, and the effects of grazing on soil fauna and flora are part of understanding the effects of grazing on soil properties and processes.

2.1.3. Mathematical models

Mathematical models which are able to simulate plant growth and/or water and nutrient movement either at a point or within a catchment, are becoming useful tools with which to investigate the likely effects of particular management practices and grazing strategies. Such models are not systematically reviewed although modelling work is considered in relation to some processes. The view was taken that, since models can only be based on our understanding of system function, the first priority was to assess our understanding and knowledge of the way landscapes and catchments are functioning — if our understanding is not adequate, neither will be our models.

2.1.4. Monitoring and decision support systems

The North Australia Program recognizes that monitoring the state of soil, water and biological resources used or affected by the northern Australian beef industry is central to any adaptive management that maintains the integrity of the resource base. Similarly, decision support systems can be a useful tool for helping graziers with strategic and tactical decisions relating to managing their stock and properties so as not to degrade the vegetation and soil resources.

Different monitoring programs are already in place within Queensland, the Northern Territory and Western Australia but these, along with possible developments, are not considered in this review. Neither are any of the decision support systems available or under development. As with mathematical models, monitoring programs and decision support systems useful for improving management, can only be developed if the underlying understanding of landscape and catchment processes, and the effects of management, is sound. Consequently, since time was limiting, priority was given to a review of landscape and catchment processes.

2.1.5. Social and economic issues

The focus of subprogram 2 of NAP3 is to improve resource management. While technical understanding is clearly critical to such improvement, social and economic issues are also just as important. These have an overriding influence on the extent to which available information is taken up and put into practice. While this review recognizes their importance, it was not part of its scope to consider social and economic constraints to uptake and use of information, and how these constraints might be overcome. The review has focussed on current technical understanding.

2.2. Conceptual framework for the review

This review is essentially concerned with components of the hydrological cycle and closely associated nutrient cycles in northern Australian landscapes, how these have been modified through the introduction and management of extensive grazing systems, and the effects of these modifications on the land and water resources, including their biota. Of particular interest is whether the modifications have resulted in changes in landscape properties and processes which are undesirable from the perspective of continued productivity of our natural resources. Here the term 'productivity' is defined broadly and refers to the maintenance of the native biota as well as to production that has obvious and immediate economic benefit.

The prime focus of the review has been to identify changes in water, nutrient and sediment fluxes at different spatial scales (i.e., the amount of water, sediment and nutrient leaving different sized areas — a plot, hillslope, small catchment, etc) that are attributable to grazing and its interaction with climate and land management. While such information can provide insight into the effects of the grazing industry, on its own it is likely to be of little use in devising appropriate management strategies. Effective management requires an understanding of how a system (the land and its biota, both natural and introduced) is functioning — the processes operating, how they are influenced by land characteristics and management, and their inter-relationships. Three important factors must be taken into account in understanding system function — place, time-frame and spatial scale.

While the fundamental hydrological and geochemical processes operating are the same for all landscapes, their rates and exact nature vary with place, depending on the land characteristics (climate, geology, topography, soil and vegetation) and through time. Since processes vary in spatially and temporally, what happens over a large catchment (the Burdekin, for example) cannot be determined by observing what happens in one place and period of time within the catchment and then extrapolating this effect over the entire catchment, and over different time periods. We need to understand processes in different places (land types), over different time periods. We also need to understand how the processes operating in different places interact and how this interaction changes as the size of the area under consideration is increased.

Consequently, in addition to identifying changes in water, sediment and nutrient fluxes and their effect, this report has aimed to provide an overview of what is known of how the land and its biota function at different spatial scales, ranging from patch and small plot (square metres) through river basin and off-shore marine environment (thousands of square kilometres). What is known of changes in the functioning of large systems (for example large catchments) over long time periods, is reviewed where possible. Such knowledge is important in helping distinguish changes in large systems due to grazing from those which occur naturally. They also provide a context for any current changes which may be occurring. It would be useful to know, for example, if fluxes of sediment to the Great Barrier Reef Lagoon are currently greater than those in the recent past (last 2000 years or so). Such information may help to determine whether the estuarine and reef systems can withstand current sediment fluxes. Consideration is also given in this review to work that is attempting to identify likely changes in system function as a result of possible climate change. The history of past climates and associated changes on land may also be useful in this context, providing insights into possible changes in the future.

Given that the NAP3 program is concerned with the profitability and ecological sustainability of beef production in northern Australian, the review also considers the effects of on-site degradation and changes in processes, on the beef industry.

The conceptual framework, which forms the basis of the review, is illustrated in Table 1.1.

2.3. Form of the review

In order to assess the information available, the approach adopted was to pose and seek answers to a series of questions. These questions were:

- Are there any identified off-site degradation problems that can be clearly attributed to the northern Australian beef industry? The associated question is, are there potential off-site problems and what evidence is there that suggests these potential problems are likely to eventuate?

- What are the changed water and nutrient fluxes at local scale (up to tens of hectares) due to grazing management, clearing and pasture improvement, drought and fire?

- What do we know about processes and system function at the local scale, including any affects of changes in processes and functioning on cattle production?

Table 1.1. The framework used to consider the effects of grazing, burning and climate, tree clearing and pasture improvement

	PLOT	LANDSCAPE UNIT/SMALL CATCHMENT	RIVER BASIN/REGION (Including estuary)	LAND-SEA SYSTEM
SPECIFIC SYSTEM PROCESSES Hydrology			*Catchment outputs*	*Fate catchment outputs (eg, amount sediment/ nutrients reaching inner/outer reef)*
Erosion/sediment yield				
Nutrients				
SYSTEM FUNCTION Functioning in undisturbed condition				
Land use effects on system function — change in processes and degradation problems (including loss of biodiversity); susceptibility of land systems to degradation and potential for causing unwanted off-site effects				
System function under conditions of global change				

OTHER ISSUES WHICH DO NOT FIT INTO THE ABOVE MATRIX

- Management tools available (including monitoring)
- Effects of changes in system processes on profitability of the beef industry

- What are the changes in fluxes of water, sediments and nutrients that have occurred at regional and large catchment scales (up to thousands of square kilometres) and are these the result of the introduction of grazing or changed grazing practices?

- What work has been done in understanding system function at regional and large catchment scales and, in particular, do we know how changed sediment and nutrient fluxes at local scale affect fluxes at large scales?

- Do we know if fluxes of fresh water, nutrients and sediments at river mouths have changed or are changing, and whether they have the potential to alter the functioning and structure of estuarine and off-shore ecosystems?

- What information and management tools are currently available that could be used or developed to assist in managing grazing enterprises to ensure that productive potential of the land and water resources is maintained?

Component reviews were undertaken to help answer the above questions, and these reviews are provided in Section 2 of this report. Section 1 of the report contains a summary of the major findings of the component reviews (Chapters 2&3). It also discusses some of the on-site effects of overgrazing which are likely to impinge on animal production (Chapter 4) and briefly considers the importance of land resource survey and assessment (Chapter 5) in providing the necessary base for planning and evaluating land management. The final chapter, Chapter 6, assesses what research is needed and recommends priorities for NAP3 funding.

2.4. Overview versus review

Given the large geographic area involved, the amount of research completed and the number of groups involved in relevant work, this project was unable to provide a comprehensive review. Rather its aim has been to determine major areas of relevance and, within these areas, to identify past, current and proposed work. From this information an assessment has been made of where the significant deficiencies in understanding appear to be. Some work will have been overlooked in the process. At the workshop held in early August to allow comment on the draft review, some important gaps were identified and these have been rectified where possible. Even so, other gaps remain. This is not intentional and the author apologizes to those whose work has not been included. It should be noted that review of the international literature to provide a more complete understanding of the possible effects of grazing, was not part of this project.

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2. REAL AND PERCEIVED PROBLEMS

This chapter discusses the effects on water resources, both local and downstream, that can result from extensive grazing. It identifies the real and perceived threats associated with the northern Australian beef industry and, from the information available to this review, assesses their extent and the degree to which these problems can be clearly linked to the grazing industry. It also considers potential problems and the likelihood of their development. The focus is on the different *forms of degradation* of water resources that can be attributed to changes in water, sediment and nutrient movement in the landscape and, in the case of riparian zones, to the direct changes to habitat from cattle access or pasture management practices (clearing, burning and introduction of exotic species). The effect that grazing and grazing management have on land characteristics (soil and vegetation) and hence the processes involved in water, sediment and nutrient movement, is the focus of the next chapter, although the principles are discussed briefly here as part of identifying the forms of degradation that can result from grazing.

2.1. Potential effects of grazing in the context of the north Australian environment — principles

Processes involving the transfer of energy, water, and nutrients are fundamental within all landscapes and are involved in plant and animal production as well as soil and landscape development. The actual pathways and fluxes of energy, water, and nutrients within the landscape are determined by the characteristics of the landscape in question — its climate, geology and geomorphic history, topography, regolith and soil, and vegetation. For example, in flat terrain with deep sands, infiltration of rainfall is likely to be high and runoff very small to negligible. On the other hand, runoff of rainfall is likely to be relatively high on hilly terrain with poorly structured shallow loam soils developed on, say, sedimentary rocks.

The vast area covered by the north Australian grazing industry means that it incorporates an enormous variety of landscapes, and as a result natural processes are likely to vary considerably throughout the region. To begin with there are major differences in climatic regime, ranging from the humid wet/dry tropics with high summer rainfalls to the arid inland areas where annual rainfall is low but with high interannual variability. Major variation occurs between the more humid coastal catchments, in which water moves relatively quickly to the coast taking suspended and dissolved materials with it, and the flatter, more arid inland catchments. In these catchments, river flows tend to occur only after episodic rainfall events and much of the water infitrates into the river beds and floodplains or is evaporated before reaching the inland lakes in which the rivers terminate.

The introduction of any land use affects the natural environment and the processes within it, by altering characteristics of the vegetation and soils. For example, extensive grazing can affect species composition (through selective foraging), plant cover, plant root depth and soil surface condition. Management practices, such as burning or clearing and pasture improvement, also affect these vegetation and soil characteristics and, in addition, pasture improvement introduces non-native species to the landscape. Changing the soil and vegetation properties changes the rate at which various processes operate in the landscape. Where the change in processes leads to a decline in the productive capacity of land or water resources (including their capacity to maintain the native biota) we regard the processes as degradational and land and water degradation as having occurred. For example, reduction in plant cover exposes the soil to raindrop impact and this, combined with the associated loss of organic matter, can lead to surface sealing. Surface sealing reduces the infiltration of rainfall, and water which previously would have entered the soil, runs off and is unavailable for plant growth. This can lead to a further decline in plant production and, with continued grazing, plant cover.

Increased runoff can, through the additional energy associated with the increased volume of water, move sediment and attached nutrients, seeds and other organic matter. By this process, resources necessary for plant growth can be transported out of the local system and lost from the grazing land. Organic matter, sediment and nutrients transported to waterways will be variably transported through the drainage network to the catchment mouth. Changes in water, sediment and nutrient inputs to aquatic and marine environments have the potential to change the ecology of these systems. Such changes may be deleterious in that there is a general loss of biological diversity and unwanted species may flourish (eg, toxic blue-green algae or macroalgae on coral reefs). Users dependent on the continued healthy functioning of freshwater and marine ecosystems may be affected.

Management practices such as tree clearing and the introduction of leguminous pastures can have a different set of effects. Land cleared of trees and sown to exotic pastures often has a different water use regime from the natural vegetation that was replaced. In southern Australia, for example, replacing the natural forests and woodlands with introduced pastures has typically resulted in reduced interception and evopotranspiration which means that a greater volume of water is available to move through the soil profile and recharge groundwater. Recharge to groundwater will cause water tables to rise and eventually, to intersect the land surface causing increased waterlogging. Where the groundwater is saline or the rising water moves through regolith with a high salt content, salinisation of soils and surface water may result. The length of time for groundwaters to rise depends on the rate of recharge, on the permeability and water holding capacity the regolith, and on the depth of the water table.

Leguminous pastures may also have an indirect effect on water movement. There is evidence that the leguminous pastures introduced to northern Australia are resulting in increased rates of soil acidification (Moody and Aitken 1997; Noble *et al.* in press) as is occuring under clover pastures in termperate grazing systems. Increased soil acidity will affect the growth and production of pasture plants both as a result of plant sensitivity to soil pH and as a result of increased manganese and aluminium availability and hence toxicity. Reduced plant growth and productivity will reduce plant cover, with similar affects to that caused by grazing. There will also be reduced uptake of nutrients, which will increase the potential for nutrient leaching to groundwaters.

The extent to which land processes are affected by grazing and grazing management depends on the extent of alteration produced by cattle and/or land management. For example, light grazing may exert relatively little affect as loss of foliage cover may not exceed either the threshold which leads to reduced plant vigour or that which results in increased runoff and erosion. The threshold to change also depends on factors such as climatic and soil conditions and whether the plant is already stressed, for example, through reduced water and nutrient availability. Thresholds to change are therefore variable in space and time. It is for this reason that management practices, such as stocking rates, need to be adjusted for different conditions.

Land characteristics also influence the extent to which land processes are affected by grazing and grazing management. Different land types have different inherent susceptibilities to degradation (Aldrick *et al.* 1988) so that, for example, grazing which results in similar levels of plant cover and soil exposure may result in different degrees of soil loss. Factors influencing the inherent susceptibility of the land to erosion include the topography (slope length, angle and shape), presence of a lag deposit, soil texture and structure and soil organic matter content.

Understanding the effects that cattle and grazing management can have in a particular landscape is consequently not a simple task. General principles can be determined but the specific effects will vary from landscape to landscape, and catchment to catchment. It is only possible in a review such as this to identify the possible effects of grazing and grazing management, rather than to provide specific information on the possible changes for different landscapes and for particular stocking rates. Also, in most instances, this review does not provide any indication of the extent to which degradational processes are occurring. As should be apparent from the discussion above, an extensive grazing enterprise need not necessarily be having adverse effects on land and water resources — whether it is or not depends on the appropriateness of the management practices adopted in relation to the land types present within the property.

2.2. Issues

Listed below are the *possible* changes in processes associated with hydrological and nutrient cycles that can be caused by grazing and grazing management, and the deleterious water quality effects that can result. All perceived problems have been listed, irrespective of whether they are actually occurring. It is the place of subsequent sections to assess the actual or potential occurrence of the problems. It should be noted that degradation of water resources only is considered since the main focus of the review was the downstream effects (including groundwater and ecological status of aquatic ecosystems) of grazing land management. It is recognized, however, that there will also be associated on-site degradation of the land resource.

- Increase in groundwater recharge as a result of clearing — an increase in recharge can cause increased waterlogging as a result of rising watertables, and a decline in plant productivity. In areas where salt is stored in the groundwater and/or regolith, there may be increased soil and water salinity. Increased water salinity can affect in-stream biota as well as use of water for domestic, industrial and agricultural purposes (including stock watering and irrigation).

- Increased inputs and leaching of nitrate associated with pasture improvement — nitrate contamination of waterbodies and increased soil acidification; the effects of increased soil acidification are described above.

- Increased fluxes of sediments to waterways and standing waterbodies — sediments may reduce the utility of dams and water storages, including property dams; increased sedimentation is known to affect the ecology of some systems, for example, estuarine seagrass beds.

- Increased fluxes of nutrients to waterways and standing waterbodies — the concern is that inputs of nitrogen or phosphorous may stimulate algal blooms in inland waterways and off-shore, and may also affect the species balance of communities, for example favouring macrophytic algal growth to the detriment of corals.

In addition to the deleterious effects on aquatic environments brought about by increased sediment and nutrient inputs, cattle can also cause direct changes to riparian and wetland flora through grazing and trampling. This has consequent implications for the fauna dependent on the riparian vegetation. Change in vegetation may also have indirect effects on stream and wetland ecology through changed energy fluxes (light, temperature), and organic and mineral nutrient inputs. Indirect effects of cattle trampling and wallowing result from compaction of the soil which may inhibit plant regeneration.

A further potential effect of cattle on aquatic environments is the increased input of microbial pathogens and nutrients from cattle excreta. There appears to have been little investigation of such inputs and the probability of them causing a decline in water quality. Consequently they are not considered further in this section of the report.

The provision of artificial watering points is another aspect of grazing land management that affects the hydrology of landscapes in northern Australia. The water used comes both from stored surface runoff after rain and from groundwater, either under pressure from confined aquifer systems (artesian bores) or pumped from unconfined aquifers. Landsberg *et al.* (1997) report that artificial watering points are now so numerous in the arid and semi-arid rangelands that there is rarely more than 10 km between them. These artificial watering points have two potential effects. One is the effect of removal of water from the groundwater system, the other is the effect on the land and regional biota.

2.3. Salinity

2.3.1. Summary

Extensive areas of dryland salinity exist in southern Australia as a result of altering the water regime by tree clearing and establishing more shallowly rooting, often annual, pasture and crop species. To date, dryland salinity in northern Australia has not developed to anywhere near the same extent as in the south. There are differing views as to whether this is purely because tree clearing has not yet occurred on the same scale in the north, or whether it is because the potential for dryland salinization is much lower.

Surveys and hydrological studies in Queensland and the Northern Territory indicate that the conditions necessary for salinization, that is saline regolith and/or groundwater, and potential for an increase in water movement beyond the root zone following clearing, are present in at least some areas. Evidence for increased water movement below the root zone following clearing comes from modelling the water balance for soils near Charters Towers (Williams *et al.* 1997). These simulations have shown that recharge in the seasonally wet/dry tropics is likely to be highly episodic. The potential for increased recharge is also likely to be highly variable for the different climatic regimes and landscapes across northern Australia. No relevant literature on the potential for salinization was found for north-west Western Australia.

Assessments to determine the susceptibility of land to salinization, identified during this review, include that for the Northern Territory (Tickell 1994), the Dalrymple Shire in Queensland (Bui 1995) and the study in the Ipswich and Kingaroy areas of Queensland (Searle and Baillie, in prep). These assessments are regarded as providing a first approximation only and further refinement in the assessment of areas susceptible to salinization is necessary to help develop land clearing guidelines. Not all areas with saline regolith appear to be susceptible to salting. Studies at the Brigalow Research Station in Queensland, for example, found little difference in recharge between cleared and uncleared catchments (Lawrence and Thorburn 1989) and this was attributed to the generally relatively shallow rooting depth of brigalow (*Acacia harpophylla*).

Current work being undertaken in the Balfes Creek catchment suggests that paleodrainage lines are considered possible major sites of stored salts, as in SW Western Australia. The work in the Northern Territory identified higher than average salt storage in the lateritised Cretaceous claystone on the Barkly Tablelands and Sturt Plateau. Further investigation of relationships between salt storage and particular landscapes (defined by climate, geology and geomorphic history) would seem warranted. Hydrological work (including use of simulation models) is necessary to determine effects of clearing on rates of water movement below the depth of plant rooting and actual groundwater recharge, in landscapes with salt stores.

The risk of dryland salinity occurring in the north depends not only on the potential for salinization inherent in the land, but also on the extent to which changes in the vegetation which affect components of the water balance, are likely to occur. Walker and Weston (1990) estimated there to be about 22.1 m ha which is easily available for development to sown pastures. They estimated development of 42.5% of this potential had occurred, with 4.4 m ha with sown grasses and 5.0 m ha with naturalized pasture. The extent of sown grass and legume pastures in Queensland in 1985 is shown in Figure 1.

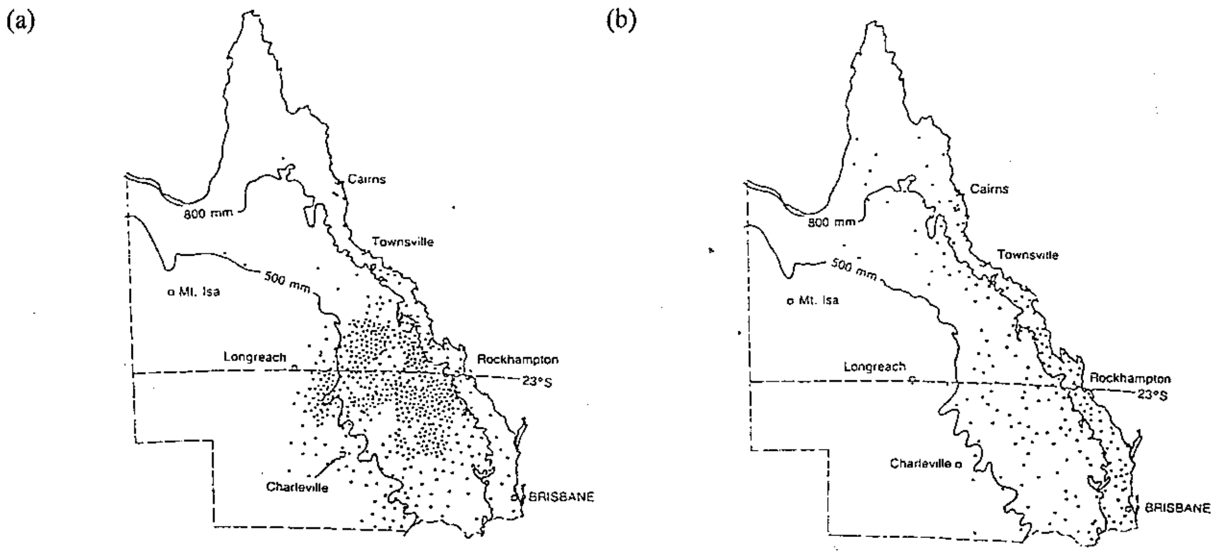

Figure 1. Distribution of sown grass pastures (a) and of pastures sown with legumes (b) in Queensland in 1984-85. Each dot represents 5 000 ha. (From Walker and Weston 1990)

It was not possible to obtain an accurate assessment of the amount of clearing that has already taken place although Figure 2 provides an estimate of the amount of clearing up till 1983. The current State-wide Land use And Tree clearing Study (SLATS) is mapping the rate of tree clearing from 1991-1995 at 1: 250 000 scale, using Landsat images with 30 m resolution. There are now clearing controls in place and permits to clear land are required. Guidelines have been developed for clearing land with indicators of possible salinity and these are being upgraded as more specific information on the susceptibility of land to salinization becomes available.

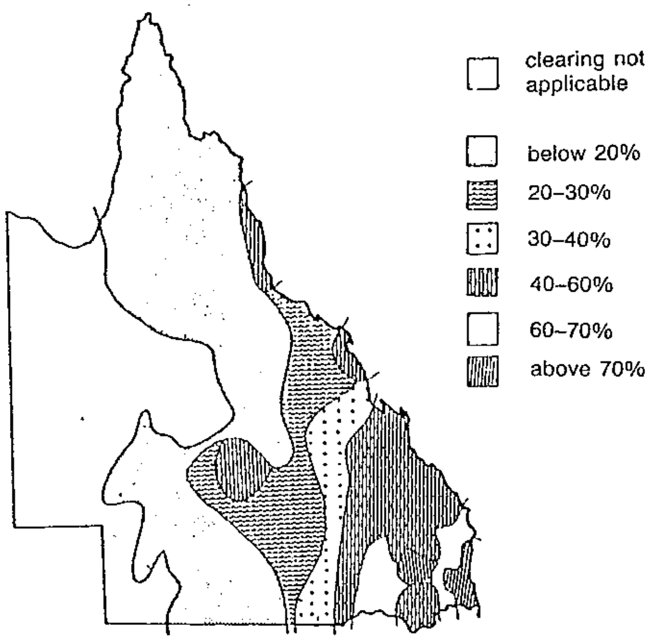

Figure 2. The extent of clearing of open forests and woodlands in Queensland up to 1983. (From Walker and Weston 1990, derived from Burrows *et al.* 1988).

2.3.2. Current relevant projects

(Details of some projects given in Reviews 3&4)

Title and contact	State	Catchment/region	Issue	Status
Estimation of sustainable groundwater pumping rates Derek Eamus	NT	Near Darwin (1600 mm rainfall)	Water balance including groundwater recharge	Current; intention of extending work to other land types
Groundwater resources of Balfes Creek Catchment Jason Keys	QLD	Balfes Creek (Burdekin National Dryland Salinity Program focus catchment)	Development of a hydrological map of Balfes Ck catchment and interpretation of groundwater movement.	Current
Paddock scale guidelines for salinity management in the Balfes Ck catchment Ian Gordon	QLD	Balfes Creek, Burdekin catchment	Integrating point and catchment scale models to develop vegetation management strategies which will minimize salinity risk in the Balfes Ck catchment.	Just starting
Evaporation from trees and regrowth Steve Kalma	QLD	Balfes Creek, Burdekin catchment	Measure transpiration in established old growth and regrowth vegetation.	
Upper Alice River catchment Project George Bourne and Michael Herring	QLD	Upper Alice River, Barcoo catchmen (representative of the Desert Uplands)	Assessment of areas potentially at risk from dryland salinity for given tree clearing options	

Salinity hazard mapping in SE Queensland Ross Searle and Justine Baillie	QLD	Kingaroy and Ipswich regions	Pilot study of use of landscape characteristics to map salinity hazard at 1: 250 000 scale	12 month trial; in the final report stage
Sustainability of Stylosanthes *based pasture systems in northern Australia (subproject 1)* Andrew Noble	QLD, one site in NT	Northern and central Queensland; Manbulloo, NT	While nitrate leaching is the focus, this project will provide comparative water balances for soils under *Stylosanthes* and native pasture.	1997-2000
Sustainable groundwater use in northwest NSW and southern Queensland Jim Kellet	QLD and NSW	Southern Queensland catchments overlying the Great Artesian Basin (Condamine, Culgoa-Barwon)	Recharge studies to provide improved information for groundwater models of the GAB	Proposed

2.4. Soil acidification and nitrate contamination of groundwater

2.4.1. Summary

Stylosanthes pastures (*S. scabra* and *S. hamata*) have been introduced to northern Australian grasslands to improve their quality and dietary value in the dry season. Legume pastures in southern Australia have been found to be associated with accelerated soil acidification, a problem which is now being investigated in the north. Preliminary studies have measured increased rates of acidification under *Stylosanthes* pastures and increased rates of nitrate leaching have been suggested as a possible cause (Noble *et al.* in press). A project, *Sustainability of* Stylosanthes *based pasture systems in northern Australia: managing soil acidity*, has recently been initiated, funded by the MRC, to investigate the long-term sustainability of legume based pasture systems in the semi-arid tropics. Its focus is on quantifying the inherent fertility status of various pasture production systems through the establishment of long-term monitoring sites at various localities.

The possibility of increased rates of nitrate leaching associated with *Stylosanthes* pastures raises the possibility of nitrate contamination of groundwater. The potential for nitrate contamination of groundwaters seems to occur wherever nitrate can accumulate in soil prior to the onset of rains sufficient to leach the nitrate below plant roots and the activity of any denitrification. There have been few investigations of nitrate dynamics under northern Australian legume pastures so the potential for these systems to cause groundwater contamination, is unknown although not particularly likely (Andrew Noble, pers. comm). The current project *Sustainability of* Stylosanthes *based pasture systems in northern Australia: managing soil acidity* should provide data that will give a better indication of the probability of this process. Relatively high nitrate concentrations are known to occur in some arid zone groundwaters. In at least one case, this has been attributed to leaching of nitrate from nitrogen fixation by cyanobacteria and in termite mounds (Barnes 1992).

2.4.2. Current relevant projects

Title and contact	State	Catchment/region	Relevant issue	Status
Soil acidification and fertility decline				
Sustainability of Stylosanthes *based pasture systems in northern Australia: managing soil acidity* Andrew Noble	QLD, one site in NT	Northern and central Queensland; Manbulloo, NT	Monitoring soil fertility and water changes; predicting risk of acidification; development of sustainable legume-based pasture systems; communication of results.	1997-2000

Nitrate contamination of groundwater

Sustainability of Stylosanthes *based pasture systems in northern Australia: managing soil acidity (Subproject 3.4)* Andrew Noble	QLD	"Lansdown", Burdekin Catchment	Quantifying mineral nitrate dynamics under a *Stylosanthes* dominant pasture	1997-2000

2.5. Effects of grazing on wetlands and riparian habitats

(Summary from the review: "*The impacts of the northern Australian grazing industry on wetlands and riparian habitats*" by Michael Douglas and Alison Pouliot).

In this report, riparian areas are "that part of the landscape which exerts a direct influence on stream channels or lake margins and on water and aquatic ecosystems contained within them" (Bunn and Price 1993). The term wetland broadly follows the definition used by the Ramsar Convention: "areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water depth of which at low tide does not exceed six meters" (Davis 1994). The focus, however, is on natural freshwater wetlands, which, following the definition above, also includes streams and waterways. Generally the literature on the effects of grazing is based on observation and/or highlights potential problems; there is an extreme paucity of specific information.

Riparian habitats and wetlands tend to be areas of high utilization by cattle. Firstly they are close to, or provide water. Secondly, riparian areas often have higher fertility with the result that cattle have a greater preference for riparian pastures. The potential for cattle to affect the biological diversity of these areas is increased by the fact that in the dry season, and particularly during droughts, riparian habitats and wetlands are not only increasingly attractive to cattle but can act as refugia for native species.

As well as the direct of effects of cattle utization of riparian habitats and wetlands, management practices associated with the grazing industry, such as burning and the introduction of ponded pastures, can also have a marked affect on the native biota.

2.5.1. Riparian biodiversity

The direct effects of grazing on riparian vegetation are clearly visible and involve damage to the vegetation and loss of cover, and trampling and compaction of the soil and stream banks. As a result weed invasion can occur and the regeneration of native plants can be limited or prevented. Despite the visible signs, there has been very little work quantifying the areal extent of damage or the loss of communities or species. With respect to fauna, a little more is known although there is still a dearth of information. No studies were identified, for example, that have investigated the response of invertebrates to grazing. There also appears to be no report of decline in specific mammal populations in northern Australia although various studies have shown that mammals utilizing riparian areas are likely to be particularly susceptible to grazing. In central Australia, grazing has been implicated in the decline and extinction of several mammal species. Some amphibians and reptiles, for example freshwater turtles, have also been found to be highly dependent on riparian zones and hence susceptible to the effects of grazing in these areas.

The most well documented effects of grazing on bird populations are those on the Purple-crowned Fairy-wren (now listed as vulnerable, Garnett 1992) and the White-browed Robin (Smith and Johnstone 1977; Boekel 1980; Rowley 1988; Woinarski 1992; Rowley 1993). These insectivorous species have disappeared from riparian grasslands and fringing *Pandanus* from many areas in the Kimberley, following the loss of this vegetation through overgrazing. Finches of tropical woodland in the NT have also declined with increasing grazing pressure (Tidemann 1990) and, since riparian zones are important for granivorous and nectivorous birds, they are possibly implicated. In a review of the conservation status of arid zone bird species, overgrazing was considered the principle cause for a decline in species, with species having a preference for grassy riparian habitats and chenopod shrublands being disproportionately affected (Reid and Fleming 1992).

2.5.2. Wetland biodiversity

As for riparian habitats, there has been little investigation of the effects of grazing on wetland vegetation, even though northern wetlands may be more susceptible to grazing pressure than those in southern Australia due to seasonal drying giving cattle greater access. Some work, however, has shown that lignum (*Muehlenbeckia cunninghammi)* and species such as wild rice (*Oryza* spp.), which are important for wildfowl, have declined or disappeared from parts of the black soil lakes of the Barkly and Sturt drainages where grazing has occurred (Jaensch *et al.* 1995).

In-stream fauna are most likely to be indirectly affected by grazing. Trampling of stream beds and increased sediment and silt in rivers from erosion and slumping of banks, can totally destroy in-stream habitat. Also, since riparian vegetation affects various inputs to streams (organic material, light, temperature), change to riparian vegetation can markedly affect in-stream conditions. Despite the vulnerability of aquatic invertebrates and fish, little is known of what changes have occurred to populations of these animals as a result of habitat changes. With respect to invertebrates, some correlations have been made between reductions in diversity and abundance over time, with catchment disturbance, including increased stream-bank degradation and turbidity due to grazing. The only known investigation on the effect of grazing on fish, is a study of red-finned blue-eye from the Edgbaston Spring complex in central Queensland. This work suggests disappearance of the fish from two springs could be due to habitat destruction caused by stock trampling and by excavation of the springs to increase water storage for stock watering.

2.5.3. Weeds

Tropical wetlands and riparian habitats are particularly susceptible to weed invasion. Of the top 18 environmental weeds, 14 occur in wetlands or riparian areas in northern Australia and 8 are clearly linked to aspects of cattle grazing (Humphries *et al.* 1991). Grazing may influence weed establishment in several ways. Trampling and erosion may make riparian and wetland areas more susceptible to weed invasion, and selective grazing may prevent regeneration of native species, facilitating the establishment of weeds. An example is invasion of Rubber Vine (*Cryptostegia grandiflora*), a species known to choke riparian vegetation, thereby removing important bird habitat. Many species such as Parkinsonia (*Parkinsonia aculeata*), Rubber Vine, Prickly Acacia (*Acacia nilotica*), Mesquite (*Prosopis* spp.) and possibly Buffel grass (*Cenchrus ciliaris*), are spread by cattle through their faeces or attached to their skin.

Pastoral managers may actively introduce and spread exotic species in wetland and riparian areas in an effort to reduce land degradation or to provide shade or fodder for stock. For example, Mesquite, originally introduced to provide shade and fodder for cattle and as a garden ornamental, now forms dense stands around some watercourses. Dense riparian stands of Mesquite and Parkinsonia can inhibit wildlife movement and access, and are a cause of concern for wetlands on the Barkly Tablelands and in central Queensland. Similarly Buffel grass was introduced to the NT and the Kimberley as a pasture species and to ameliorate erosion from overgrazing and is now well established in riparian and other mesic habitats throughout the arid and semi-arid zone. The environmental affects of many of these weed species are virtually unknown.

2.5.4. Ponded pastures

Ponded pastures, where water is retained in natural or artificial wetlands through the constructed earth banks and levees, are most widespread in central Queensland where about 22,000 ha have been ponded (Coffey 1991). However, proposals to develop ponded pastures in southern Cape York Peninsula and introduce pasture species with known potential to become serious weeds (Clarkson 1991), are a major concern. Species introduced to ponded areas which are on the list of nationally important weeds, include Para grass (*Brachiaria mutica*), Aleman grass (*Echinochloa polystachya*) and Hymenachne (*Hymenachne amplexicaulis*). Species used in ponded pastures have also been observed to spread and displace native vegetation that is of importance to wetland birds. For example, Fisk (1991) has noted that as Para grass becomes established in some areas, fauna dependent on vegetation that grows along wetland margins, such as brolgas which feed on Bulkuru bulbs, suffer a serious decline in food resources.

Other environmental concerns associated with ponded pastures include:

- reduction in diversity and change in hydrology of natural wetlands which will affect habitat value;
- affect on passage of migratory fish (e.g. migration of juvenile barrumundi);
- interference with the role of coastal plains as nursery areas and refuges for juvenile stages of many estuarine species;
- reduction in freshwater runoff to estuaries and changes in tidal flows and freshwater/saltwater interactions;
- potential for diversion of freshwater with consequent ill effects on the system from which water was taken;
- development of mosquito breeding areas with ineffective natural controls; and
- development of habitat favouring some native wildlife species, allowing populations to reach nuisance levels.

Others have highlighted the beneficial affects of grazing, and the role of cattle in keeping the weeds in check once these pastures have been established. The need for on-going grazing, however, can also be regarded as negative aspect of ponded pastures as it highlights the potential of these areas to cause problems should management be reduced for any reason.

2.5.5. Fire management

Relatively little is known about the affect of fire regimes on riparian vegetation. The invasion of riparian areas by grasses such as buffel grass which can increase the intensity and extent of fires, has possibly changed the relationship between fire and riparian vegetation and affected the habitat value of riparian areas. In contrast, grazing of riparian areas in Queensland is thought to have kept fuel loads at low levels, reducing the frequency of fire and thus helping the establishment of rubber vine. Experiments with fire regimes (no burn compared with late-dry season burning) in Kakadu National Park showed a decrease in richness of vines and woody species with burning, and an increase in richness of aquatic macrophytes and invertebrates (Douglas and Lake 1996).

2.5.6. Repair of degradation

Restoration of riparian habitat and wetlands following damage by grazing, seems to be a neglected area of research. Rehabilitation of degraded areas requires a knowledge of the ecosystem and its processes prior to disturbance (Ludwig and Tongway 1996) and for many riparian and wetland areas such knowledge is not available. In addition, successful and cost-effective re-establishment of vegetation requires a knowledge of the regeneration ecology of the species involved. For many northern Australian species, such information is limited. For example, factors limiting the regeneration of Eucalyptus miniata, one of the widespread trees of northern Australian savannas, were only recently identified (Setterfield *et al.* 1993).

2.5.7. Unpublished and current projects

Table 1 lists relevant current, unpublished projects, but excludes articles based only on reviews of literature.

2.5.8. Conclusions

This report is unable to provide an adequate assessment of the effects of grazing and pasture management on riparian areas and wetlands because of the extreme dearth of quantitative data, as distinct from anecdotal and observational reports. Even so, sufficient information is available from both sources to clearly indicate that grazing and pasture management can have a pronounced effect on wetland and riparian communities, leading to changes in, or in some cases loss of, floral and faunal populations. If declines in natural habitat and wildlife

Table 1. Summary table of projects listed by state, catchment, and issues.

Contact	State	Catchment/Region	Issue	Status	Organisation	Division
Douglas	NT	Alligator Rivers Region	Fire and aquatic vegetation	Current	NTU	CTWM
Douglas	NT	Alligator Rivers Region	Fire and macroinvertebrates	Current	NTU	CTWM
Douglas	NT	Alligator Rivers Region	Fire and riparian vegetation	Current	NTU	CTWM
Stowar *et al.*	NT	Alligator Rivers Region	Fish and erosion	Completed	ERISS	
Stowar *et al.*	NT	Alligator Rivers Region	Macroinvertebrates and erosion	Completed	ERISS	
Douglas *et al.*	NT	Alligator Rivers Region	Para grass	Proposed	NTU	CTWM
Jaensch	NT	Barkly Tablelands	Birds in Riparian	Completed	PWCNT	
Reid	NT	Central Australia	Birds in Riparian	Completed	CSIRO	
Whitehead	NT	Mary River	Grazing of wetland vegetation	Current	PWCNT	
Woinarski	NT	Micthell Grasslands	Birds in Riparian	Proposed	PWCNT	CRCSDTS
Woinarski	NT	Various	Birds in Riparian	Current	PWCNT	CRCSDTS
MRHI	NT	Various	Macroinvertebrates	Current	DLPE	
Dostine	NT	Various	Macroinvertebrates in Riparian	Current	PWCNT	CRCSDTS
Cheal	NT	Various	Plants in Riparian	Current	PWCNT	CRCSDTS
Haytesbury	NT	Victoria River District	Rehabilitation	Current		
Boekel	NT	VRD	Birds in Riparian	Completed	?	
Douglas		Various			NTU	CRCSDTS
Bunn and Davies	QLD	Bamboo Creek, Innisfail	Para grass	Completed	GU	CCISR
Arthington	QLD	Brisbane River	Macroinvertebrates	Completed	GU	CCISR
Arthington	QLD	Brisbane River	Water quality	Completed	GU	CCISR
Brown	QLD	Burdekin	Landscape restoration	?	CSIRO	CRCSDTS
Lucaks	QLD	Burdekin	Grazing of riparian vegetation	Completed	JCU	ACTFR
Lukacs	QLD	Burdekin	Grazing of wetland vegetation	Completed	JCU	ACTFR
Lucaks	QLD	Burdekin	Water quality	Completed	JCU	ACTFR
Duivenvorden	QLD	Central Fitzroy	Macroinvertebrates	Current	CQU	CLWR
Duivenvorden	QLD	Central Fitzroy	Algae	Current	CQU	CLWR
Noble	QLD	Central Fitzroy	Water quality	Current	QDNR	CQU
Bunn and Davies	QLD	Cooper Creek	Algae trampling	Current	JCU/UWA	CCISR
Lorimer	QLD	Desert Uplands	Rehabilitation	Current	QDEH	
Rowley	QLD	Gulf	Birds in Riparian	Completed	CSIRO	
Williams	QLD	Townsville	Hymenachne	Current	QDEH	
Pearson	QLD	Townsville	Macroinvertebrates	Completed	JCU	ACTFR
Williams	QLD	Townsville	Para grass	Current	QDEH	QNPWS
Brown	QLD	Townsville	Riparian biota/water quality	Current	CSIRO	TA
Pearson	QLD	Townsville	Water quality	Completed	JCU	ACTFR
MRHI	QLD	Various	Macroinvertebrates	Current	QDPI	
Rowley	WA	Kimberley,	Birds in Riparian	Completed	CSIRO	
Woinarski	WA	Kimberley, Purnululu	Birds in Riparian	Completed	PWCNT	
Pettit	WA	Ord River	Riparian vegetation	Current	ECU	
Davies	WA	Pilbara	Water quality	Completed	UWA	
MRHI	WA	Various	Macroinvertebrates	Current	WAWA	

ACTFR	Australian Centre for Tropical Freshwater Research
CCISR	Centre for Catchment and Instream Research
CCNT	Conservation Commmission of the Northern Territory
CQU	Central Queensland University
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CTWM	Centre for Tropical Wetlands Management
DLPE	Department of Lands Planning and Environment
ECU	Edith Cowan University
ERISS	Environmental Research Institute of the Supervising Scientist
GU	Griffith University
JCU	James Cook University
NTU	Northern Territory University
PWCNT	Parks and Wildlife Commission, NT
QDPI	Queensland Department of Primary Industry
QNPWS	Queensland National Parks and Wildlife Service
TA	Tropical Agriculture
UWA	University of Western Australia
WAWA	Western Australian Water Authority
WRD	Water Resources Division

populations are to be halted, there is an essential need to determine the levels of grazing compatible with maintaining the natural biological diversity of different wetlands and riparian areas. This necessitates base data on our wetland and riparian flora and fauna; such data are relatively sparse in northern Australian landscapes.

Given the observed preference of grazing animals for riparian areas in many environments, strategies for managing grazing in riparian areas also need to be developed. Such a need was also identified as important in the National Wetlands R&D Scoping Review (Bunn 1996). Fencing off riparian areas is one possibility that has been found, in one instance at least, to be financially neutral, with benefits offsetting costs. It is recognized, however, that this solution may not be appropriate for large areas of the rangelands. In some situations, total exclusion of grazing may not be necessary but more needs to be known about the sensitivity of different riparian areas to grazing and the capacity of local flora to regenerate in the presence of, or after, grazing activity.

In deriving information on grazing pressures compatible with maintaining the natural riparian flora and fauna, management within the whole catchment, and not just the riparian and wetland areas, must be considered, as processes in the whole catchment have the capacity to impinge on riparian zones and wetlands. Investigations also need to include the seasonal variability in the wet/dry tropics and the considerable interannual variation in rainfall. Rainfall pattern determines the movement of both stock and native biota as well as the degree of their dependence on wetland and riparian areas. It is essential to obtain information during critical dry periods when these habitats act as refugia for native fauna.

Methods for restoring or rehabilitating riparian areas and wetlands are very poorly understood, particularly where heavy weed invasions have occurred . While many Landcare and other restorative programmes are underway, more research is needed to provide a sound scientific basis for these schemes and to ensure that large scale channel instability does not occur if dense infestations are removed. Monitoring and assessment of the success of these programmes should also be a priority.

The problems associated with eradicating weed infestations raises the issue of the introduction of ponded pasture species, known to be problem weeds, to new areas. While there is no doubt that ponded pastures are profitable additions to grazing enterprises, it is also clear that weed invasions cost the community extremely large sums of money in eradication programs. Clearly it is essential not to let the problem develop in the first instance. At the *Beef Production from Ponded Pastures* workshop held in 1993 (Pittaway *et al.* 1996), the potential seriousness of expansion of ponded pastures was pointed out while it was acknowledged that minimal envirionmental research has been carried out and that we do not yet have the information to determine how likely are the undesirable effects. Research is required to help resolve some of the issues and the recommendations of Lukacs (1996) are noted here. Lukacs recommended that research associated with use of potentially invasive exotic grasses should include: "an international biogeographic survey to quantify existing populations and their ecological parameters; the development of predictive models to assess potential invasive spread; monitoring of selected ponded pastures; autecological studies of pasture species utilised; and the development of competition based experimentation." He also suggested investigation of the use of native species in ponded pastures.

2.6. Eutrophication and algal blooms in freshwater systems

2.6.1. Summary

(From Review 1: "Eutrophication and algal blooms in freshwater systems of northern Australia" by Terry Donnelly)

Nearly all standing waterbodies in Queensland are susceptible to blue-green algal (cyanobacterial) blooms (Gary Jones, National Algal Manager, *pers. comm.*). The recognition of the susceptibility of Queensland freshwater systems seems only to have developed in the last five years or so as the result of an increased monitoring and recording program. In contrast, freshwater systems in the NT and the NW of Western Australia seem to have low nutrient status and low susceptibility to bloom development, at least under present conditions, with very few cyanobacterial blooms having been recorded.

The relationship between algal bloom development in Queensland and grazing in pastoral lands is unclear. This is mainly because our understanding of the mechanisms involved in algal bloom development in Australia is still far from complete. It is now thought that the anthropogenic point source inputs of phosphorus, which can give rise to eutrophication problems in the northern hemisphere, are unlikely to be major contributors to nutrient concentrations in Australian freshwater systems, other than locally. This is attributed to the large in-stream sediment stores which, under the anoxic conditions following stratification of a waterbody, can release large amounts of phosphorus, and also to the capacity of these sediments to remove added soluble phosphorus from the water column. Other factors implicated in controlling bloom development in Australian freshwater systems are the usually high turbidities, high temperatures, low river flows (particularly following river impoundment), usually high clay contents of sediments, and the activity of sulphate-reducing bacteria. The role of sulphate in the release of phosphate from sediments has been confirmed by Chiswell *et al.* (1995). In Australian systems, sulphate is usually derived either from the influx of saline groundwaters or from the use of agricultural fertilizers, including superphosphate.

Since the large algal bloom on the Darling-Barwon River in 1991, change in water phosphorus concentration to levels above a limiting threshold, has been regarded as a major stimulant to bloom development and much work has focussed on the processes and mechanisms whereby this change has been produced. It is becoming apparent from current and recently completed work, that nitrogen may be playing a larger role in the development of blooms than currently thought (Richard Davis, coordinator National Eutrophication Management Program, pers. comm). A project in the Fitzroy catchment currently being developed for the National Eutrophication Management Program will provide an indication of whether nitrogen plays a role in the growth of cyanobacteria in rivers and storages, and about the role of denitrification (Harris 1997). High river turbidities are also being increasingly regarded as limiting bloom development. One corollary of this is that attempts to improve water quality by reducing turbidity, may have the effect of increasing blooms if the other factors that control algal growth (particularly nutrients) are not limiting (Richard Davis, pers. comm).

The reports of cyanobacterial blooms in Queensland catchments with little disturbance, indicates that blooms can occur naturally. However, the increased storage of water and any increased nutrient (N & P) and sulphate input can exacerbate an existing problem, although the exact extent to which this is the case cannot be defined. Certainly reducing the frequency of blooms must involve ensuring the influx of sediments and nutrients to waterways is reduced, and in catchments where pasture improvement is occurring, that fertilizer inputs to waterways do not occur. There is a need to ensure that sulphate concentrations in waterways do not exceed their pre-European values. Given that blooms are toxic to animals as well as humans, such reductions are not only to prevent downstream effects for other users but are in the graziers' own immediate interest. The potential for toxins to accumulate in animals is still being investigated. It is an important issue with regard to the purity of our agricultural products.

The lack of cyanobacterial blooms in the NT and north-west of Western Australia is interesting, particularly given their occurrence in Queensland, and an investigation of the reasons may provide insight into the mechanisms causing bloom development in other parts of Australia. Possible causes for the difference between freshwater systems in the NT and north-west of Western Australia, and those in other states, include:

- generally lower fertility (P status) of the NT and northern WA soils;
- the seasonal wet/dry climate which provides both flushing and mixing of water over the wet season, and an extended dry period — there is evidence to suggest that drying of sediment bound phosphorus reduces its bioavailability;
- the presence of good macrophytic growth which both filters the input of phosphate as well as removes phosphate from the water column;
- cattle numbers and cattle access to streams being below the critical thresholds needed to create a bloom problem; and
- monitoring and awareness not being sufficient, although this is considered unlikely.

While the precise role of the northern grazing industry in the development of algal blooms will be difficult to define until the mechanisms of bloom development are better understood, it is clear that increased nutrient inputs associated with increased runoff (see next chapter) can only be exacerbating any problem that exists naturally. It is also worth noting that studies referred to in the review by Douglas (this report) indicate that cattle access to streams resulted in locally elevated nutrient levels leading to eutrophication (Butler and Faithful 1991). Also, in the Northern Territory, one algal bloom that has been recorded was associated with cattle access to a billabong.

2. 6.2. Relevant current and proposed projects in the National Eutrophication Management Program

(Details of projects given in Review 1)

Title	Contact	State
Modelling nutrient release from sediments and lowland river storages	Prof. Barry Hart	Generic
The interaction of physics, biology and nutrient regimes on the initiation and development of algal blooms	Dr Susan Blackburn	Generic
Retrospective study of nutrient variations in some riverine systems	Dr Andy Herczeg	NSW, Qld, SA, Vic, WA
Movement of phosphorus through soils	Dr Jim Cox	SA
Measurement and treatment of phosphorus and carbon subsoil movement	Dr Jim Cox	SA
Effects of episodic events on aquatic ecology in tropical and subtropical areas	Project still in scoping phase	Fitzroy, Qld
Mamagement strategies for control of cyanobacterial blooms in the Fitzroy River barrage	Dr Miriam Bormans	Fitzroy, Qld
Whole lake biomanipulation for the reduction of nuisance micro-algae	Dr Vlad Matveev	Fitzroy, Qld

2.7. Sedimentation of waterways, dams and the marine environment

Heavy grazing pressures can have a definite effect on runoff and erosion, increasing the loss of water, soil and nutrients wherever loss of cover exceeds critical thresholds. This is the result of a number of changes in soil properties and processes (see Chapter 3). Water and dissolved nutrients tend to flow directly from the system although nutrient cycling processes within waterways and the sorption, release and transformation processes cannot be ignored in considering the effect of these nutrient inputs on biological processes. The movement of sediment is complicated by the fact that larger particle sizes tend to be deposited in channels or on floodplains downstream so that not all sediment eroded from a paddock will be immediately transported to the catchment mouth. The length of time that such sediment is stored within a catchment is unknown.

2.7.1. Effect of sedimentation on stream, estuarine and marine environments

While there is no doubt that overgrazing of pastures has increased the mobilization of sediment, with increases in sheet, gully and channel erosion, where this sediment is being deposited, the effects of deposition and the effects of increased river sediment loads/turbidity are not clear. That there are effects is beyond doubt but this project was unable to identify any specific documented cases of effects on apart from the studies on changes in stream invertebrate populations, identified in the review by Michael Douglas, and reports of dieback of seagrass beds associated with flooding and sediment deposition. Seagrass losses in Moreton Bay in the 1970s were attributed to increased sedimentation and a rise in substrate levels; loss of an estimated 902 km^2 of seagrass in Hervey Bay in 1992-3 is thought to have been due to high turbidities resulting from flooding of the Mary and Burrum Rivers.

The lack of documented deleterious effects could be due to a number of factors, including the complexity of natural systems that results in some inputs not having immediate effects, and insufficient base information. For example, coastal seagrass communities are known to be susceptible to smothering by sediments but seagrass communities along 6500 km of the coastline of northern Australia have not been surveyed (Poiner and Peterken 1995).

2.7.2. Sediment deposition in dams and lakes

Sediment tracing work has been undertaken for Lake Argyle and this showed most sediment was derived from subsoils rather than topsoils. That is gullies and stream channels close to the Lake were identified as the major source of Lake sediments. It is difficult to define what proportion of this sediment input is attributable to grazing, but given that gully development in this catchment is considered the result of grazing, it can be assumed that grazing has increased sediment inputs to the Lake. Also, since Lake Argyle seems to have a very high sediment trap efficiency (reported by Wasson *et al.* 1994 at >99%), very fine sediments in surface runoff would be contributing to sediments within the Lake. Plot studies (Review 4) have shown grazing can increase the amount of fine sediment in suspended loads.

This review was unable to find data that indicate where sediment lost by sheet erosion of grazing land is deposited. Sedimentation of farm water storages shows that these are sites affected by local soil loss, but as these are often located on waterways, it is not always possible to determine whether the sediment is from sheet erosion or from erosion of channels and gullies. Similarly, for storages on large waterways in downstream locations, sources of sediment have generally not been identified.

2.7.3. Current research

Individual/organization	Area of research
Australian Geological Survey Organization David Heggie	Eutrophication in estuarine environments
Australian Institute of Marine Science (incomplete listing of relevant projects)	
Dan Alongi	Human impacts on coastal food webs and nutrient cycles
Gregg Brunskill	Environmental history from sediments
Barry Clough	Rivers and mangroves
Peter Isdale	Environmental history from corals
Laurence McCook	Algae as indicators of reef degradation.
CSIRO Division of Marine Research	Projects not determined
Great Barrier Reef Marine Park Authority	Water quality monitoring
James Cook University	
Earth Sciences Department Reef Research Centre	Projects not determined
Queensland Department of Primary Industries Warren Lee Long	Distribution and condition of sea grass communities
Southern Cross University, Centre for Coastal Management	
Peter Saenger, Bradley Eyre	Estuary classification; hydrology, sediments and nutrients
Leon Zann	Effects on the marine environment due to land use
Peter Harrison	ENCORE projects (nutrient fertilization of corals)

2.8. The effect of artificial watering points

2.8.1 Effect on groundwater resources

The extent to which extraction of groundwater by the pastoral industry is having an effect on groundwater resources was not a major component of this review and hence was not investigated to any great extent. It is worth noting, however, that the heavy withdrawal of water from the Great Artesian Basin aquifers by the large number of freely or mainly free flowing artesion bores has caused a marked lowering of regional pressure levels. Falls of several tens of metres have been reported in heavily developed areas with some bores showing falls of more than 100 m (Reville and Habermehl 1996). In 1989, a program of bore rehabilitation that involves piping and control of water flow was begun, to help conserve the groundwaters of the Great Artesian Basin.

As well as the need to conserve groundwater to maintain supplies for the pastoral and mining industries, and the rural communities dependent on them, groundwater is also critical for some vegetation communities. Hatton and Evans (1997) have recently reviewed what is known of the dependence of Australian ecosystems on groundwater. It is clear from this review that numerous vegetation communities in northern Australia are dependent, at least to some degree, on groundwater. These communities are not restricted to swamps and wetlands. The authors note, for example, that there is growing evidence that the upland tropical savanna woodlands (as well as the paperbark swamps and patches of monsoon rainforest) are dependent on groundwater in the dry season.

2.8.2. Effect on land and the regional biota

Cattle grazing is concentrated around watering points, with pasture utilization decreasing with increasing distance from permanent water. This concentration of grazing can result in pasture decline and loss of cover with consequent effects for soil erosion and soil condition. These effects of overgrazing are dealt with in other sections of this report (Chapters 3 and 4).

Artificial watering points can affect the regional biota by introducing permanent water to previously dry environments and through the heavier utilization by cattle (and kangaroos and feral animals) of land nearer the water supply. As indicated in Chapter 1, the effects of the grazing industry on the biological diversity of northern Australia was not encompassed by the scope of this review. Consequently, this issue is not dealt with here other than to note that in flora and fauna surveys along transects radiating out from watering points, major changes in the composition of the biota were found with increasing distance from the watering point (Landsberg *et al.* 1997). Some species increased, while others decreased, in abundance nearer to water while other species showed no change along the transect.

2.9. Summary

There is documented evidence that overgrazing pastures, clearing, pasture improvement (including ponded pastures) and fire management can all have deleterious effects on waterbodies and waterways, including wetlands and the marine environment. Effects include salinisation (clearing); damage to, and reduction in habitat value of, riparian areas and wetlands (grazing, pasture improvement, ponded pastures, fire management); and loss of flora and fauna. In these cases, the issues are the susceptibility of different land types and communities such as wetlands/riparian areas, to the processes of degradation, and the local grazing management regime.

The role of grazing and pasture improvement in the development of algal blooms is more equivocal. Several mechanisms seem to be involved in bloom development and greater understanding is needed of when and where particular factors give rise to excess algal growth before the role of grazing land management can be determined. However, input of phosphate and nitrogen to waterways can give rise to processes that are suspected of having a role in bloom development. Consequently, grazing management that leads to soil erosion or the direct input of nutrients to standing waterbodies, may be exacerbating bloom formation.

The effects the grazing industry may be having off-shore are also not so clear. There is evidence of deleterious effects of flooding and sediment deposition on seagrass beds but the extent to which this can be attributed to increased inputs of sediment and water due to grazing practices is unknown. In addition, our knowledge of the biotic communities of the north Australian coast is limited and this is another factor that restricts our knowledge of the effects of that grazing management may be having. There is no incontrovertible evidence for eutrophication in the Great Barrier Reef. There is anecdotal evidence for eutrophication in enclosed bays and nearshore fringing reefs. It is significant that in other bodies of water of similar size to the Great Barrier Reef, in which eutrophication has been documented, there was little evidence for eutrophication prior to major ecosystem collapse. Detecting anthropogenic eutrophication is also made difficult by the fact that the scale of natural variation is greater than that detectable by long-term trend analysis.

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3. POSSIBLE EFFECTS OF GRAZING AND LAND MANAGEMENT PRACTICES ON WATER, SEDIMENT AND NUTRIENT FLUXES

This chapter summarizes work on, and current understanding of, the effects that grazing and grazing management practices can have on water, sediment and nutrient fluxes from areas ranging from small plot through to large catchment. In extensive grazing systems, the principal management tool is stocking rate (head/ha). Levels of pasture utilization, however, are influenced by the length of time particular paddocks are stocked. Watering points and fencing are the main means by which the distribution of stock can be controlled, though fencing generally is limited in the rangelands. Other management practices of importance in the rangelands are burning of pastures, and in regions with relatively fertile soils, tree clearing and pasture improvement with sown grasses and legumes (see Chapter 2 for estimate of area suitable for pasture improvement).

3.1. Effects of grazing and grazing management on fluxes at patch to small catchment scales

3.1.1. Infiltration studies at patch scale

There have been investigations of the differences in the hydraulic conductivity/infiltration rates of surface soils in both grazed and ungrazed pastures at several localities in Queensland and the Northern Territory. These have typically measured differences in soil hydraulic conductivity between vegetated and non-vegetated patches (both natural and arising from heavy grazing) within particular plant communities. All studies, regardless of soil type and climate, have found rates of water movement into the soil profile to be higher under grass patches than in bare open areas, with rates in bare areas influenced by the period of time for which the soil had been exposed. Reduced infiltration rates in bare areas are generally attributed to surface seals as a result of raindrop impact. Loss of soil organic matter once plants are removed is thought to promote sealing in some instances, for example in the red-earth soils studied by Mott *et al.* (1979). Also plant tussocks are associated with the presence of macropores which increase soil hydraulic conductivity. Possible origins for the macropores are that they are old root channels or that they are due to soil organism activity.

Differences in infiltration rates between sites with different plant species growing on the same soil type have been found in some experiments. For example, infiltration rates under *Heteropogon contortus* patches have been found to be higher than under *Chrysopogon fallax*. Although macroporosity was higher in soils under *H. contortus*, the reason for this difference was unclear. In some preliminary infiltration studies carried out with a disk permeameter at the Galloway Plains Grazing Trial (Calliope River catchment, Qld), pastures with Seca Stylo were found to have infiltration rates lower than those with either *H. contortus* or *C. fallax*. There have been limited infiltration experiments associated with burning. The effect on infiltration rate seems to be associated with the resultant soil exposure.

3.1.2. Plot scale hydrological studies

Large plot scale (30 m^2 to 0.25 ha) hydrological studies have been undertaken in the seasonally dry and semi-arid regions of Queensland and the Northern Territory. These have mostly been associated with grazing trials and have investigated the effects of stocking rate on plant cover, runoff and sediment movement. Only two of the studies from which information was obtained for this review, have measured nutrient loss. One study, that by Bonell and Williams (1986, 1987) involved investigation of the natural hydrology of an undissected plain near Torrens Creek in Queensland. This investigation found substantial variation in runoff and infiltration within the slope although only 2% of total rainfall was exported from the slope. A severe fire increased the amount of sediment movement within the 100 m slope but there was no increase in the net loss of sediment during the time frame of the experiment.

The results from measurements of runoff and soil loss under different grazing regimes were highly variable and depended on cover and rainfall intensities and amounts, although losses under heavier stocking rates were nearly always higher than under lighter grazing or in exclosures. For example, low runoff and sediment losses from plots have been shown to be correlated with high plant cover. As cover decreases, the amount of water and sediment loss increases. In some studies (eg, McIvor *et al.* 1995), around 40% cover has been found to be a threshold value above which runoff and sediment loss are relatively low but below which there is an exponential increase in water and sediment loss.

While small plot studies have shown that increases in runoff will result in increased export of sediment and nutrient, significant runoff events from small plots do not always translate into significant runoff from landscape plots (for example, Sallaway and Waters 1994). Runoff from plots is controlled by the spatial variability in surface hydraulic properties, particularly between bare and vegetated patches. Not only have vegetated patches been found to have higher hydraulic conductivities, but they increase the microtopography of the soil surface, creating surface depressions which increase surface water storage and reduce runoff. They also increase surface roughness which reduces the velocity, and hence the erosion potential, of overland flow. In ungrazed and lightly grazed pastures, there is usually a high degree of heterogeneity in soil surface properties associated with the distribution of numerous tussocks. In the tropical and subtropical seasonally dry woodlands with grass understoreys, for example, this spatial heterogeneity occurs in areas of less than one metre while in arid and semi-arid landscapes, the distance between patches is larger (Williams *et al.* 1993). With an increase in grazing pressure, plant cover is reduced, the bare areas increase and there is consequently a reduction in spatial heterogeneity. The increase in bare patches reduces the amount of infiltration and increases runoff. Once critical thresholds in plant cover are reached, more water is generated than is able to infiltrate within the remaining patches and there is an increase in net water loss. Associated with the increased runoff is an increase in erosion and sediment loss.

In the arid zone, soil loss studies have focussed on the development of 'erosion cells' rather than on plot measurements. 'An erosion cell' (Pickup 1985) encompasses the sediment production zone, the sediment transfer zone and the sediment deposition zone or sink. The deposition zones are generally associated with higher plant productivity. Under natural conditions, terrain in the arid zone is characterized by a mosaic of erosion cells, often superimposed on each other and with areas or relative stability between them. With the imposition of grazing, soil from the small erosion cells tends to be mobilized first, creating larger runoff or production zones. Increased runoff and sediment transport occurs and the increased sediment is only able to be trapped in the larger deposition zones. Consequently as a result of grazing, 'erosion cells' tend to decrease in frequency and increase in size. Grazing similarly induces a loss of spatial heterogeneity in these environments as was described above for the seasonally dry woodlands.

From the point of view of water quality, the important consideration is the net water and sediment loss from the local landscape (ie, the amount of water and sediment actually reaching the drainage channel). David Tongway (pers. comm.) has commented that although we can observe increased losses from patches and plots, we mostly do not know what is being lost from the local landscape. Losses from the local landscape will depend on the heterogeneity in soil properties and vegetation type as well as on the local topography.

3.1.3. Small catchment studies

Losses of sediment have been measured for small catchments in the Burdekin, Dawson, Burnett and Nogoa River catchments in Queensland. The investigations in the Dawson and Burnett catchments involved paired catchment approaches to determining the change in runoff and sediment loss following clearing and sowing to pasture. Clearing of Brigalow (*Acacia harpophylla*) and planting to buffel grass (Dawson catchment) resulted in an increase in mean runoff from 23 mm to 47.4 mm while average suspended sediment loss per event was 19 kg/ha for brigalow and 32 kg/ha for pasture (Lawrence and Thorburn 1989). In the Narayan small catchment study, it was concluded that provided a good grass cover were maintained, clearing woodland with *Eucalyptus melanophloia* and black spear grass (*Heteropogon contortus*) and sowing to improved pasture would not greatly affect runoff.

The Springvale catchment study (Nogoa River catchment) compared runoff from the catchment under grazing and, subsequently, with grazing excluded. Runoff from the catchment after the pasture had grown following exclosure from grazing was about 15% of rainfall while during grazing, runoff averaged 28% of rainfall over a period of four years.

3.1.4. Water balance studies and recharge investigations

The low topographic relief in many regions of northern Australia suggest relative high infiltration rates. Despite what would seem to be a geomorphic predisposition to high rates of infiltration in many areas of northern Australia, there have been few studies quantifying components of the water balance, including deep drainage, and the effects of grazing land management on recharge.

Williams and Coventry (1979 and 1980) investigated the soil water regime of red, yellow and grey earth profiles at Torrens Creek in the Burdekin catchment and found soils saturated during the wet season in some years. As a result, they concluded that there was potential for episodic groundwater recharge below these soils, despite the semi-arid environment. Barnes *et al.* (1992), in a study of nitrate contamination of groundwater near Ayers Rock, concluded that significant episodic recharge was occurring. A subsequent study using pre-existing bore data suggested a long-term annual recharge rate of about 20 mm/yr (Barnes *et al.* 1994). This latter study also noted that although localized recharge occurs in the arid zone as a result of infiltration through the beds of ephemeral streams, distributed recharge was likely to be the major source of groundwater renewal in the area they studied.

Circumstantial evidence for an increase in recharge following clearing comes from the development of dryland salinity in the south-east of Queensland, particularly in basaltic areas (Gordon 1991). The only field studies that have investigated the effect of clearing on soil water regime are those at 'Redlands' (45 kms west of Charters Towers in the Burdekin catchment), and the paired catchment experiments at the Brigalow (Dawson) and Narayan (Burnett catchment) Research Stations. The 'Redlands' field experimental work involved measuring the comparative water balance of the natural eucalypt woodland, the native grasses (*Heteropogon contortus* and *Chrysopogon fallax*), and *Stylosanthes* pastures with adequate and suboptimal levels of phosphate application. Clearing and the introduction of pastures had a clear effect on the water balance, with plant water use reduced in treatments with native grasses and *Stylosanthes* pastures only (Williams *et al.* 1997). Numerous studies in southern Australia have shwon that reduced plant water use results in higher soil water contents and an increase in the likelihood of recharge. .

At the Brigalow experimental site, clearing brigalow and its replacement with buffel grass pasture resulted in a 23 mm/yr increase in recharge (30 mm/yr under pasture compared with 7 mm/yr under natural brigalow) in a very high rainfall year prior to complete pasture establishment (Lawrence and Thorburn, 1989). In lower rainfall years there was no recharge under either the brigalow or buffel grass pasture. Similarly, Prebble and Stirk (1988) found little change in the soil water regime and deep drainage at the Narayan catchments between cleared sites sown with Sirato and green panic and the *Eucalyptus melanophloia* open woodland with *Heteropogon contortus*. The lack of change in the water regime was attributed to most trees having similar rooting depths to the pasture plants.

In addition to field studies, simulations of the soil water regime using models have also been carried out to help determine the potential for increased recharge following clearing and pasture establishment. Williams *et al.* (1997) used the SWIM and PERFECT models to extend the soil water balance measurements made at the 'Redlands' site. These simulations suggested that:

- over the period January to June 1980, deep drainage increased by a factor of ten in the native grassland without trees compared with the woodland (86.1 mm and 8.9 mm respectively);
- a red earth, sandy red earth and yellow podzolic soil each exhibited increased drainage under native grasses compared with under trees and native grasses; and
- over a 100 year rainfall record period (1889-1988), deep drainage was episodic, with the occurrence of deep drainage increasing from 17% to 66% of years in the red earth soil once trees were removed from the landscape. For the neutral red duplex soil, the suggested increase was from 4% of years to 42%.

3.1.5. Current and proposed research

Listed below are current research projects and projects which have been put forward for external funding but not yet approved.

Title	Contact	Issue	Location
Water balances in the natural system			
Water use by savannas	Derek Eamus, NT University	Estimation of sustainable groundwater pumping rates	Savanna woodlands near Darwin, NT
Hydrogeology of the Great Artesian Basin	Jim Kellet, Australian Geological Survey Organisation	Quantification of recharge from all sources, particularly river leakage compared with diffuse rainfall	Great Artesian Basin
Suppression of meso-scale heterogeneity by the tree layer in a tropical woodland	Joel Brown, CSIRO Tropical Agriculture	The effects of individual trees and tree clearing on the distribution of soil resources including water	Near Charters Towers, Qld
Soil water and nutrient change following clearing and pasture improvement			
Sustainability of Stylosanthes *pasture system in northern Australia: managing soil acidity*	Andrew Noble, CSIRO Land and Water	Assessment of long-term soil fertility and soil water trends under *Stylosanthes* and native pasture systems	Various sites in northern Qld and the NT
Surface water, sediment and nutrient fluxes			
Brigalow Experimental catchment studies	Bruce Cowie, Qld Department of Natural Resources	Nutrient and sediment losses in runoff	Brigalow Research Station, Qld
Coping with rainfall variability: grazing management strategies for seasonally variable tropical savannas	Peter O'Reagain, Qld Department of Primary Industries	Water, nutrient and sediment loss from 50 ha subcatchments	Near Charters Towers, Burdekin Catchment, Qld
How long will soils last with current grazing practices?	Mark Silburn, Queensland Department of Natural Resources,	Effect of sediment and nutrient losses on pasture productivity	Balonne and Nogoa catchments, Qld
Land management to reduce nutrient movement from catchments	Geoff Titmarsh, Queensland Department of Natural Resources	Nutrient composition and contribution from different soil types and land uses	Qld catchments within the Murray-Darling Basin
Water quality in the Fitzroy catchment	Don Yule, Queensland Department of Natural Resources	Effects of agricultural production on water quality	Fitzroy catchment, Qld

3.2. Effects of grazing and grazing management on fluxes from large catchments and river basins

3.2.1. Studies investigating the effects of grazing on catchment sediment and nutrient fluxes

Although "overgrazing" has been found to reduce infiltration and increase runoff and erosion within patches and small plots, this increase does not immediately translate into increased sediment and nutrient fluxes at a river mouth or even the outlet of a large subcatchment. Determining the change in fluxes that can be attributed to grazing is much more problematic at large catchment to river basin scales (thousands of square kilometres). While in the more humid climates at least, runoff and dissolved nutrients will be carried relatively rapidly from source areas to the coast, the same is not true for sediments and their sorbed nutrients. Sediment and associated sorbed nutrients eroded from a slope can be deposited downslope or downstream either on floodplains or within the channel network. The distance sediment is transported before deposition is related to its size — very fine particles tend to remain in suspension, and hence these particles and their associated nutrients will be transported further than larger, heavier particles. This further complicates the pattern of sediment generation and transport.

While changes in runoff and erosion (sediment generation) as a result of grazing have been investigated at plot and small catchment scale, there have been virtually no attempts to determine how far and over what periods of time, the eroded material is transported through a catchment, and how subsequent transport and deposition processes are themselves influenced by grazing. Consequently there is little understanding of how grazing has affected the flux of sediment and nutrients leaving large catchments.

Despite the limitations of the method, several studies have adopted a 'scaling up' approach using plot and small catchment measurements to estimate the effects of grazing on whole catchment sediment and nutrient fluxes. For example, Moss *et al.* (1993) developed two simple statistical models to estimate sediment and nutrient exports from Queensland coastal catchments. The first was based on flow-weighted sediment concentrations and annual average stream discharge. The second took into account land use, catchment erosion rates and a sediment delivery ratio. Moss *et al.* estimated current sediment loads from all Queensland coastal catchments as being 3-4 times greater than pre-European loads. They also concluded that about 84% of sediment from Queensland coastal catchments is from grazing land. Given the large area of the coastal catchments occupied by grazing, however, this figure is hardly surprising. It appears to be indicative more of the proportion of land used for grazing than of the amount of erosion and sediment transport from grazing land.

Neil and Yu (1996) used sediment concentration and daily streamflow data for the Barron, Tully, Herbert and Burdekin Rivers, Babinda Creek and the headwaters of the Flinders River, to estimate sediment yields of all streams discharging into the Great Barrier Reef lagoon. They estimated the proportion of current nutrient export to the Great Barrier Reef lagoon attributable to natural processes, grazing and cropping as 26%, 66% and 8% respectively. Again, these estimates are probably a reflection of the proportion of the total area occupied by these land uses. Although the estimates of sediment yields in this study do not represent a 'scaling up' from plot and small catchment data as much as the estimates of Moss *et al.* (1993), there are extrapolations between catchments, not all of which have the same climatic regimes and land types.

An alternative to summing runoff, sediment and nutrient fluxes measured on plots and for small catchments across the whole catchment, is to monitor fluxes at the catchment mouth and to correlate change in flux with a major change in catchment land use, such as the introduction of grazing. An immediate problem here, however, is the subsequent deposition of eroded sediment that may occur, resulting in the episodic movement of sediment through a catchment and unkown time-lags between the introduction of changed land use or management and change in sediment flux at the catchment mouth. Another problem is that monitoring records post-date changes of interest or a sufficiently long monitoring record is not available to distinguish between changes due to variation in climate and those attributable to grazing. Consequently, no studies using river monitoring data to investigate the effects of the introduction of grazing on fluxes of sediment and nutrient were found during this review. Andrew Ash, however, has a proposal to correlate plant cover with rainfall and Burdekin River flow regime (A. Ash, pers. comm.). Since heavy grazing is known to influence cover, a correlation between river flows and cover would strongly suggest a grazing influence on flows.

Other methods for investigating changes in catchment sediment and nutrient flux over time include examination of near-shore sediment cores. Changes in the rate of sediment deposition can be used to indicate changes in sediment flux due to land management changes. There are, however, several criteria which must be satisfied for a locality to be suitable for obtaining cores. For example, the locality should not be subject to physical disturbance, there need to be sufficient rates of sediment deposition for deposition to occur over relatively small time intervals and the period of deposition must be of sufficient length to cover the time span of interest. It is often difficult for all these criteria to be met. Sediment core work is currently being undertaken in the Herbert River catchment and a project to use sediment cores to reconstruct changes in carbon and nitrogen inputs is planned for the Fitzroy River catchment in Queensland.

In a similar but slightly different approach to assessing changes in terrestrial inputs to the Great Barrier Reef lagoon, scientists at the Australian Institute of Marine Science are using cores taken from coral colonies. Coral colonies have life spans greater than 200 years and, since they contain a record of the natural variability in coral growth prior to European settlement, cores from them can be used to assess growth changes due to anthropogenic activity.

Despite these various investigations of terrestrial inputs from coastal catchments, the issue that is still not clear, is the increment in the flux of sediments and nutrients from the land over that which occurred in the ungrazed state. Given the large proportion of many catchments that is used for grazing, it is to be expected that land used for grazing will contribute a high proportion of the sediment and nutrient transported from a catchment. It is the increment in sediment and nutrient transport within and from catchments as a result of grazing that is important, not the total amount of sediment contributed by grazing lands. It is not realistic to try to reduce the flux of sediment and nutrient to below that which occurred under natural conditions.

3.2.2. The capacity of landscapes to generate and transport sediment

As indicated in Section 3.2.1., there have been few investigations of how large catchments function in terms of sediment and nutrient generation, transport, and deposition or of the effects of grazing on these processes. Estimates of catchment sediment and nutrient fluxes have either been based on plot studies, which effectively assume that land use is the primary factor controlling runoff and soil loss, or they have investigated exports from the whole catchment and correlated these with known changes in grazing management to obtain an indication of the effects that grazing may be having. An aspect of catchment function which generally has not been considered, let alone investigated, is the variation in the inherent capacity of different landscapes within a catchment to generate and transport sediment.

Work by Aldrick in the Ord and Roper River catchments and the Southern Gulf Region of the Northern Territory (Aldrick *et al.* 1978, Aldrick and Wilson 1990, 1992), suggests that not all landscapes are equally likely to contribute sediment at a catchment mouth. In the land resource assessments of these areas, Aldrick has identified geomorphic provinces, where a geomorphic province is "*an area of land having attributes of landform and/or soils and/or vegetation that differ consistently from those of other terrain, because of the direct influence of a geomorphological landscape-forming process or processes operating there but not operating elsewhere at the same rate*" (Aldrick 1985). Geomorphic processes that have operated in a landscape over long periods of time, and that are still operating there today, exert a dominant natural influence on sediment supply and transport. Some of these geomorphic provinces are relatively stable and unlikely to deteriorate substantially, but others are inherently unstable. Disturbance of vegetative cover and topsoil in the more vulnerable geomorphic provinces can increase sediment and nutrient output substantially; much more so than in the more stable geomorphic provinces. As a result each province has an inherent capacity to generate and transport sediment towards the coast. Whether this inherent tendency is accelerated or not depends primarily on whether the controls imparted by the vegetation and soil are impaired, for example by grazing and land management practices.

As well as this landscape scale variation in the capacity of land to contribute sediment to a river mouth, there is also variation at more local levels. Recently several authors have pointed out (eg. Finlayson and

Silburn 1996, Wasson 1996) that the relationship between slopes and channels is important in determining the time-frame over which sediment eroded from a slope is likely to be transported from the subcatchment. Where slopes and channels are directly connected, sediment from the slope will more quickly reach a channel compared with areas where the slope is separated from the channel by flat or very gently sloping land, such as a floodplain. Sediment reaching the flat terrain is likely to be stored there for considerable periods before being eroded by floodplain scour or eventually channel erosion. Riparian vegetation has also been considered to be important in filtering, and storing at least temporarily, sediment and absorbed nutrients from water running off the land into the waterway. Despite recognition of this possible role of vegetation, there are very few data quantifying the effect that vegetation can have, how this might vary for different land types and stream orders, and the effect that grazing riparian vegetation has on this filtering function. Work on the filtering role of riparian vegetation is being undertaken in the National Rehabilitation and Management of Riparian Lands Program being funded by the Land and Water Resources Research and Development Corporation. There are few investigations, however, directly associated with grazing lands although generic information will be provided which should be tested in the northern Australian rangeland environment.

Sediment tracing studies can be used to determine the source of sediment, both in terms of geographical location and whether the sediment is derived from sheet and rill erosion, or from gullies and channels. The only sediment tracing work identified during this review was that by Wasson *et al.* (1994) for the Ord River catchment. An important outcome of this work was that only about 10% of sediment in Lake Argyle was considered to be derived from sheet erosion, the remainder coming from gullies and channels.

Given the likely importance of gullies as a source of sediment, the possible effects of grazing on gully development and stability are just as important as the possible effects of grazing on sheet and rill erosion. There have been, however, fewer studies relating to gullies. Finlayson and Brizga (1993) have investigated the incision of an anastomosing stream in the Nogoa River catchment in central Queensland. Incision occurred subsequent to the introduction of grazing and Finlayson and Brizga suggest that loss of vegetation cover and disturbance of the soil surface by cattle may have initiated channel incision.

3.2.3. Current and proposed river basin water quality and catchment management projects

Title	Contact	Issue
Water quality research for the Fitzroy River, Qld		
Water quality in the Fitzroy catchment	Don Yule, Department of Natural Resources, Qld	Effects of agricultural production on water quality
Coastal zone research in the Herbert River catchment		
Climate record	Janice Lough, Australian Institute of Marine Science	Climate variability over the past several centuries using proxy records from massive corals
Isotopic studies of organic carbon	Michael Bird, Australian National University	Processes controlling the carbon-isotope composition of carbon in the terrestrial carbon pool
Effects of rural land use on water quality	Rob Bramley and Christian Roth, CSIRO Land & Water	Quantification of the effects of rural land uses in water quality in the lower Herbert River
Nutrient and sediment delivery from the Herbert River	Chris Barnes, CSIRO Land & Water	Quantification of major nutrient fluxes from the Herbert River to the Great Barrier Reef lagoon.

Sediment history of the Herbert River floodplain	Bob Wasson, Australian National University	Quantity of sediment and P deposited on the Herbert River floodplain and any variation in post-European deposition
Marine biogeochemistry and sedimentation history	Gregg Brunskill, Australian Institute of Marine Science	History of sediment accumulation on the continental shelf near the Herbert River mouth
Biological resources of beds of the tropical continental shelf	Roland Pritcher, CSIRO Division of Marine Research	Factors determining the distribution the distribution, abundance, population dynamics and productivity of tropical continental shelf seabed resources
Decision support development	Andrew Johnson and Daniel Walker, CSIRO Tropical Agriculture	Effective tools for assisting the management of natural resources in northern Australia
Research in the North Johnstone River catchment, Qld		
National Rehabilitation and Management of Riparian Lands Program —Aspects of physical and chemical processes	Ian Prosser, CSIRO Land & Water	Sediment budgets, sediment and nutrient filtering by riparian vegetation and effect of cattle access to streams on sediment and nutrient fluxes to waterways
National Rehabilitation and Management of Riparian Lands Program —Ecological issues	Stuart Bunn, Centre for In-Stream and Catchment Research, Griffith University	Para Grass, Bamboo Creek, Innisfail
Nutrient balances and transport from agricultural lands	Brian Prove, Qld Department of Natural Resources	Nutrient and sediment removal from agricultural land and the mechanisms and pathways for their removal
Water quality monitoring and modelling	Heather Hunter, Qld Department of Natural Resources	Quantification of sediment and nutrient loads entering the GBR from the Johnstone River

3.3. Summary

Cattle grazing can have a marked effect on sediment and nutrient loss when losses are measured at patch and small plot scale. Not all grazing, however, results in increased loss of sediment and nutrient. Erosion studies have shown runoff and sediment loss to be related to plant and ground cover. At relatively high covers, net water and sediment fluxes from erosion plots mostly have been small, increasing with a decrease in cover. In several studies in the wet/dry tropics and subtropics, ground cover of around 40% has been found to be the value below which there is a marked increase in runoff and erosion. Consequently, while stock numbers and grazing pressure are such that relatively high plant and ground cover levels are maintained, there is little water and sediment loss. Once grazing pressure increases, however, plant and ground cover are reduced. Loss of cover increases the exposure of soil to raindrop impact and surface sealing is likely. Loss of plant cover is also associated with a loss of soil macropores although the mechanisms involved are not clear. It may be related to loss of soil organism activity and/or loss of plant roots. Sealing and loss of macroporosity reduce infiltration, increasing runoff. Loss of cover also reduces the degree to which surface flow is impeded and exposes soil to removal by flowing water. The increase in runoff and its velocity, along with the exposure of soil to erosion, result in an increase in sediment loss.

In addition to exposing soil to raindrop impact and overland flow, loss of cover exposes the soil to trafficking and compaction by cattle. Compaction not only reduces infiltration, as with sealing, but reduces the surface microtopography. Small depressions in the soil surface store rainfall, reducing runoff and increasing infiltration. Their loss further increases runoff.

The head of cattle per hectare which will cause critical ground cover levels to be reached, is highly variable both in time and space. The amount of cover at any time depends on the relationship between plant growth and plant consumption. Different land types have different capacities for plant production, related to their inherent nutrient fertility as well as to their soil water holding capacity. They also have different inherent susceptibilities to soil loss as a result of different slopes, inherent tendency to seal, particle size characteristics of surface soil, and so on. There are also marked differences in plant productivity over time in any given land type, arising from differences in seasonal rainfalls. As a result of differences in land type and season, cattle numbers need to be adjusted both spatially and temporally. From the point of view of tactical management, the concept of 'average' carrying capacity has little meaning. A large part of the degradation that is currently observable in the rangelands (see Tothill and Gillies 1992) is the result of the mismatch between animal numbers and plant production (for example, see Figure 1.1 in Chapter 1). Avoiding pasture degradation and the resultant loss of soil and nutrients will require improved management of stock numbers. In the past, large properties and holdings throughout the rangelands enabled pastoralists to move stock and adjust stock numbers according to seasonal conditions on any property. Reduced property sizes limit this capacity and economically viable alternatives for adjusting stock numbers are required. In those areas of the rangelands where seasonal conditions are usually related to the Southern Oscillation Index, improvements in prediction of the index should help pastoralists with strategic stock management.

Burning pastures is another mechanism by which plant and ground cover can be reduced. Consequently, this management strategy has also been found to increase runoff and sediment loss in comparison with unburnt pasture, with the increase depending on the length of time for which the soil has been exposed following burning. Differences would also be expected between different land types.

Modelling work indicates that an increase in episodic recharge is likely in many parts of the semi-arid to wet/dry tropics as a result of clearing, although very few experimental hydrological investigations have been carried out. This is changing, however, with the work being done in the NT on water balances in the natural system and in the Balfes Creek area in the Burdekin Catchment. Also, sustainable water use in the Great Artesian Basin is increasingly becoming an issue. The Australian Geological Survey Organisation has developed a groundwater model for the Basin and now require quantified data for recharge flux from all sources, both river leakage and diffuse rainfall recharge, to be able to confidently predict resource performance. It is therefore likely that some recharge studies will be undertaken in landscapes overlying the intake beds of the Great Artesian Basin. Likely change in components of the water balance following clearing and pasture improvement in different land types, remains one of the major unknowns across northern Australia.

While increases in the flux of water, sediment and nutrient have been measured at local scales, at particular stocking rates and as a result of burning or pasture improvement and clearing, the effect of these increases on the flux of sediment and nutrient leaving a large catchment is virtually unknown. Consequently, the downstream effects of stock numbers exceeding the productive capacity of pastures is also unknown. Various estimates have been made of the effect of increases in local fluxes on the discharge of sediment and nutrient from whole catchments but these estimates take no account of eroded material that is subsequently deposited before reaching a catchment mouth. It is expected that any increase in very fine sediment transported to a channel as a result of grazing, will result in an increase in the export of very fine sediment, and attached nutrients, as such sediment is likely to remain suspended in the water column. The same is not true, however, for coarser particles. The estimates of changes in sediment and nutrients exported from a catchment often also assume that different land types will have similar soil losses provided land use is the same. Consequently, the estimates can best be considered a first approximation.

Alternative methods for assessing the effect of the introduction of grazing on catchment sediment and nutrient export include examination of near-shore sediment cores for changes in the rate of sediment deposition, and of corals for changes in growth rate. Work currently being undertaken by the Australian

Institute of Marine Science is assessing the use of coral cores for determining the past occurrence of episodic flooding.

Work is needed to delineate the different landscapes and to determine their inherent tendencies to contribute sediment at a river mouth. This involves both an understanding of the inherent tendency of a landscape to produce and transport sediment of different size classes as well as sediment tracing to help identify the different geographical locations and sources (slopes and plains, gullies, channels or floodplains) contributing sediment to the channel network. Only then can the effects of grazing in different landscapes within a catchment, on catchment sediment and nutrient fluxes, be determined.

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4. POSSIBLE EFFECTS OF GRAZING ON LAND RESOURCES AND THE GRAZING INDUSTRY

The main focus of this review has been the off-site effects that grazing and grazing management can have. While these are extremely important given the wide geographic spread of the northern Australian beef industry and hence its potential to affect a large number of riverine, wetland and marine environments, it is also worthwhile to briefly consider some of the on-site effects grazing and grazing management can have on the vegetation and soil, and the processes within them. Effects on the land are critical for the grazing industry itself as they will eventually influence animal production and hence profitability. Some of these effects are discussed in this chapter.

As was noted in Chapter 3, not all grazing or grazing management is associated with land degradation and off-site water quality effects. Most degradational problems only arise when pasture utilization levels and trafficking and trampling are such as to allow thresholds in biophysical properties of the land to be exceeded, such as percent cover, so that processes which reduce the productive capacity of the land, and which are regarded as deleterious, occur. It should be noted, that other grazing animals, such as kangaroos and feral animals, can all contribute to the pressure on the pasture resource, and that erosion and other degradational processes can be initiated by activities other than grazing. Tracks, for example, can be a major cause of erosion.

4.1. Loss of landscape function

The introduction of grazing, as with any land use, affects the natural environment and the processes within it, by altering characteristics of the vegetation and soils. The degree of change within the landscape depends both on the characteristics of the particular landscape and on the degree and type of utilization of the area by cattle. In landscapes with heavy use, loss of vegetation cover, change in species composition and change in condition of the soil, are readily apparent. While change in species composition has direct implications for biological diversity, the other important issue from the point of view of sustainability of the grazing resource, is the change in processes or land functioning. Such changes are not easily visible although there has been considerable work within the CSIRO Division of Wildlife and Ecology to link land function with indicators that can be readily observed in the field (eg, Tongway and Hindley 1995).

Loss of landscape function is associated primarily with loss of vegetation, though current work associated with the project *The determinants of land degradation in wet/dry tropical savannas*, suggest that other factors may also be necessary (Garry Cook, pers. comm). Loss of vegetation exposes the soil to raindrop impact and this, combined with the associated loss of organic matter (through greater oxidation and reduced litter return), can result in surface sealing and reduction in water infiltration. Soil organisms can also exert a significant influence on infiltration. For example, Holt *et al.* (1996) showed that a reduction in the biomass and diversity of termites caused by heavy grazing pressure over a period of six years, caused a 70% decline in soil hydraulic conductivities. An increase in bare, sealed areas increases runoff and also represents a loss of "patchiness" in the landscape. Grass patches have been found to trap litter, sediments and seeds and as patchiness is reduced, these materials are lost from the local landscape. The role of vegetation patches in landscape function has been extensively described in the recent book *Landscape Ecology, Function and Management: Principles from Australia's Rangelands* (Ludwig *et al.* 1997).

4.2. Implications of increased water, sediment and nutrient loss for land and animal productivity

4.2.1. Water

The data of Silburn *et al.* (1992) for a site in central Queensland demonstrate quite clearly the significance of water loss from systems with very low plant cover. They measured runoff that accounted for 50-60% of the annual rainfall on plots with less than 10% plant cover. As the authors point out, at this site, a pasture with low cover effectively experiences a drought (320-420 mm water available for growth) in a year of average rainfall (790 mm). Various studies (eg Friedel 1981a, McIvor *et al.* 1995) have quantified the reduction in biomass production that can occur on land in poor condition. Some of this reduction would be due to the reduced water availability from the decrease in infiltration and increased runoff.

4.2.2. Nutrients

Plot and small catchment studies have generally not measured nutrient export so that there are very few data on nutrient loss rates associated with runoff and erosion, and on the significance of these losses either in terms of the proportion of nutrient removed from different land types or the affect of this removal on future productive capacity. Silburn (1996) in a project proposal for NHT funding (*How long will soils last with current grazing practices*?) quotes loss rates of 10% of total N and P over two recent very dry years, for a site in SE Queensland. This was the only data found that correlated measured nutrient loss rates from a soil, with the soil nutrient reserves. Further data on the affect of grazing on soil nutrient losses and soil nutrient reserves will be available from model simulations in this project for soils (which ones were not specified) of *Aristida—Bothriochloa* woodlands in the Balonne/Maranoa and Nogoa/Fitzroy catchments.

Several studies give data on the distribution of nutrients within the soil which allow some assessments to be made of the effects of erosion. For example, Pressland (1985) provides data on organic carbon, total N and P, and available P at various depths in the top metre of the profile for mulga lands, although the particular soil type is not given. He points out that loss of the top 5 cm of soil results in loss of 13% of the available P, 9% of total N and 11% of organic carbon. Further more, when the top 5 cm of soil is removed, the next 5 cm contains only 50% of the P that was available in the original surface soil. Production of wire, mitchell and buffel grasses grown in pots with soils from 5 cm depth was found to be about half that of the same grasses grown in soil from the top 5 cm. Similarly, Tongway and Ludwig (1994) provide data on nutrient reserves for a neutral red earth soil with a wooded grassland near Katherine in the Northern Territory. In grassy areas, organic carbon and available phosphorus in the top 1 cm of soil were more than double the amounts from 1-3 cm. Low fertility soils commonly seem to have a relatively high proportion of total nutrients in the topsoil (Charley and Cowling 1968, cited in Friedel 1981).

Losses of topsoil nutrients would seem to be critical for the long-term sustainability of pastures but there seems to be little knowledge about long term effects. The GRASP (GRASs Production) model developed for northern Australian pasture systems is being used in the project "*How long will soils last with current grazing practices*?" to estimate the effects over time of continued nutrient loss on plant biomass production. As well as total production, another critical issues is the affect of loss of nutrients on vegetation state. That is, do we know if once a certain nutrient threshold has been crossed, whether it is possible to return to an alternate vegetation state?

Friedel *et al.* (1980) did some work that investigated the relationships between nutrient deficiencies and range condition in Central Australia. They concluded that P is the only nutrient which is potentially more deficient on degraded rangeland soils compared with healthy rangeland soils but that evidence for a relationship between range condition and phosphorus deficiency was inconclusive. They did find, however, under glasshouse conditions, that decreaser species growing on mitchell grassland and open woodland soils from poor condition areas responded better to phosphorus addition than they did if growing on soils from areas in good range condition. Increaser species growing on soils from degraded areas of mitchell grassland also responded better to phosphorus addition than those growing on soils from good areas while increaser species growing in woodland soils were insensitive to phosphorus addition.

A further study (Friedel 1981a,b) that sampled nutrients in soils from *Astrebla* grasslands, open woodlands and *Acacia* shrublands in excellent, good and poor condition found some evidence for correlation between extractable phosphorus and range condition in *Astrebla* grasslands and open woodlands. When soil from sites in different condition over a larger geographic area were sampled, little correlation with extractable phosphorus (or nitrogen or sulphur) was found.

The studies of Friedel suggest that in the vegetation communities studied, nutrient level on its own is not determining plant composition in the degraded state. The factors resulting in changed species composition are not clear and it would be useful to know the mechanisms involved, for example, whether factors such as reduced activity of soil biota and reduced infiltration, increased soil temperatures, and/or reduced seed production are involved. It may also be that a lower nutrient status can cause other factors to become limiting for a particular species when they would not be limiting at higher nutrient levels. The current project, *Determinants of land degradation in tropical savannas* may provide some further information.

4.2.3. Effects on animal production

Ash and McIvor (1995) investigated the effects of land condition at sites on different soils at Katherine and Charters Towers, on herbage quality. Over all sites, they found a significant increase in digestibility and nitrogen concentration and a significant decrease in phosphorus concentration, as condition declined. This suggested that, at least in the short-term diet quality may be higher on land in poor condition. A study of the effect of land condition on animal production showed variable changes in animal liveweight (g/hd/day) depending on stocking rate. At both Charters Towers and Katherine, low stocking rates (1 or <1 animal per ha, and 2 or <2 animals per ha, respectively) on land with State II vegetation resulted in greater liveweight gains than land with vegetation in State I. At higher stocking rates, the reverse was true due to the effect of the decreased production of State II vegetation.

That animal production is not simply related to land condition suggests that using vegetation and soil indicators of land condition on their own will not necessarily lead to management changes. It will be necessary to demonstrate to graziers the economic and ecological benefits of returning to State 1 vegetation. These benefits may be related to the greater productivity of State 1 vegetation, lower risk of fodder shortage (particularly during dry periods), and long-term maintenance of soil fertility.

4.3. The dynamics of land and grazing systems, and some knowledge gaps

Hutchinson (1997) identified the key linkages which we need to understand in our land—grazing systems if we are to manage them so that the productive potential of the land resource is maintained, where the land resource includes pasture, soil and water (figure 1). It is useful to consider the research in northern Australian grazing systems in terms of these linkages. It seems that there is understanding about the effects of grazing on pasture species for at least some vegetation communities, as shown by the development and use of the various state and transition models (eg. *Tropical Grasslands* 28, 195-279). There also seems to have been considerable work on pasture species and animal production, and the effect on these of soil fertility though these aspects have not been covered by this review. This review has identified work on the effects of overgrazing on infiltration and runoff, and in reducing the heterogeneity of the soil surface and vegetation cover. For example, a reasonably large body of information seems to be being built up on the functioning of rangeland landscapes in terms of the distribution of vegetation and its effect on water and material (sediment, nutrient, litter, seed) transfer and accumulation processes, and of the effect of grazing on these processes (see, for example Ludwig *et al.* 1997 and numerous references within this).

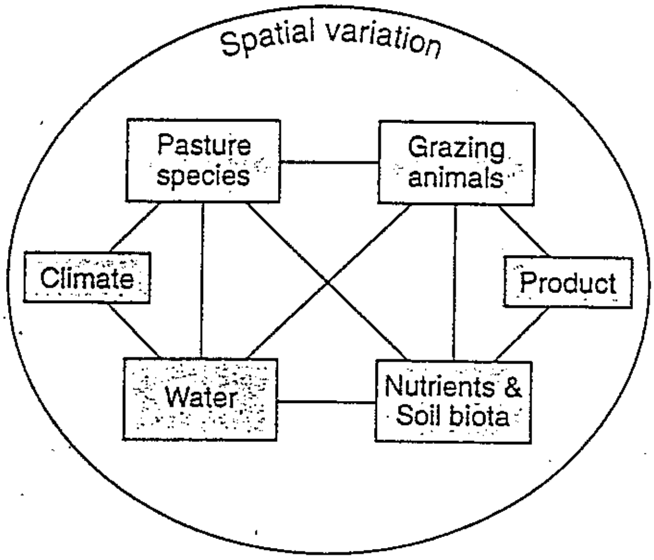


Figure 1. Key linkages between grazing system components (From: Hutchinson 1997)

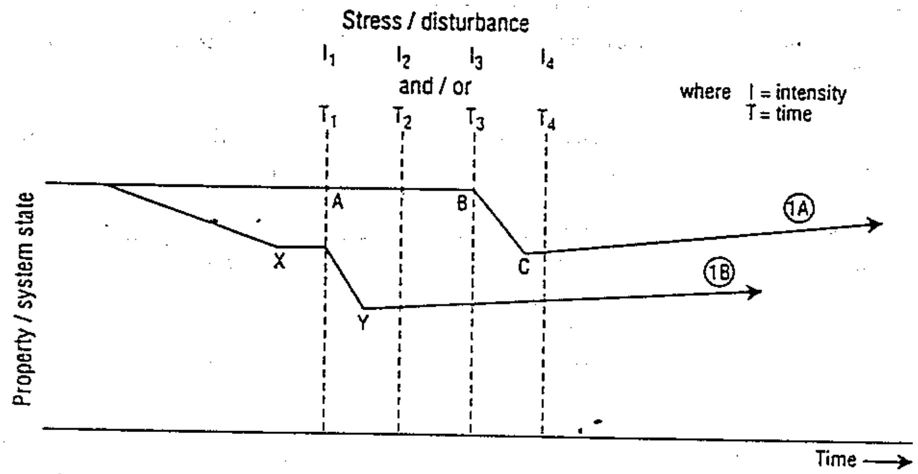
Some of the linkages, however, seem not to be so well known. Some examples are:

- nutrient cycling, including litter production and the role of soil biota (microorganisms as well as termites) in different pasture communities and different vegetation states within these communities, and the role of nutrients and biota in determining pasture composition;
- the role of soil biota in water infiltration and runoff — the various plot studies which have measured runoff under grazing have not documented the changes in biological properties of the soil; and
- the effect of grazing and grazing management practices on soil biota and nutrients. Christie (1979) for example, noted two possible detrimental effects of grazing on nutrient cycling. One was a reduction in litter yield following over-utilization of the vegetation, a change which would also be expected to affect soil biota. The other was a reduction in nutrient uptake due to reduction in the volume of soil exploited by the root system. Other processes are also regarded as being involved, for example, loss of cover is expected to increase soil temperatures and this will also affect the soil biota.

A major gap in understanding, however, is not the individual linkages between particular components, but how the various components all inter-relate, the spatial variation in these processes, and how processes at one location impinge on those in another. Piecing together this type of understanding will take time. Sallaway *et al.* (1993) provide a good example of where our understanding of relationships between components of the grazing system is poor. These authors found that replacement of *Heteropogon contortus* patches by *Aristida spp.* patches greatly reduced infiltration and increased runoff, a change that was associated with differences in macroporosity and possibly linked with biological activity by soil microfauna. They noted, however, that it was impossible to tell whether the change in vegetation was a cause or result of the change in macroporosity.

Also, while spatial aspects of system function have been considered within particular range types, variation in functioning between range and land types also needs to be considered. For example, are soil biota more important in maintaining infiltration and nutrient availability in particular soil types? Another spatial consideration is the way grazing animals utilize different land types and the associated vegetation. In other words, the different linkages need to be considered at paddock scales and not just plot scales. Finally, more attention needs to be given to grazing management strategies and their effects on system function over time and to the corresponding feedbacks on productivity and returns over time. Up until now the focus seems to have been on maximizing product output in the short-term, but often this is associated with higher risks of soil and pasture damage. It may be that alternative strategies can return a greater income over time.

A factor not incorporated in the figure of Hutchinson, but which also needs to be understood, is the role of time. It may be that some processes can continue for limited periods without degradation occurring but continuation beyond a critical time, will result in a threshold to change being exceeded. Similarly, timing of a stress in relation to system condition may also be critical. These concepts are shown schematically in Figure 2. The implications are that experimental work must be sufficiently long to cover potential time thresholds, and also changes in land condition that may be caused by other factors, such as drought, but which will affect thresholds to change. The short-term time-frames of much current research means that the effects of time and changes in land condition are often ignored. In many instances we do not even know how land and soil properties are changing over time, let alone whether any critical thresholds from the point of view of land function, are likely to be exceeded. For example, there have been few, if any, time-series studies of changes in soil carbon (John Carter, pers. comm.).



(a) Property/ system 1A exhibits resistance to change with stress/ disturbance until I_3/T_3 at which point a change of state occurs from which return to the original condition is not possible within the time span of interest. I_3/T_3 represents a threshold in stress intensity or time period of stress.

Property/ system 1B undergoes a natural change in state prior to application of stress/disturbance. In this state the system has no resilience to even the lowest intensity stress of shortest stress duration.

I_1, I_2, I_3 and I_4 represent increasing intensities of stress, and T_1, T_2, T_3 and T_4 increasing duration of stress.

Figure 2. Effects of variation in timing and duration of applied stress or disturbance on resistance and resilience of grazing system properties. If a property reaches a condition from which it is unable to return without the application of remedial treatment, resource degradation is considered to have occurred. (From Williams *et al.* 1993).

Understanding these inter-relationships between grazing and soil/land resources is necessary in order to develop management practices which do not impair landscape function as well as to develop and assess rehabilitation strategies for areas that have become degraded. Some of the current research investigating aspects of inter-relationships between grazing system components is given in Attachment 1.

4.4. Biodiversity

Figure 1 does not consider maintenance of the natural flora and fauna. Retaining the natural biotic diversity within different landscapes is increasingly regarded as part of retaining system function. The effects of grazing on biological diversity other than that associated with wetlands and riparian zones was not a part of this review. It is noted, however, that if the biological diversity of regions are to be maintained, this in itself becomes an objective which needs to be considered in management plans. Meeting the objective will require a knowledge of the biota of regions, areas of particular significance and levels of grazing pressure (including exclosure from grazing), compatible with maintaining the diversity.

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ATTACHMENT 1 — CURRENT AND PROPOSED RESEARCH

Soil — vegetation inter-relationships

Distribution of Roots Among Neighbouring Plants of a Tussock Grass Species in a Tropical Grassland

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Background: Distribution of root systems of perennial grasses within the soil profile is one of the key factors to plant productivity and survival. Root distribution influences acquisition of water and nutrients needed for photosynthetic activity, growth and development of physical structures, and production of new propagules.

Use of the soil profile by root systems of important tussock grasses is not widely understood. It is not known, for example, whether tussock grasses have roots inhabiting large portions of the interspaces between tussocks. An additional knowledge gap is the effect of landscape degradation on use of the soil profile by perennial bunch grasses. Characterizing the area of soil profile occupied by roots of grasses will be important in understanding resource use by grasses and the dynamics in degradation and recovery of pastoral lands. It will also be an important focal point for modelling landscape productivity and plant growth. Data collected in this study will allow examination of whether tussocks of perennial grasses extensively utilize soil resources within interspaces between plants.

Objective: To define the micro- and meso-scale spatial distribution of roots of neighbouring plants of tussock grasses.

Methods: materials to be analyzed will be collected from 3 different pasture state classes with different levels of utilization, within paddocks at the Cardigan experimental site, near Charters Towers. State classes included will represent a range of different stages in the desertification of landscapes in Queensland.

Sampling will be conducted between pairs of tussocks of the predominant species *Bothriochloa ewortiana*. Soil cores to 1 m depth will be collected in a transect from the center of a tussock to the center of the neighbouring tussock. Cores will be taken at: 1) tussock centers; 2) tussock edges; 3) center of inter-space distance; 4) between interspace center and tussock edges. Collected soil cores will be divided into 6 depths: 0-10 cm; 10-20 cm; 20-40 cm; 40-60 cm; 60-80 cm; and 80-100 cm. Below 40 cm, root distribution under native perennial tussocks is not known. A preliminary survey indicated that the highest rooting activity occurred in the top 20 cm, and moderate amounts were present from 20-40 cm.

Sampling will be conducted to examine plant responses to environmental stresses to see whether the distribution of roots expands or contracts into interspaces with changes in abiotic factors. Small exclosures will be established around sets of plants, and two different factors will be manipulated: 1) soil moisture level; and 2) defoliation. Root dynamics within the wet and dry seasons will be determined. Root characteristics (length, surface area, size class distributions) will be measured with scanning imagery equipment and biomass (g dry matter) of samples will be determined.

Additional soil materials of the upper 5 cm of the soil profile will be collected at each location along the transects for analysis of soil microbial biomass.

Spatial Distribution of Soil Resources Around Perennial Tussock Grasses in a Tropical Grassland

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Background: It has been proposed that scarce or limiting resources in semi-arid and arid regions are patchily distributed across the landscape, and concentrated in "fertile" patches that comprise a minor segment of the total land area These resource islands supposedly form by aeolian and fluvial deposition of materials in micro-sites protected by standing organic matter of plants, and further enhanced by biological activity (particularly micro-faunal) in the immediate area. Both biological and physical transport mechanisms then serve to increase concentration of limiting resources in these fertile islands; they gather nutrients from surrounding areas, and retain resources already present. Soil micro-flora and fauna around tussocks may help mediate these processes by converting materials and re-locating them through the soil profile. It is probable that tussock grasses alter nutrient levels (particularly nitrogen), soil moisture regimes, and solar radiation input, thereby ameliorating local conditions and serving as recruitment foci for herbaceous species in managed ecosystems in Queensland.

Degradation of natural landscapes with long-term excessive grazing causes loss of basal area of tussock grasses, and litter cover, as bare interspace increases. Soil characteristics (soil pH, bulk density, water holding capacity) important in water movement and nutrient levels, are adversely effected. Microbial communities, which are important in mineralisation of key nutrients, rely on carbon found in litter and dead roots to supply carbon for growth and reproduction. Increases in bare interspace may limit availability of nutrients in these zones, and help hamper landscape recovery.

Objectives: The aim of this study is to quantify the micro and meso-scale spatial distribution of various soil resources in tropical grasslands in different stages of desertification. Data collected in this study will allow a test of whether tussocks of perennial grasses in Queensland actively "capture" resources in runoff from inter-patch areas that could affect biogeochemical cycles, or affect future community structure at the micro-topographic scale. Areas of specific interest will include: 1) seed-bank dynamics; 2) dynamics in the microbial population; and 3) nutrient load around tussocks of different grass species and related bare inter-patch zones. Description of changes in distribution of soil properties may provide an index of the states in desertification of grasslands in Queensland.

Methods: Materials to be analysed will be collected from experimental paddocks exhibiting different pasture transitional states and with different levels of utilization, within the Cardigan site near Charters Towers. State classes included represent different stages in the desertification of landscapes. Areas sampled will include tussocks of *Heteropogon contortus, Chrysopogon fallax, Bothriochloa ewartiana* and bare patches to serve as a control.

Plant properties measured will include basal diameter and/or circumference of tussocks; above-ground biomass, with standing biomass and litter determined separately; biomass density (from standing biomass/basal diameter) and stem density (if time and manpower permits).

Soil samples will be collected at a fine scale of resolution laterally, with sampling oriented in an upslope-downslope direction. Vertically, soil will e collected from the 0-5 cm layer (the zone of maximum microbial activity and nutrient load), and from 5-10 cm. Little is known about microbial activity at this depth, though it is thought to be low. Characteristics to be measured include:

- Soil seed bank — total numbers of seeds and total number of seeds will be determined. Determination of numbers of species will also be completed. Viable seeds will be separated from samples.
- microbial biomass — microbial biomass will be determined with the fumigation-extraction method and the density and richness of microbial species will be determined (if resources are available).
- mineral nitrogen and phosphorus.

N_2O emissions from savanna soils (aspects of N cycling)

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Proposed Study: Description of the Desertification Process in Soils of a Tropical Grassland

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Background: spatial variation in soil physical and chemical properties within native plant communities can be high, with organic matter, pH, and different mineral element concentrations varying by an order of magnitude over < 5m. Such variation has been shown to be related to changes in plant densities, and shifts in species distributions. Similarly, nutrient cycling in disturbed and natural ecosystems are spatially variable processes, and this variability alone may affect the structure of plant communities, potential states achieved, or transitions followed. It has been suggested that availability of limiting nutrients and the spatial patterns in availability of these nutrients, are critical components (though largely unquantified) of plant community structure.

Objective: the aim of this study is to use sophisticated analytical techniques to model spatial changes of important soil nutrients and plant biomass in tropical grasslands, associated with different vegetation states.

Methods: A multi-phase study will be undertaken to assess changes in nutrient distributions in Queensland plant communities at fine scales of resolution, in response to different levels of desertification. Each phase will focus on different surface elements, ranging from individual plants, to small patches. Results attained will be applied in an additional phase to interpolate distributions at a medium-scale level (paddock or part of a paddock).

Phase I. Response of individual plant root systems to different levels of landscape degradation.

The objective is to characterise the vertical and lateral distribution of the roots of important tussock grass species, associated with different vegetation states. Materials to be analysed will be collected from three different state classes with different utilization rates in experimental paddocks within the Cardigan site, near Charters Towers.

The vertical and lateral distribution of root biomass within plant-soil polygons of the three predominant grass species *Heteropogon contortus, Chrysopogon fallax* and *Bothriochloa ewortiana* will be examined. The size of the polygon to be described will depend on state condition of the paddocks, and mean inter-plant spacings. The initial proposal is that a polygon will be the tussock, plus 25 cm in the four cardinal directions. Root distributions will be determined by sampling within a 2-dimensional grid originating at the center of plants, and extending outwards to the edge of the root distribution profile. This sampling scheme will focus on accurately defining variance in the zones of maximum rooting activity (eg. 0-90 cm depth, and center to ~ 20 cm outward). The majority of roots will likely occur in the upper 50 cm.

Root characteristics (length, surface area, size class distributions) will be measured with scanning imagery equipment and biomass (g dry matter) of samples will be determined.

Climate — soil, vegetation, disturbance inter-relationships

The determinants of land degradation in wet/dry tropical savannas

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Objectives:
1. To define the relationships between soil type, mean annual rainfall and the vegetation communities within the wet/dry tropical savannas of north-western Australia, using existing data held on geographic information systems.
2. To apply two disturbances (exclusion of stock, severe defoliation of grass layer) at a series of selected sites along the rainfall gradient south of Darwin, and compare with ambient conditions by measuring the rate, degree and processes of land degradation and/or recovery.
3. Develop an improved understanding of the processes of land degradation in the wet/dry tropical savannas, and to formulate a rating of soil/rainfall/vegetation associations based on risk of degradation.
4. Make the results and interpretations available to management and research agencies across northern Australia, with a focus of assisting development of policies and guidelines for land use and for the monitoring of changes in land condition.

Methods:
1. The relationships between mean annual rainfall, soil type and the composition, height and cover of major woody and herbaceous species will be determined for Northern Territory vegetation north of 18 degrees S. The data already exists on GIS.
2. A matrix of experimental sites will be established along the rainfall gradient between Darwin and Kalkarinji, and on a range of soil types. At each site, three treatments will be imposed: (a) stock excluded; (b) ambient conditions; and (c) artificial clipping of herbaceous vegetation. A range of soil and vegetation parameters will be measured to assess the degree and processes of land degradation across the range of soil types and rainfall levels.

Sponsors: Land and Water Resources R&D Corporation and Conservation Commission of the NT

Grazing — vegetation — soil inter-relationships

Foraging behaviour in tropical grasslands

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Objectives: To measure herbivore resource use at a landscape scale (422 ha paddock) and to relate this to vegetation response.

Location: 30 km NW of Charters Towers, north-east Queensland

Chapter 4. Attachment 1 —Current and proposed research

Coping with rainfall variability: Grazing management strategies for seasonably variable tropical savannas

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Core project objectives:

1. Assess and demonstrate the ability of different grazing strategies to copy with rainfall variability in terms of their effects on animal production, economics, pasture condition, soil loss and biodiversity.
2. Develop, in conjunction with graziers, practical and sustainable grazing management strategies to copy with present and future rainfall variability.
3. Promote adoption of these strategies through demonstration and direct links to PMP, LCD and local Landcare/grazier groups.
4. Synthesise available data into simulation models to allow extrapolation to a range of different environmental and economic conditions.

Subproject objectives:
Biodiversity: To determine the effects of different grazing management strategies on faunal and floral biodiversity.
Plant population processes: To determine the effects of different grazing management strategies on major plant population processes such as mortality, seed production and recruitment of important pasture species.
Soil and nutrient loss: To determine the effects of different grazing management strategies on soil loss and nutrient discharge into catchments.
Dietary selection and foraging behaviour: To determine the effect of different grazing management strategies on dietary quality, intake and foraging behaviour in cattle.
Patterns of plant defoliation: To determine -
(i) the effect of selected grazing strategies on the frequency and intensity of defoliation of individuals of selected plant species through the grazing season;
(ii) the effect of landscape position on the frequency and intensity of defoliation, and
(iii) the effect of the above variables on plant survivorship and mortality.
Remote sensing to assess herbage availability: To investigate the use of, and possibly develop, remote sensing as a tactical tool to estimate herbage availability at the paddock scale.

Location: Wambiana Station, approximately 100 km S of Chartres Towers, in the Burdekin Catchment, in the semi-arid tropical savannas of northern Queensland.

5. LAND RESOURCE SURVEY AND ASSESSMENT

Land resource surveys and assessment have been, and are being, carried out within the rangelands of Western Australia, the Northern Territory and Queensland. This section briefly comments on some of this work and the use that is being made of it.

5.1. Rationale for land resource mapping

While the fundamental processes of material (water, nutrients, etc) and energy transfer operating in all landscapes are the same, their rates, extent and interactions are determined by the particular landscape in question — its climate, geology and geomorphic history, topography, regolith and soil, and vegetation. Landscapes with similar characteristics tend to have similar process rates and interactions, and hence potential for productivity as well as susceptibility to deterioration. Land systems, and the land units which comprise them, therefore provide a useful basis for planning land management, monitoring programs and research as they group together areas of land which tend behave in a relatively similar fashion. In addition, in rangelands where there is generally relatively little alteration of the native vegetation, vegetation structure and species composition are usually well correlated with the other land features. As a result, land systems also offer a useful basis for identifying vegetation and habitat diversity. Understanding vegetation—land type inter-relationships can also have important implications for land management. For example, it is important to know whether differences in vegetation composition and structure are the result of differences in land type or grazing management (stocking rate, use of fire).

5.2. State land resource survey and assessment programs

A full review of land system survey coverage and other resource mapping programs (including flora and fauna surveys) in the northern Australian rangelands has not been undertaken. Given here is some information on land survey work that is being done and on use being made of this information.

5.2.1. Land resource survey and assessment in Western Australia

(From Van Vreeswyk 1996)

Land resource inventory and assessment surveys are carried out by a combined team from Agriculture Western Australia and the Department of Land Administration. The objective of land surveys in the rangelands of Western Australia is to map and comprehensively describe their biophysical resources and to evaluate soil and vegetation condition. The resulting maps and reports are intended primarily for land managers, land management advisers and land administrators. They contain information useful for planning land management at sub-catchment, lease or paddock scale and also for locating land types of particular land use or conservation value.

Using land system information to plan pastoral management is facilitated by a companion report which provides, for each property, information on its land systems, their range condition and suggested carrying capacity. There is also a 1: 100 000 scale map of land systems occurring on the property that can be used by pastoralist for planning grazing management and the repositioning of fencing and waterpoints which will ensure that management strategies are specific to the pastures within each management unit and that overgrazing of preferred pastures or under-utilization of poorer pastures is avoided. The assessments of range condition allow pastoralists to identify degraded areas and plan their rehabilitation.

The land survey information has also been used to assess the representativeness of existing nature conservation reserves in at least some areas for which surveys have been undertaken. One such assessment has found that the reserves are dominated by types of land least suitable for pastoralism and areas preferred for grazing are poorly represented, if at all. Land survey information is also being used in the rangelands to locate strategic vegetation monitoring sites across the region on the basis of both representativeness of land types and susceptibility of the land to degradation.

5.2.2. Land resource survey and assessment in the Northern Territory

Land resource surveys in the Northern Territory are administered by the Lands, Planning and Environment Department. Both land system (1: 100 000 scale or smaller) and land unit (1: 100 000 to 1: 10 000 scale) are being undertaken in the rangelands. The goal of the NT land resource survey and assessment program is to identify the resources of the Territory, evaluate their capabilities for sustainable use and monitor their status. In recent years, the National Landcare Program has helped fund part of the program to accelerate acquisition of land capability information for Property Management Planning. Priorities for this mapping program have been determined on the basis of existing map cover and the known susceptibility of areas to degradation, and include the Victoria River District, the Barkly Tablelands and the Alice Springs region (Shields *et al.* 1996).

5.2.2.1. Land resource survey and capability assessment in the Victoria River District, NT
(From van-Cuylenburg 1996)

A program of land resource surveys and capability assessments has been undertaken in the Victoria River District (VRD) of the Northern Territory since 1990, with support from the National Landcare Program. The programs prime objective is to map, describe and evaluate pastoral areas and to extend this information to landholders. The base information allows the development of property plans which includes identifying areas degraded through inappropriate management and planning their rehabilitation.

Fieldwork in the program is designed to map resources on a property basis with fifteen properties and a total area of 60 000 km^2 mapped by the beginning of 1996. Information is collected on the landforms, soils and vegetation and sites are grouped to form the unique vegetation community of each land unit. The five most dominant species within the grasslands community has the five most dominant species listed with each species given a rating of one to five, where rating is based on a system incorporating nutrition, digestibility and palatability. Pasture rating maps can be produced though care must be used in using a map produced in one year, as a guide in subsequent years due to pasture production being dependent on seasonal rainfall.

Historically, the Victoria River District has tended to be overstocked and overgrazed, particularly where covenants required minimum stocking rates and where uncontrolled grazing caused extensive degradation along waterways. Land unit mapping in the VRD has also assisted in the production of erosion hazard assessments for each land unit, which allow areas of the landscape prone to sheet erosion to be identified.

Surveys have involved close liaison with property managers and land unit descriptions have been produced in layman's terms, where all soils and vegetation are referred to by their common names. The maps, along with the pasture and erosion hazard ratings, have increased the pastoralists knowledge of the land resources of their properties and have been used in the development of more sustainable land use practices.

5.2.2.2. Land resource assessment in Central Australia and Barkly Tableland
(From Grant 1996)

Ecologically-based land resource assessments of central Australian properties began fifteen years ago, with additional resources to accelerate this work being committed by the National Landcare Program over the past five years. This has allowed extension of the program to the Barkly Tableland.

The primary aim of these assessments has been to provide individual property managers with land capability information at an appropriate scale to guide property development and management.

Cattle properties in both Central Australia and on the Barkly Tablelands are large, typically around 1500-5000 km^2 in the Alice Springs district and 5000-14 000 km^2 on the Mitchell grass downs of the Barkly Tableland. Fencing on these properties has increased in recent decades, primarily in response to brucellosis and tuberculosis disease eradication programs, but the typical management unit on these properties is still the área lying in grazing distance of a water point. This is usually 8 km, with the total grazing area covering about 200 km^2. Most property mapping has therefore been at a scale of 1: 1000 000 to allow the land capability of management units to be determined. At 1: 100 000 scale, mapping units can describe relatively uniform tracts of country in terms of landform pattern, soil type and vegetation community. Experience has shown that mapping at scales of less than 1: 100 000 fails to identify areas of land susceptible to degradation. Emphasis is placed on air photo interpretation with detailed descriptions at a density of 6 sites/ 100 km^2. Satellite imagery interpretation has been trialed as a cost effective method of small to medium scale mapping but has had disappointing results at 1: 100 000 scale, particularly on the Barkly Tablelands.

The mapping program has found that the pastoral industry is receptive to appropriate resource information and that demand for mapping by property managers currently exceeds the rate of coverage. The use of on-property GIS systems is also being investigated.

5.2,3. Land resource survey and assessment in Queensland

There has been a long history of land system mapping and land resource assessment in Queensland. Until recently, the Queensland Department of Primary Industries had major responsibility for such programs. Resource mapping and assessment now has a more regional structure although the Enhanced Resource Assessment Program within the Department of Natural Resources has state-wide cover. This program aims to evaluate new techniques for resource mapping and assessment.

5.3. Resource condition assessments

In addition to land surveys, the aim of which is to map land types, several land condition surveys have been carried out. The aim of these surveys is to assess the condition — degree of degradation — usually of the soil and/or vegetation (pasture). The most extensive of these surveys was that undertaken by Tothill and Gillies (1992) which assessed pasture condition across northern Australia. These authors graded pastures into one of three groups: A: 'desirably sustainable'; B: 'deteriorating'; and C: 'degraded'.

Within Queensland, a land condition survey of the Dalrymple Shire has recently been completed (Rogers *et al.* in press) and several resource condition surveys have also been undertaken in the Kimberley region of Western Australia (eg. Payne *et al.* 1979).

5.4. Other current land survey and resource assessment projects

Attachment 1 lists other projects involving land resource survey and mapping that are not covered by the state programs.

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ATTACHMENT 1 — CURRENT AND PROPOSED ASSESSMENT PROGRAMS AND PROPERTY EXTENSION

Land resource survey

Catchment management in the desert uplands

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Background: The Desert Uplands of central Queensland are the remnants of an extensive Tertiary surface, stretching from Pentland in the north, south to near Blackall. The region is dominated by sandy infertile soils prone to rapid degradation if over-utilized. In the northern part of the region there are extensive internal drainage basins containing Lake Buchanan and Lake Galilee. Both are considered to be of State significance for waterfowl.

Due to the relatively low agricultural productivity of the region there has been little attempt to define the regional resources in detail or to clearly define management strategies that would enable their sustainable use. Recent land use changes, including extensive clearing near Lake Galilee, and increasing land degradation in both catchments, suggest that detailed catchment management plans should be prepared if the natural resources are to be sustained.

Objectives: The objective of this project is to map the land resources of both catchments (6-7,000 km^2) at 1: 100 000. Some representative sites will be selected from air photo interpretation, for soil sampling. Sampled soils will be sent for analysis of chemical and physical properties.

Project status: two maps have been published and the final report is being prepared for publication. The report contains three parts: Part 1 contains the land resource data; Part 2 contains the technical details and Part 3 a proposed management plan. The draft catchment management plan identifies the main issues, highlights the limitations of different land types and recommends appropriate management practices. The draft plans are the basis for a new project proposal for NHT funding (Lake Buchanan - Lake Galilee Catchment Management Plan: Implementation) which is seeking funds to explain the plan to, and discuss the plan with, a broad section of the rural community and officers of lead government agencies.

Desert Uplands land resource mapping

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Objective: To produce a land resource map that is consistent for the whole Desert Uplands bioregion, at a scale that relates to individual properties, and which can be used to adjust land use and land management practices according to the capability or limitation of different land types.

Methods: All existing land resource studies will be updated to the required level of accuracy, scale and detail, using a combination of remote sensing and field work. Any areas without land resource information will be surveyed separately. The final report will be in the form of maps at 1:250 000 and a database with land resource information at 1:100 000.

Proposed project duration: July 1997 - June 2000

Enhanced Natural Resource Information System, Balonne-Maranoa District (proposed)

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Background: The Balonne-Maranoa district is poorly served by relevant and reliable information on land resources; only a very broad land system study at nominally 1:500 000 scale is available, with some larger scale information for the Roma area and for the St George irrigation area. Despite considerable land use change and the potential for agricultural and other development, useful information on current land use, land condition and land suitability for a variety of uses is not available or easily accessed. The South West Strategy and Balonne Shire Council have requested that the DNR provide more reliable and appropriate information for land use planning in the district. The NRMS funded Murray-Darling Soil Information Strategy has determined that the Balonne-Maranoa area is a priority for land resource assessment and would facilitate completion of a consistent and complete coverage of information for the Queensland section of the MDB at 1:250 000 scale. Current information is inadequate for land use planning, land management decision support, carrying capacity assessment and rural reconstruction.. The DPI/DNR Business Plan for land resource assessment suggested that 1:250000 scale information was a priority for the area.

Objectives and products:

- The project aims to produce a comprehensive natural resource information system for the Balonne/Maranoa to provide a basis for land use planning and sustainable resource management.
- Central to the project will be a comprehensive study of land resources including soils, landforms, regolith, land use and condition and trend of the Balonne and Maranoa Catchments at 1:250 000 scale, complemented by nested larger scale key area studies (1:100 000 in dryland cropping areas and 1:50 000 for the irrigation areas of the Balonne floodplain).
- New and enhanced technologies including the use of digital terrain models, remote sensing, quantitative land evaluation methods linking crop production models with spatial data bases, and explicit soil-landscape modelling within GIS will be incorporated to improve the reliability and usefulness of the information and to enhance the efficiency of survey.
- Information will be readily available and integrated in an advanced geographic information system, and available in a variety of thematic forms and media via the Internet, reports, a manual detailing management guidelines, maps and GIS coverages in formats useful to land users, planners and managers, complemented with field days and workshops.
- Maps will include: soils and soil properties, land suitable for dryland agricultural uses and pastures, irrigated agriculture where appropriate, agricultural land classes for town and shire planning (Good Quality Agricultural Land), current land use and degradation state and potential.
- Reference sites for long term monitoring of land condition and to extend information to land managers will be established.

Soil unit mapping — Dotswood property of the Townsville Field Training Area (TFTA)

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Objective: To map soil units of the Dotswood property at 1: 50 000 scale

Land capability assessment, including carrying capacity and susceptibility to degradation

Desert Uplands — land condition assessment and on-ground works

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Background: The Desert Uplands Buildup and Development Committee, together with the Departments of Environment and Natural Resources, have identified an urgent need to have a comprehensive, accurate assessment of the condition of the land within the Desert Uplands region. Such information will allow:

1. the location, extent and causes of severe land degradation to be identified;
2. priorities to be established for restoring degraded land;
3. a revision of land management practices for specific land types; and
4. the identification of land that is suitable or unsuitable for development.

Objectives: The aims of this project are to develop an appropriate method for assessing land condition in consultation with the Desert Uplands Buildup and Development Committee and officers of government agencies. The method will take into account cleared versus uncleared land and the condition of the soils, pastures, tree canopy, fauna habitat and natural biodiversity. It will involve a combination of field work, remote sensing (satellite imagery) and consultation with Landcare Groups and individual landholders. The final report will identify the nature and extent of degradation associated with each land type together with a rating for the susceptibility of each land type to various degradation processes. Data entry into a Geographic Information System (GIS) will be at a scale of 1: 100 000 but the final map will be at a scale of 1: 250 000.

Proposed project duration: July 1997 - June 2000

Dryland Farming for Catchment Care Program — catchment scale erosion hazard

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Objective: to conduct catchment scale assessment of erosion hazards in some of the rangelands west of Townsville (Balfes Creek Catchment; Dotswood/TFTA. The approach includes point scale assessment of runoff/sediment sources, linking to DTM and routing runoff/sediment through paddocks or landscapes. For Dotswood, the basis for this is the survey and compilation of a 1:50000 soil unit map.

Sustainable grazing management for eastern Queensland river catchments (proposed project)

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Rationale: Grazing management is the major land management issue threatening the sustainability and bio-diversity of the black speargrass grazing lands in the Burdekin, Fitzroy, and Burnett River catchments. In many cases, unrealistic expectations of carrying capacity, together with failure to adjust stock numbers in response to availability and condition of pasture, have contributed to chronic shortages of forage, loss of desirable perennial grasses, increased bare ground, and increased density of native and exotic trees and shrubs. Consequently, the safe carrying capacity, bio-diversity, and habitat value of much country is being eroded. While the problem is complex, being related to many social, climatic and market factors, there is no doubt that improved grazing management and a greater level of "land literacy" are central pre-requisites for sustainability and maintenance of bio-diversity. Information on soil types, pasture growth, and effects of grazing is available for the catchment areas but there has been no synthesis into sound, credible guidelines for pro-active grazing management. This is a major impediment to improved industry performance in grazing land management.

Objectives:
To develop and promote sustainable grazing management in the Burdekin, Fitzroy, and Burnett River catchments by:
1. Collating and integrating technical and landholder knowledge on a range site basis.
2. Developing and road-testing methods for assessing carrying capacity, and condition and trend, of land types (range sites) in each catchment.
3. Increasing awareness and understanding of land condition and its relationships with land management, bio-diversity and productivity ("land literacy") amongst landholders and agency staff.
4. Supporting whole property planning via provision of credible grazing management guidelines.

Methods:
1. Identification of a range site framework: developing land literacy
Necessary tasks:
- obtain regional Land Resource Data Base (LRDB), and overlay with geology, vegetation, and cadastral data.
- assess use of LRDB for identifying land types within paddocks.
- assess need to distinguish between land types on the basis of the types and amounts of forage production (see part 2 below).
- record producer perceptions of land types and determine correspondence with LRDB land units.
- road-test range site framework with sub-catchment groups.
- link to regional land resource descriptions, through DroughtAlert project.

2. Operation of GRASP on a land-unit basis
GRASP is a computer model for simulating forage production from native pastures. It has already been successfully used at land system and regional scales. To operate on a range site basis, the following activities are required:
- identify functional characteristics of soils and set parameters for land units.
- establish reference exclosures on a representative sample of land units and demonstrate ability of GRASP to adequately match real-world data over 2-3 growing seasons.

3. Making our understanding of pasture ecology relevant to each land type

- Current research is helping to distinguish the effects of grazing, climate, and fire on condition and trend of native pastures. However, for many land types there is little agreement on what pasture species are most desirable or on what pasture composition is possible under different conditions. In co-operation with sub-catchment groups, we will locate and sample areas on each major land type that have had different grazing pressures, due either to fence-line effects or to distance from water. From this, we will deduce the relevant indicator species for assessing range condition. Small exclosures will be used to measure primary production on selected patches within each land system, to demonstrate the effects of land condition and recent utilisation level on forage growth.
- A pragmatic approach to assessing condition and trend will be developed and road-tested with the sub-catchment groups. In combination with assessments of pasture growth and standing crop, this will allow integration of pasture-based information into tactical decisions on stock numbers.

4. Carrying capacity estimates at the paddock level

A method for assessing carrying capacity for each land type/land condition/tree density combination will be developed based on estimates of forage production (from part 2 above) and "safe" utilisation levels; the latter will correspond with data obtained from researchers, extension staff, and sub-catchment groups. This follows the approaches developed for Queensland's eucalypt woodlands (Scanlan *et al.* 1994) and mulga shrublands (Johnston *et al.* 1996). Providing paddock-scale estimates of carrying capacity also requires accounting for patterns of pasture and landscape use due to selective grazing, preferential use of land systems, location of watering points, topography, and location of shade. The assessment method will be tested against producer experience and property records.

5. Delivery of guidelines, training and decision tools

Grazing management guidelines and decision support tools will be produced that meet needs for (1) development of sustainable whole-property grazing plans and (2) variation of grazing pressure in response to changing vegetation condition. Specific products will include:

- Grazing management manuals (and associated training workshops) for each sub-catchment that provide guidelines on carrying capacity, tactical stocking decisions, and measurement and interpretation of land condition.
- Decision-support software, and equivalent paper-based versions, for calculation of safe carrying capacities and short-term variation in stocking pressure.
- A database which links land resource information (land systems, soils), ecological condition, woody plant cover, and pasture production.
- Training workshops in grazing management offered as part of, or in addition to, property-management planning activities

Project duration: July 1997 - July 2000

Locality: Burdekin, Fitzroy, and Burnett Catchments

Sponsors: NHT, Queensland Department of Natural Resources and Queensland Department of Environment

6. RECOMMENDATIONS

This chapter provides recommendations for new research relevant to improved resource management, that might be appropriately funded by Phase 3 of the MRC's North Australia Program. The first sections of the chapter discuss issues and gaps identified during the review, including from discussions with research personnel, and at the workshop held by the MRC early in August. It also gives the recommendations presented for consideration at the workshop. This workshop was held specifically to allow input by research and producer groups on the draft report and its recommendations (see Appendix 2 for a list of workshop attendees). The last section of the chapter gives the priority recommendations for research and the guiding principles that were developed at the workshop.

6.1. Issues considered in making recommendations

6.1.1. The need for uptake of current knowledge

Improved management of the northern Australian grazing lands cannot wait until our knowledge of the resource base and understanding of the underlying processes are more developed. Sufficient is known about the deleterious effects of some grazing management practices, particularly high herbage utilisation rates, to initiate programs to try and ensure that such practices do not occur. In making recommendations for such programs, it is necessary that variation between different land types is recognized. Relationships between grazing management and soil and vegetation response that have been developed for particular climatic regions and land types cannot necessarily be extrapolated and transferred to others. Consequently, it is not possible to recommend management practices and strategies that will be applicable to the northern grazing industry as a whole, or to particular agroecological regions, other than in broad general terms.

6.1.2. The need for further research

Having acknowledged the need to apply current knowledge now, however, it is also very important that we do not regard our current understanding of the land, how it is functioning and its response to management, as adequate. While full use is not being made of current knowledge and this must be addressed, there are also many aspects of land function that are not understood. Management and monitoring strategies need to be underpinned by sound science and the concern has been expressed that in many areas the science is not keeping sufficiently ahead of the requirements for practical information. Two examples are given as illustration. One is the view that the ecological techniques underpinning current vegetation monitoring are not properly understood at the scientific level. A second is the opinion that the "downs" and alluvial plains of the Barkly Tableland contain essentially two different pasture types that reflect differences in geomorphic processes. The alluvial plains carry predominantly annual grasses while the "downs" support predominantly Mitchell grass pastures. A commonly held view, however, is that the annual pastures have lost their perennial component and are indicative of pasture deterioration. It is clearly critical to management that our understanding of the cause for variation in pasture types is correct.

6.1.3. Improved land management versus the need to understand off-site effects

There is a difference of opinion both within the research and grazing industry communities, over the need to define and quantify the effects the grazing industry is having on land and water resources. One view is that implementing conservative management will ensure that the degradation caused by grazing is the minimum that can be achieved within a productive industry and that there is no need to concentrate on the effects of particular practices or to distinguish between processes and fluxes under natural conditions compared with those where the land is used for grazing. The alternate view is that the effects of various grazing industry practices, both on-site and downstream, need to be identified and compared with the natural condition, and an assessment made of the extent to which degradational processes can be reduced.

The view adopted here is that a prime and proper concern of the grazing industry is on-property management to maintain and rehabilitate the land and pasture resource. The need to identify the effects on land and water resources that various grazing management practices are having, however, is also regarded as important, as is the need to identify processes under natural conditions. There are several reasons for adopting this approach.

1. There is a growing requirement from the community that our agricultural products are "safe" from a human health perspective and are produced in a way which does not cause degradation of the environment. With continuation of current trends, a marketable and competitive product will depend on the grazing industry being able to show that its activities are not having adverse environmental effects. The industry will need to fund work to identify the effects that it is having, particularly off-site, so that these can be remedied, and/or to demonstrate that off-site effects are not significant. It was noted during this review that the sugar and cotton industries are far more active in such research than is the beef industry.

2. It is suggested that by taking a responsible and proactive role with respect to its off-site effects, the industry will be in a stronger position than if it chooses to ignore such issues. If the industry does not take a responsible role, government intervention and regulation is more likely, particularly if downstream users and other community groups are concerned about the effects the industry is having on them. A good example of the benefits that can accrue from work not initially seen as relevant to the industry, is the tree monitoring studies carried out by Dr Bill Burrows. This work has shown that the increase in woody vegetation in northern grazing lands has lowered Australian greenhouse gas emissions by 15-20% and such information can now be used to advantage by the industry. It needs to be recognized that we cannot always know the benefits of particular lines of research in advance.

3. It is only by knowing the effects that particular practices are having in particular environments, that any deleterious practices can be remedied. It is important that identifying deleterious practices is seen as an opportunity by the industry, rather than as a criticism. A popular view is that extensive grazing is one agricultural industry that is inherently compatible with maintenance of our land and water resources, including their biotic diversity.

6.1.4. Appropriateness of research for funding by NAP3

All recommendations made are regarded as relevant to NAP3. An issue not considered in making the recommendations, however, is whether other research organizations or funding bodies, would be more appropriate to take responsibility for some recommendations. There are two reasons for this. One is that this review is seen as providing an information base to research groups and agencies beyond the MRC. The second is that many government research agencies are currently in a considerable state of flux and their objectives and roles are not clear and well defined. The view of the author is that some activities, such as monitoring, would best be supported by state government agencies as these programs need to be long-term and government organizations should be in the best position to take the long-term perspective. It seems that this is not the case at present. Until the roles of various organizations are clearer, it is premature to assign areas of responsibility to them.

6.2. Principles recommended for adoption by NAP3

Given here are general recommendations which pertain to the orientation of NAP3, and the reasons for the recommendations.

6.2.1. Pasture types versus land types

- It is recommended that NAP3 consider land as well as pasture differences in the design of research and monitoring programs.

Pasture communities traditionally have been used to distinguish the various grazing lands in northern Australia. This is understandable given that pasture is a major resource for the industry. Land degradation and productivity, however, are determined by other characteristics of the land — climate, geology and geomorphic history, topography, and regolith and soil. It is therefore essential that these features are taken into account in the design of research and monitoring programs that aim to improve sustainability by reducing resource degradation. This will mean, for example, that research and monitoring programs will need to be located in representative land systems and types rather than representative pasture types.

6.2.2. Monitoring

- Indicators identifying thresholds and changes in land processes need to be developed.

A review of monitoring programs and methods, including those for on-property use, was not undertaken as part of this project. It is apparent from research on landscape processes, however, that indicators identifying thresholds and changes in land processes are needed and that monitoring should not be restricted to only monitoring vegetation or soil condition. What we term land or soil degradation are changes in the condition of the land or soil (eg, loss of soil structure, loss of soil depth, decrease in soil pH) that result from change in various processes. In order to prevent degradation from occurring, it is necessary to understand the inherent processes involved and to be aware of their occurrence before degraded states are reached. Indicators of processes will be required to prevent degradation occurring and will be more useful than indicators of a final degraded state.

6.2.3. Best practice

- For the north Australian beef industry, "best practice" needs to be generic and defined in terms of principles (eg, sediments and nutrients should be retained locally and not lost to the drainage network) rather than in terms of specific practices (eg, retaining a specific percentage ground cover). There also needs to be continual monitoring of recommended practices to ensure that they are achieving the desired results and that they are consistent with new research findings.

There is a current trend within industry to define best practice. The extensive area covered by the north Australian beef industry and the consequent enormous variation in land systems (including climate) means that standardized management practices for northern Australia cannot be developed. It is therefore appropriate that best practice is defined in terms of principles, although these can be translated into specific practices designed to suit the local land systems, where graziers require more prescriptive advice.

6.2.4. Education and awareness programs

- It is recommended that the different needs of various groups within the industry be identified/ recognized and appropriate extension programs developed to address these specific needs.

The grazing industry consists of a diverse group of people with a range of management skills. Some graziers, for example, can use principles and adapt them to their own situations while others need prescriptive guidelines. Some graziers already have a good knowledge of the biophysical and economic systems with which they are dealing while others have very little. These differences should be identified and recognized, and programs developed which have the capacity to meet the various needs of producers.

6.3 Identified knowledge gaps and recommended research

Knowledge gaps and recommended research are discussed under headings that relate to the different topics reviewed in this report. The exception is '*Uptake of information*' which has not been covered in previous chapters.

6.3.1. Uptake of information

The terms of reference for this review included identifying critical gaps in uptake of knowledge. Major gaps identified are listed below.

6.3.1.1. Overgrazing

Trials with exclosures have shown that even during droughts, low stocking rates can reduce grass cover to below that which would occur naturally and lead to higher runoff, sediment and nutrient losses. Grazing management following drought has also been highlighted as a particular problem though there has been no R&D to help determine appropriate management practices that reduce degradational processes. Water, soil and nutrient losses not only result in short-term reductions in biomass but are probably also reducing the long-term productivity of the land, although the time-frame necessary for long-term productivity decline to become apparent has not yet been satisfactorily quantified. There is no doubt, however, that overgrazing is contributing to decline in the productivity of soil resources. Overgrazing is defined here as the utilization of resources (through both grazing and trampling/trafficking) past thresholds which lead to the initiation of undesirable processes.

Another point to be considered is that while droughts can result in the initiation of processes leading to loss of land productivity, these are naturally occurring phenomena over which we have no control. Degradational processes initiated by grazing management practices can be controlled and prevented. There is no logic in regarding degradational processes resulting from grazing as not an issue because similar processes may be initiated naturally. The aim of grazing management is to ensure that utilization of the resource is within its productive capacity and that degradational processes are not exacerbated.

Discussions during this review indicated that there is poor awareness within the grazing industry as a whole, of the land degradation that is occurring as a result of stocking strategies. It seems that often any land degradation that is acknowledged is generally attributed to drought rather than a combination of drought and stocking management. There is also the view that the land is resilient and will "come back". These are obviously perceptions that hinder the on-farm development of profitable and sustainable grazing systems, recognition of a problem being the first step to its solution. A critical need is therefore to increase the awareness and understanding within the grazing industry of the land degradation being caused by overgrazing.

Other factors identified by various people as hindering the adoption of more sustainable practices are:

- lack of data to show that profitability and sustainability are compatible and counter the belief that they are not;
- insufficient information on how management to maintain resources can be integrated with marketing and herd replacement strategies to allow an enterprise to be profitable in the longer term; and
- external pressures, such as loan repayments, and taxation arrangements that favour particular practices.

The first two issues are taken up under the specific recommendations below. External pressures need to be acknowledged as constraints to the adoption of ecologically sustainable grazing systems and included among the constraints identified as part of the Subprogram 2 strategy for addressing key issues (see Chapter 1).

6.3.1.2. Specific management practices

The assessment of this review is that there are few specific management practices that can be prescribed uniformly for the entire north Australian grazing industry. For example, maintaining a pasture cover of 40% has been found to be a useful guide to cover levels to prevent very high runoff, sediment and nutrient losses in more humid areas, but it is inappropriate in arid regions. Similarly fire is regarded as a useful management tool for maintaining some species but its use is not universally supported. There appears to be concern, for example, over its role in the loss of perennial grasses from some pastures in the north where perennial plants will grow in pastures now dominated by annuals if fire is excluded (David Tongway, pers. comm).

Rather than identify and promote prescriptive management practices, it seems more appropriate for this review and NAP3 to define and promote principles. For example, such a principle may be that grazing should be managed so as to retain sufficient plant cover and patchiness to ensure that materials are only transferred locally (on a slope) and not out of the system, or that soil biomass and carbon are not reduced below particular critical levels. Indicators are needed of land-soil-vegetation interactions and of key processes for different land types so managers can make sure stocking rates comply with these principles. The trigger-transfer-pulse framework (developed by CSIRO Division of Wildlife and Ecology) and the indicators of soil condition based on this framework (Tongway and Hindley 1995) are being found to be relatively robust for identifying the functional behaviour of the land over a range land types.

6.3.1.3. Grazier knowledge of land resources

The knowledge of graziers of pasture species and their awareness of differences in land type seems to be variable, though it is generally agreed that ecosystem processes are not well understood. Some graziers know their land and grasses even if they do not know the technical terms, while it seems that other graziers do not have the same knowledge of their property resources. It is not possible for graziers to adjust management to suit differences in land and pasture productivity and susceptibility to degradation if they cannot recognize their land and pasture types. There still appears to be a need for increased knowledge of land resources and ecosystem processes if land management is to be improved. The guides to pasture plants and native species that have been produced over the last few years should go a long way in helping to achieve this goal.

6.3.1.4. Property planning and protection of sensitive areas

Management that occurs purely in response to particular events, without clearly defined objectives and strategies, is unlikely to maximize profitability or protect the land. Stock management needs to be planned, taking into account the biophysical resources of the property and the way these are utilized by cattle, as well as climatic forecasts based on the Southern Oscillation Index (SOI), and profitable marketing strategies. Improving property management is a separate subprogram of NAP3 but it is important that this subprogram includes improvement in the knowledge and planned use of land types (including pasture); that is, that improved property management includes improved resource management through improved knowledge and planning of resource use.

Options for managing resource use in the rangelands are not great and have traditionally involved stocking numbers, location of watering points and the use of fire. While fencing is not a major management tool because of the extensive nature of grazing operations, increased consideration will need to be given to fencing off areas highly susceptible to degradation because of soil properties and/or because of the degree of selective utilization by cattle. Riparian areas, for example, are usually heavily utilized and loss of vegetation and soil degradation in these areas is likely to be particularly important in terms of sediment and nutrient transport to waterways. Protecting areas of particular significance for native flora and fauna from heavy grazing also has been recognized as an objective that will need to be incorporated in management plans if the natural biological diversity of the rangelands is to be preserved.

6.3.1.5. Recommendations

- Education and awareness programs need to be continued to increase knowledge of farm resources (land types and their vegetation and soils), and awareness of degradational effects of overgrazing, including the short-term profitability at the expense of the land and long-term productivity. They need to counter current faulty perceptions of land resilience and capacity to "come back".

- There is a need for monitoring programs, the objective of which is to help improve grazier decision making with respect to property management. These programs probably need to be distinct from monitoring that has state or national planning and management objectives. There appear to be several programs or schemes already in place. Before recommendations can be made with respect to appropriate monitoring programs, there needs to be more information on their objectives, scientific basis and the actual information needed by managers.

- Developing economically viable and ecologically sound management strategies at paddock and property scales - can it be done? There appear to be numerous recommendations for improved management arising from research trials, most of which are being incorporated into various extension programs. A question that arises is whether we know how to integrate the various recommendations. For example, recommendations for use of fire to control woody weeds or manage pasture, may not be appropriate for maintaining biological diversity. Another question is whether practices which maintain the resource base can be combined with marketing and herd replacement strategies that are economically viable in both the short and longer terms. There is a need for putting together and demonstrating property and resource management strategies that integrate recommendations from various research areas, coupled with demonstrating that such management can be economically viable as well as ecologically sound.

  This is not a simple research area in that no organization has the expertise or facilities to undertake all the necessary work. A combination of approaches involving some research trials, case study analyses and co-operative research/on-farm projects will probably be necessary. Economic and resource evaluations are obviously major components of such work.

6.3.2. Land processes and the effect of grazing at patch, paddock and small catchment scales

Issues discussed here are primarily those relating to water, sediment and nutrients as these were the focus of the review; weeds and biological diversity are other aspects that have not been dealt with in this review though it is recognized that research associated with these areas needs to be integrated.

6.3.2.1. Patch scale

There are major gaps in our understanding of the interactions between the various components of the grazing system (see chapter 4 for details of components), and their variation with different land types and in time and space within a given land unit. Past work seems to have focussed predominantly on pasture—animal interactions, particularly the effect pasture composition and biomass have on animal production although more recently the effect of grazing on vegetation state has been considered in some detail. Greater emphasis needs to be given:

- to other system components and their interactions as the processes involved are critical to the proper functioning of the grazing system and must be understood if we are to manage the system effectively as well as repair systems which are degraded;
- to understanding the effects of different management strategies — these effects need to be understood both in terms of animal production and performance, as well as in terms of effects on the land resources and their functioning; and
- to integrating the different component processes to give a fuller understanding of how the grazing system is functioning.

Recently a number of projects have been initiated which are investigating inter-relationships between nutrients, soil biota and vegetation states. Even so, further investigation of the following interactions are considered necessary to obtain a better understanding of important processes and critical thresholds beyond which undesirable changes in land condition will probably occur.

- Pasture species/cover — nutrients — soil biota: improved knowledge is needed of nutrient pools (within the whole profile and not just the top few centimetres), budgets and cycling, including litter production and the role of soil biota, for different pasture communities (including improved pastures), and for different vegetation states within these communities.
- Soil properties (including biota) — pasture condition — water: the interactions between, and relative importance of, soil properties and soil biota in water infiltration and runoff, ie the factors predisposing different soils to sealing and loss of macroporosity under grazing and on exposure to rainfall, and the processes involved, need to be better understood. Similarly, knowledge is needed on the soil properties that need to be restored to restore infiltration, how restoration can be achieved and the length of time such restoration takes.

The effect of grazing and grazing management practices on the above inter-relationships need to be understood over long time-periods and for different land types. Long term changes are particularly important as such changes are easily overlooked due the short-term perspective that is generally currently taken in funding research.

6.3.2.2. Water balances —large plot to small catchment scale

There are relatively few quantitative data on components of the water balance at plot to small catchment scale either under natural or disturbed conditions. Simulation modelling has been used to indicate the likely episodic nature of recharge in some environments and its increase with land clearing. Very few experimental studies have been carried out.

Most work has focused on changes in runoff associated with increased grazing pressure. While heavy grazing has been found to reduce infiltration and increase runoff at patch scale due to reduced soil macroporosity and microtopography, and to loss of litter and plant cover, very little is known about how much of this water is actually lost from the local landscape (the area between the local catchment divide and the stream channel). Water that is lost upslope, may infiltrate further down the slope. Similarly, there is not a very good understanding of the extent to which sediments and attached nutrients are redeposited within the local landscape rather than being transported out of it. There is also little, if any, knowledge of the effect of such nutrient and soil loss on productivity.

6.3.2.3. Foraging behaviour —plot to small catchment scale

The way cattle utilize different land types and pasture communities and species patches within them at paddock scale, is needed to determine actual grazing pressures on different land types, communities and species, and also animal productivity. Greater understanding of foraging and animal behaviour is necessary to develop management strategies that are productive but which do not degrade areas attractive to stock. This is particularly so in those environments in which cattle movement is determined more by vegetation and soil types than by the distribution of watering points. Foraging behaviour is also important in understanding the effect of cattle on riparian and wetland areas, and whether all such areas are particularly susceptible to degradation through excessive use. Any investigations of foraging behaviour needs to incorporate years of below average rainfall.

6.3.2.4. Recommendations

- Further research is needed into processes involved in the loss of infiltration capacity for various land types under different grazing pressures, and the soil and vegetation properties which result in the susceptibility or resilience of the land to loss of infiltration capacity.

- Water balances at paddock and small catchment scales and their variation over time are unknown for many climatic regions and major land types, as is the effect on them of grazing and grazing management practices (control burning, tree clearing). A strategy needs to be developed for determining priority areas for undertaking hydrological monitoring/modelling work, with research projects implemented in these areas.

- Research is needed to determine the extent to which grazing is causing water, sediment, nutrient and organic matter to be transported out of, and consequently lost from, local areas and the effect that such losses are having on the functioning/productivity of land—vegetation—grazing systems. Consideration also needs to be given to the effects of drought and fire. This type of knowledge is needed for different land types.

- Greater understanding is needed at paddock scale of animal behaviour, and the factors influencing cattle preference for specific land and forage types, including their observed preference for bare and eroded land, locally known as "cattle camps". Use of riparian areas by stock and the sensitivity of these areas to grazing, is an area that particularly requires investigation.

6.3.3. Movement of sediments and nutrients within large catchments/river basins

Measurements of sediment and nutrient movement from plots and small catchments have been used to estimate the contribution of various land uses to sediment and nutrient (N and P) inputs to the Great Barrier Reef lagoon. Estimates of the contribution of grazing land range from around 66%-84%, with the percentage being much higher in individual catchments such as the Fitzroy and Burdekin. Given that grazing enterprises occupy around 87% and 95% of the area of these two catchments respectively, it is hardly surprising that land used for grazing is regarded as a major contributor of sediment. If estimates of the contribution of different land uses to catchment sediment yield are ultimately derived from the area of the catchment with that land use, then the proportion of the catchment with a particular use will influence the importance of the land use in contributing sediment. In other words, in catchments such as the Fitzroy and Burdekin, one would expect a high proportion of the sediment yield to be derived from land covering 87% or 95% of the catchment, whatever the land use.

There are two issues here. One is the extent to which such methods of estimating contributions of different land uses to whole catchment sediment and nutrient fluxes are reasonable. The other is the extent to which grazing has *increased* fluxes within, and at the outlet of, catchments. It is the increase in flux that is important, firstly, because it is this increase that represents the effects of grazing, and secondly because it is not possible to reduce fluxes of sediments and nutrients to levels below those which occurred naturally.

Estimated contributions of different land uses to catchment sediment and nutrient export that are derived from plot studies take no account of material subsequently deposited lower on the slope or within the channel system. On the other hand, where estimates are derived from small catchment measurements, the source of material could be predominantly stream channels rather than slopes. Neither type of measurement (plot or small catchment) accounts for material subsequently deposited further down the channel network or on floodplains, although standard sediment delivery ratios have been used to try and allow for this. These methods also do not take into account sediment derived from channels further downstream and there are no data indicating whether this is an important sediment source. Other problems with this approach, acknowledged by those undertaking the studies, are that the estimates of fluxes associated with different land uses are based on very limited data sets that do not encompass variation in grazing pressures, land types or rainfall regime, all of which would be expected to have considerable effect.

Clearly, for river basins, we have very little knowledge of the generation, transport and output of sediments, the time-frames involved, the effects of grazing and the variability in processes depending on the sediment size-class. For example, are sediments derived predominantly from sheet, gully, stream channel or floodplain erosion and do the principle erosional processes vary for different sediment size-classes? There is also little understanding of the capacity of different landscapes to produce and transport sediments.

Research in this area is regarded as fundamental. Until we have a greater understanding of the dynamics of sediment generation within, transmission through and output from, large catchments, the time-frames involved and the effects of grazing on these processes within different parts of the catchment, we will still effectively be guessing as to the effects that grazing is having on outputs of sediment and nutrients to coastal environments. Knowledge of these processes and their variation within a catchment is critical to developing management strategies that deal with sediment and nutrient problems downstream adequately and realistically. Without it, management strategies may be misdirected and relatively ineffective.

6.3.3.1. Recommendations

There has been so little work studying the functioning of large catchments that there are probably many areas of appropriate research and investigation. Several appropriate areas are suggested below.

- Investigation of sediment rates in estuarine/marine environments and the effects of terrestrial inputs on coral growth are both potentially techniques for determining how terrestrial inputs to the marine environment have changed over time, including in response to natural shifts in climate prior to European settlement. This knowledge would provide a context for the current input of sediment and indicate whether current rates are significantly larger than those which have occurred previously under natural conditions. Such an understanding is necessary to assess whether, and if so, to what extent, anthropogenic activities are causing the system to function outside its normal limits, and hence the management changes needed in order to return to land fluxes that are within the limits of those known to occur naturally.

- Analysis of the surface hydrology of landforms and patterns of sediment generation, transport and deposition, suggest that not all parts of a catchment are equally important in generating sediment that is exported from a catchment. Delineation of "geomorphic provinces" (see Review 4 for an explanation) on the basis of the predominant erosional/depositional regime resulting from the influence of geomorphic features (usually relative rates of opposing processes, the presence of local base-level or the presence of a specific substrate, such as weakly consolidated material) is suggested, particularly if experimental (such as sediment tracing) and water monitoring programs are to be undertaken. It would seem appropriate to develop hypotheses of sediment generation which experimentation and monitoring can help validate, rather than to hope that experimental work and monitoring will automatically elucidate important processes and landscape differences.

- Experimental work, such as sediment tracing, could be undertaken to help determine both the landscape regions within a catchment that are primary sources of sediment, as well as whether the sediment is derived from sheet or gully erosion, or floodplain scour. Different size classes of sediment would need to be considered.

6.3.4. Effects of grazing and grazing management on riparian, aquatic and marine biota

Issues that are considered particularly important in the effect that grazing and grazing management are having on the biota of different aquatic environments are listed below.

- With respect to blue-green algal blooms, the lack of bloom development in the NT and north-west of Western Australia is important. The question is whether changes in management, for example an increase in stock numbers, could lead to bloom development or whether there are environmental conditions peculiar to these areas that are inhibiting bloom formation. Either way, there are implications for management. In the first case, the implications are for the grazing enterprises in the NT and north-west of Western Australia while in the second case, knowledge of environmental conditions that inhibit bloom development could be important in elucidating mechanisms of bloom formation in those areas where cyanobacteria are a problem.

- Relatively little is known about the grazing pressures that are exerted on riparian areas in different land systems and how these vary seasonally and during periods of drought; the degree of utilization that is compatible with maintaining the natural habitat and biotic communities; and the effect of cattle exclosure. Improved knowledge of these aspects will help in managing riparian zones.

- The possible introduction of weed species to new areas with the further development of ponded pastures, is regarded as a particularly important issue given the very great difficulty associated with eradicating weeds once they are established and the enormous costs involved. While the benefits of ponded pastures are acknowledged, it would seem that the potential exists for these to be outweighed by the long term costs. If further development of ponded pastures is planned, an improved understanding of the costs and long term benefits is highly desirable. Determining environmental cost will, in turn, require improved understanding of the potential of several of the aquatic pasture species to become environmental weeds.

- Continued survey/documentation of terrestrial, estuarine and marine biota and their condition, and research into ecological and physical processes, is necessary to ensure that we understand these systems, the conditions they can tolerate and when undesirable changes are occurring.

6.3.5. Land survey and assessment of land resource capability

Generally pasture type seems to have been the basis for most research planning and resource capability assessments in the rangelands but the recommendation made in *The Assessment of Resource Capability in the Rangelands* (Smith and Novelly 1997), that resource capability assessments should be based on land system/land types, is adopted here. Climate, geology, topography, and soils are all important in determining land productivity and its susceptibility to degradation, and hence need to be considered in resource assessments.

Land system survey, in which land is classified according to variation in climate, geology, geomorphology, soils and vegetation, has a long tradition in northern Australia, the technique having been developed there with the initial survey of Christian and Stewart (1953). Large areas of northern Australia have since been covered by land system mapping but the use made of this appears to be variable, as is the information contained within the surveys and their scale of mapping.

Land system surveys are useful both as an inventory of resources, and as a basis for assessing land productivity and susceptibility to degradation. Similar land types tend to have similar processes and hence land systems also provide a useful basis for the extrapolation of research. Grazing management practices need to take account of the variation in land resources, the processes operating, and the productive potential of the land as well as its susceptibility to degradation. Consequently, land system and component land unit mapping are also regarded as providing essential information for property planning.

6.3.5.1. Recommendations

- As part of this project, it had been intended to review land system and other land resource mapping information (eg, the soil fertility mapping in central and NE Queensland, major flora and fauna surveys) available for Queensland, the Northern Territory and NW Western Australia and the resource assessment procedures in use. Some data were collected (see Chapter 5), but no systematic assessment of their scale and content was made. It is therefore recommended that a short project be undertaken to assess the current status of land system and other resource survey work across northern Australia, the information contained in the reports, and the land capability assessments (including carrying capacity estimates) relevant to rangelands that are being derived from them. It is expected that much of the information would already be collated by the Bureau of

Resource Science and relevant state agencies. The National Landcare Program has also been assessing survey coverage and this is another potential source of information.

- Without pre-empting the findings from collation of land resource information and use, it is suspected that there has been relatively little interpretation of land system/land unit data to provide assessments of the variability in inherent productivity and inherent susceptibility to deterioration within a landscape. Both are regarded as necessary inputs for property planning. Relatively rapid qualitative assessments can be derived from information obtained during land resource surveys. Methods for quantitative assessments also need to be developed and used where appropriate, and modelling is anticipated as being a useful method.

- Following assessment of the current status of land system survey work and State programs, it is recommended that priorities for improvement in current land system survey coverage need to be developed, and mapping and interpretations of resource productivity and susceptibility to degradation, undertaken. It is suggested that land system mapping should be undertaken in conjunction with the geomorphic province mapping (recommended in Section 6.3.3.). Geomorphic provinces identify the broad regional controls on landscape processes and stability, imparted by geomorphological processes. It therefore provides a useful framework for broad qualitative assessments of inherent stability/instability of the land systems grouped within them. The province framework provides a means of understanding the inherent stability, resilience and susceptibility to degradation of individual land systems/land units determined by the climatic, topographic, soil and vegetation characteristics of each.

- An important issue not investigated in this review, is the appropriateness of research techniques and models which use digital elevation models (DEMs) for providing quantitative assessments of resource productivity and susceptibility to degradation. Presumably, for example, there are the threshold values for relief (slopes) which must be exceeded if DEMs are to be useful. Similarly, there are likely to be slope values at which distribution of the vegetation and soils tend to exert greater control on surface flow than topography. It is recommended that this issue is investigated, given that DEMs and models based on them are being widely promoted as useful tools for improved resource assessment.

6.4. Guiding principles for a research program and recommended research priorities

At the workshop held in Brisbane on August 7th, 1997, the above recommendations for research were extensively discussed. A number of principles emerged and priorities for research program developed. These are outlined below.

6.4.1. Guiding principles

- The vision and design of land use takes place at a regional or catchment scale, while the changes in improved management take place at the paddock or property scale. It was felt that new work in the NAP3 program needs to be primarily at the large catchment scale. It was also considered that the problems associated with linking sediment and nutrient transport processes at different scales were more important issues than water quality per se.

- There are major biophysical and industry differences between catchments across northern Australia which makes funding research, particularly at large catchment scale, a challenge for the NAP3 Program with its limited resources. Another difficulty is the relative lack of expertise in northern Australia (in relation to size) and the concentration of research staff in a few localities. An appropriate solution is to support research, which can provide principles for adaptation and use in other northern Australian catchments, at perhaps one or two locations.

- The importance of an integrated approach to catchment management was emphasised. It was considered appropriate to bring the many other R&D players into NAP3 catchment management research relating to the beef industry because the totality of effort needed in relation to catchment management, water quality and nutrients is much larger than can be supported under NAP3 - there is a strong need to bring together and integrate the expertise (and the funding), and to deliver the sort of integrated outputs that catchment communities and landholders seek.

- In the context of integrated catchment management, it is also necessary that any R&D undertaken is linked to a range of decision-making processes, for example to catchment management for land use planning, to industry practice and also to individual decision-making at the property level. It was emphasised that changes in land management practices at the property level would not be made unless the information from the research was useful to managers and put in an economic context.

- There is a need for the research to identify broad principles that can be linked with particular mapped land systems - this is one way of providing research outputs that can be extrapolated and adapted for use elsewhere. An issue of importance is the actual location of particular land uses and management practices within a catchment or landscape, this being equally or more important than the intensity or duration of use.

- There is a need to test and develop best-bet management practices as the industry and landholders cannot afford to wait until the final bit of research information is in - there was general agreement on the important concept of adaptive management, that is, applying the best-bets of today and monitoring their effectiveness so that they can be improved and adjusted over time.

6.4.2. Recommendations arising from the August workshop

As well as these general principles, three specific recommendations were made at the workshop. The first two were recommendations for more preliminary work to be undertaken before development of the final research proposal, and the third was a recommendation for the type of research to be undertaken.

6.4.2.1. Further information on current projects

It was recommended that current projects related to water and nutrient movement, and catchment management more generally, should be assessed to identify more specifically the knowledge that is being obtained and any deficiencies of the work. This will require the collection of further details on the problems being addressed, project objectives, methods being used, where the work is being undertaken, the organization that is doing it, the timescale and the sources of funding. NAP2 projects that are being extended into NAP3 need to be included.

6.4.2.2. Identification of appropriate catchment(s) for research

Given that research will need to be limited to one or two catchments, an important issue is the catchment(s) in which the research should done. It was agreed that a scoping study should be undertaken as a matter of priority and that it should consider all catchments across northern Australia. It was also agreed that the study would begin by establishing a number of criteria against which catchments would be ranked and grouped. Some of the suggested criteria are:

- a high potential for the grazing industry to affect land and water quality;
- a catchment community that wants the sort of information that will be generated by the research;
- a catchment that is considered to be important from the point of view of the grazing industry; and
- an effective extension process already in place to pick up research results and incorporate them into catchment planning.

The first criterion requires characterisation of catchments in terms of biophysical attributes, including geomorphology, climate and land use, in an attempt to identify potential vulnerability to degradation and risk of off-site effects. Also important are whether catchments are coastal or inland and whether rivers are regulated or unregulated. It is also recommended that this scoping project assess the land system and other resource mapping information available across northern Australia. Such assessment is necessary partly as land system information is considered a necessary basis for any large scale catchment work and would need to be obtained if not already available, and partly because it is also useful for property planning, particularly if the mapping is incorporated within a geomorphic province framework which identifies the broad susceptibility of different landscapes to degradation. The assessment needs to consider the scale of mapping and the land characteristics used to delineate mapping units. Note should also be made of catchments in which NAP3 projects arising from NAP2 projects, are being undertaken.

There was agreement that the selected catchment should be broadly representative across these criteria so that the work conducted in one or two locations would have some applicability elsewhere.

6.4.2.3. Recommended research

The third recommendation was to establish a project or projects to identify and measure the significant effects that the north Australian beef industry is having on the movement of water and nutrients within the catchment and the effect of this movement on water quality and the sustainable use of other resources.

It was recommended that the objectives of this work pick up a number of the recommendations made in Section 6.3., particularly the second recommendation in Section 6.3.3.1 and the third recommendation in Section 6.3.2.4. More specifically, it is recommended that the research involve:

- an analysis of the surface hydrology, landforms and patterns of sediment generation, transport and deposition, and the delineation of geomorphic provinces;
- an interpretation of the inherent capacity of these provinces to supply sediment and nutrients to the major river systems and the susceptibility of the land within them to degradational processes as a result of specific grazing practices;
- establishing budgets for water and key nutrients at paddock to catchment scales, using the provinces as a guide to major landscapes for which budgets are required;
- examining the extent to which grazing and grazing management practices enhance loss (as distinct from redistribution) of water, sediment, nutrient or organic matter, from local areas (ie, catchment divide to water course); and
- determining the effect any such losses are having on land functioning and productivity.

It was recognized that this project needs to be linked with the biodiversity research that will be funded in NAP3.

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Appendix 1

TERMS OF REFERENCE

1. To collate, review, critically evaluate and provide a concise report on the current state of information and knowledge on interactions between clearing, pasture improvement, grazing management, drought, vegetation cover, soil erosion and downstream effects on the hydrological cycle in northern Australia. The amount and quality of surface water, the capacity of groundwater and the ecological status of riverine systems are all important aspects of this work.

This review should include both published scientific literature and current and ongoing research, identify the sources of information and provide an indication of the extent of their program commitment to such research and development work.

2. To identify the key players, whether individuals, groups or institutions, involved in R&D in these areas.

3. To identify major issues and problems in this area for both economic production and ecological sustainability within the beef industry and for downstream systems.

4. To identify those aspects of current knowledge which might immediately be translated into strategies which can be adopted by beef producers or others in the community who are seeking to improve profitability, international competitiveness and ecological sustainability.

5. To identify critical gaps in knowledge or uptake, to indicate the significance of these gaps to current land and water management, to identify the end-users of new information which might be generated and to specify R&D activities which might overcome those deficiencies.

6. To make recommendations as to work which might appropriately be funded by Phase 3 of the MRC's North Australia Program, taking account of the need to improve adoption of ecologically sustainable resource management systems and their profitable utilisation.

7. To prepare a draft report and present it for review by a forum of northern Australian beef producers and others with responsibilities in natural resource management in northern Australia. This forum would be organised by the MRC, but would require significant preparation and appropriate presentation from the review team.

8. Following that consultative forum and discussions with the MRC's NAP3 program coordinators, to prepare a final report which includes a short summary suitable for publication by MRC and circulation throughout the northern Australian beef industry, R&D agencies and relevant scientists.

Appendix 2

PARTICIPANTS AT BRISBANE WORKSHOP, 7th AUGUST 1997

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Review 1

EUTROPHICATION AND ALGAL BLOOMS IN FRESHWATER SYSTEMS OF NORTHERN AUSTRALIA

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Contents

1. Introduction

Hecky and Kilham (1988) have demonstrated that in inland waters phosphorus (P) is most likely to be the 'key' element limiting excess algal growth. Correlation models relating summer algal biomass production to the concentration of total P (Vollenweider, 1968; Dillon and Rigler, 1974 and Jones and Lee, 1986), at the start of the growing season, strongly support this 'key' element proposal.

In Australia in late 1991, the world's largest riverine cyanobacterial (blue-green algal) bloom occurred along 1000 km of the Darling-Barwon River. This event caused Federal and State Governments to react to what was actually a widespread problem. Water quality managers were then forced to carry out remedial programs where, particularly for inland Australia, knowledge of the processes driving bloom formation in this arid country was lacking. The adoption of northern hemisphere management practices to try and limit the frequency of bloom formation in Australian freshwater systems has lead to remedial programs which are either not applicable to this country or which will require decades, or longer, to produce improvement in downstream water quality (see e.g. Harris, 1995). Considering the large amounts of money being used for remedial programs, it is important that these programs are accurately targeted.

2. Background

Discussion of the sources of P in Australian aquatic environments has tended to accept as axiomatic that the predominant sources are the result of human activities. Certainly in the more heavily populated parts of the world, where the problems of eutrophication have been studied for decades (e.g. Europe and North America), there is considerable evidence for increases in P concentrations as having an anthropomorphic origin (e.g. Morse *et al.*, 1993).

There are few examples of direct human effect in Australian waterways (e.g. Birch, 1982; Hall, 1992) and it is becoming increasingly evident that the overseas experience is not directly relevant to the Australian environment. The processes/mechanisms are the same, but the balance and relative importance is not necessarily so, particularly because of the greater levels of turbidity in many of our freshwater systems. High levels of turbidity reduce light penetration and the strong particle-P association means less of the total P (TP) is immediately available for algal growth (e.g. Oliver *et al.*, 1993; Douglas, 1993). High TP concentrations can be tolerated in many of our waterways without causing excessive algal growth (Hart *et al.*, 1993).

Storm events deliver the major sediment and P loads to Australian waterways (e.g. Cullen *et al.*, 1978; Cosser, 1989; Gutteridge *et al.*, 1992; Olive *et al.*, 1994; Donnelly *et al.*, 1996). As gully density is often the parameter which best correlates with sediment loads to streams (Wasson, pers. comm.), subsoil rather than surface (fertiliser-rich) soil dominates these loads. Because of the strong particle-P association, point source contributions to clay-rich waterways may cause local problems, but this input is rapidly lost in relatively short distances downstream due to adsorption onto in-stream sediments (e.g. Jones *et al.*, 1993; House *et al.*, 1995). The degree of regolith weathering in Australia means that most Australian soils and sediments contain a large proportion of clay minerals and that there is a strong clay/Fe/P association (Norrish and Rosser, 1983; Donnelly *et al.*, 1997). This association means that during stratification, P-release from anoxic bottom sediments can be a very large source of soluble P for excess algal growth (e.g. Lawacz, 1985; Nurnberg *et al.*, 1987).

The high radiation levels in Australia, often coupled with turbid water systems, results in stratification of even relatively shallow waterbodies. The hot/dry climate results in almost all rivers being regulated to some degree and many water storages have been constructed to overcome water shortage during drought periods. Australia stores more water per capita than any other country in the world. The control of flow has resulted in the creation of many standing water bodies that undergo stratification and thus have the potential for resolubilisation of sediment-bound phosphorus. Harris (1995) noted the relatively long residence time for water in many Australian waterbodies and commented that in this country eutrophication is mainly the result of *in situ* P-release from anoxic bottom sediments.

Surveys of freshwater waterbodies experiencing algal bloom problems across Australia (Dr Gary Jones, National Algal Manager, pers. comm.) show that; (1) the potentially toxic cyanobacteria dominates this problem, and (2) the problem is widespread across southern Australia (including Tasmania) and extends into northern Queensland, but little information is available for either northern Western Australia or the Northern Territory.

Some of the processes important to algal bloom formation in Australia are listed below in point form. These provide the necessary background information for a discussion on whether the cattle industry in northern Australia is causing, or exacerbating, the problem of bloom formation.

1. Most Australian standing waterbodies (i.e. reservoirs, weirs, rivers during drought) suffer from excess phytoplankton growth and in most cases this is due to the potentially toxic blue-green algae. Toxins produced by these cyanobacteria could, under certain conditions, be harmful to the beef industry.

2. Studies on the source of the sediment reaching waterways in the Murray-Darling Basin indicate that subsoil rather than surface (possibly fertiliser-rich) soil dominates loads. Wasson *et al.*, (1996) comments that processes leading to subsoil dominated sediments may be a common feature of the Australian landscape.

3. The strong clay/Fe/P association in most Australian soils means that sediments from even relatively P-poor soils can produce a very large source of soluble P for excess algal growth in standing waterbodies.

4. Australian waterways are, in general not P-limited for excess algal growth, because of the long water residence times and the ease with which waterbodies stratify, producing deoxygenated bottom water.

5. Because of the strong clay/Fe/P association, point-source soluble P inputs to waterways (such as from intensive farm industries) may cause local algal bloom problems, but within short travel distances the P concentrations will be buffered by the major (diffuse) P load in the system.

6. The episodic nature of the Australian climate (i.e. storm events of days followed by long periods of drought) plays a major role in the eutrophication problems in our waterways.

7. Phorphorus reduction campaigns will only slowly lead to improved downstream water quality because of the *in situ* stores of P in most Australian waterbodies. To decrease the frequency of algal blooms in the short term, the major focus must be on the waterbody not the catchment. Present programs targeting waterbodies include flow management (environmental flows), destratification (hypolimnetic oxygenation), biomanipulation and sediment remediation to suppress the P-release process.

3. The P-release process

Fleischer (1978) found that a biochemical process regulated the release of P from anoxic sediments rather than the absence of oxygen. This finding supported earlier work by Hasler and Einsele (1948) that suggested that sulfate could affect the availability of P in bottom waters, because the sulfide produced by the sulfate-reducing bacteria disrupts the interconnections between the iron and P cycles.

Recently, Caraco *et al.* (1989 and 1991) used data from 23 different aquatic systems to indicate that the control of P-release from sediments by oxygen is not substantiated. Their data indicated that: (1) increased sulfate content of the waters was the major factor critical to the control of P release from sediments (through the activity of the sulfate-reducing bacteria); and (2) the difference between P-release under oxic and anoxic conditions maybe quite small, when sulfate concentrations are low. A recent study by Chiswell *et al.* (1995) confirmed the role of sulfate in P release from freshwater sediments, and a study of natural environments by Barbanti *et al.* (1995) confirmed the relationship between relatively large pore water P concentrations in anoxic bottom sediments and the activity of the sulfate-reducing bacteria.

Sulfate reaches Australian waterways by two main processes; (1) influx of sulfate-rich saline groundwater, and (2) the agricultural use of fertilisers (including superphosphate) containing calcium sulfate. There is now good evidence (from sediment cores and long-term water records) that the sulfate concentrations in waterways world-wide are increasing and that at these higher levels of concentration the sulfate is capable of promoting increases in the P-release process. Australian management options to decrease the P-release process are therefore: (1) to maintain sufficient flow in waterways susceptible to influxes of saline groundwater, and (2) decrease the use of sulfate-rich fertilisers so that sulfate concentrations in waterways are lowered back to pre-European values (i.e. <10 mg/L).

It is recognised that rangelands used by the pastoral industry for cattle would not normally receive significant amounts of fertiliser, although there is some use in areas of improved pasture. In areas of extensive grazing, the effect of grazing on increased sediment input and hence the *in situ* release of P, should also be considered in order to decrease the potential for eutrophication in these catchments.

4. Australian rangelands

The region considered in this report is north of around the 25° latitude and dominated by summer rainfall. The environment of this large part of Australia ranges from arid to semi-arid tropics to the wet/dry tropics. Annual rainfall ranges from around 200-300 mm to over 1200 mm in the tropics. The strong seasonal monsoonal climate in the tropics produces virtual drought for up to 8 months of each year, but a relatively consistent hot summer wet season. Large areas of Australia, above 25° latitude, are being used as rangelands for cattle; in the NT and WA in particular, much of this area has relatively infertile soils. Queensland has a relatively larger area of more fertile soils. It should be noted, however, that soils which are relatively infertile for pasture growth, can still provide adequate nutrients for excess algal growth due both to the lower nutrient requirements of algae and also to the *in situ* processes of P-release under anaerobic conditions in waterways. Phosphorus bound to clay and iron oxides is generally unavailable in soil but is released under anaerobic conditions in waterways.

There is good evidence that basaltic soils and the sediments derived from these soils can be a significant source of P for algal growth (Caitcheon *et al.*, 1995). In catchments with granite-derived soils (e.g. Murrumbidgee catchment), weirs and storages can also have cyanobacterial blooms. This is due to the preferential erosion and transport of very fine particle size (clays) from the mixed particle size soils developed on granites. This 'winnowing' effect can lead to a significant increase in the P concentration of river sediments over the original soil values.

Current evidence suggests, that unless sandy soils with very low clay contents dominate (e.g. the Peel-Harvey catchment in south-west WA), P will be mainly in the form of the clay/Fe/P association. Therefore, provided soils are not sands, standing waterbodies will be susceptible, during periods of hot/still conditions, to developing algal blooms. The greater the soil nutrient status, however, the greater the susceptibility. Queensland may be more susceptible to problem blooms because of the greater area of more fertile soils, a greater extent of fertiliser application and the creation of more standing waterbodies to cater for the larger population. Most standing waterbodies are however, related to farm supplies and irrigation.

5. Distribution of algal blooms across Australia

It is interesting that the first figure in Chapter 3 of the report to the Prime Minister's Science and Engineering Council, "Managing Australia's Inland Waters", shows waterbody monitoring sites covering most states; certainly a good distribution of sites in tropical Australia. However, while the authors of this chapter indicate the need for a further five years funding, the program covers only biological monitoring; the authors suggest this is a cost-effective way of monitoring river health. Unfortunately, the number of water monitoring sites across Australia measuring the data necessary to determine the extent of the algal bloom problem in this country is significantly more limited (Dr Gary Jones, National Algal Manager, pers. comm.).

The late 1991 algal bloom along the Darling-Barwon River brought attention to what was an existing problem. The much greater reporting of algal problems that was initiated, produced maps of problem areas covering most of NSW, large areas of Victoria and small parts of southern WA and SA. Later, water quality managers from Tasmania and then Queensland conceded that toxic blue-green blooms were common in many areas of their states. Identification of the problem had the effect of greater reporting and an emerging understanding of the aerial extent of the problem. However, this was a slow process as is illustrated in Volume 1 of the Queensland Water Quality Task Force (QWQTF, 1992) on freshwater algal blooms in that state (Figure 1). Maps in this report highlighted those regions of Australia, considered by the QWQTF, which were presently experiencing problems with cyanobacterial blooms, and those areas in Australia with reasonable expectation of developing problem blooms. A number of points emerge from these data.

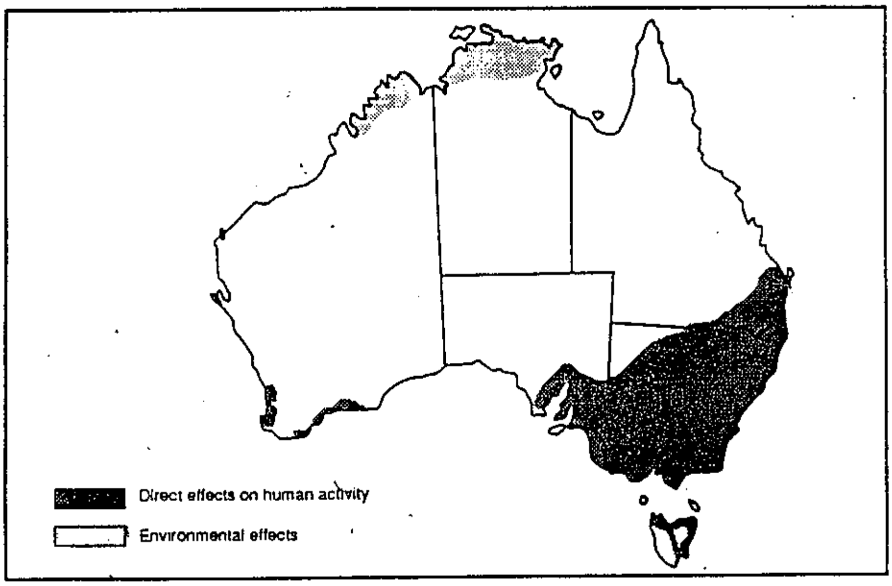

Figure 1. Areas with cyanobacterial blooms, reported by the Queensland water quality task force (1992)

According to this 1991-92 map, only a small part of southern Queensland had algal bloom problems, but within a year or so of this report it was known that almost all standing waterbodies in Queensland have algal bloom problems. Further monitoring and reporting has lead to a greater understanding of the extent of the problem and some understanding of the processes causing the blooms (e.g. Harris and Baxter 1996).

It is interesting that the 1991-92 map indicated an area in tropical Australia which would be susceptible to freshwater algal bloom problems due to environmental effects. The areas indicated covered, most of the top northern section of the NT and the top north-west section of WA. Given the present (1997) understanding the NT and WA water authorities that there are essentially no algal bloom problems in these areas, it would be interesting to know why these were considered potential problem areas in 1991-92. Their inclusion is even more unusual given that the 1991-92 report states that "to date, very few algal occurrences have been reported to the Water Resources Commission from tropical Queensland", and the tropic area of Queensland was not suggested as a potential trouble area. The report indicates that this figure was prepared by the Water Resource Management Committee of AWRC, an organisation that is now much reduced with no relevant staff from this period. Task Force members responsible for producing the QWQTF reports and who were contacted during this review, could not provide the answer as to why these tropical areas had been indicated as potential trouble spots.

5.1. Cyanobacterial blooms in Queensland

Dr Gary Jones suggests, on the basis of the reports he has received since being in Queensland (i.e. 1996 to the present), that nearly all standing waterbodies in this state are susceptible to cyanobacterial blooms. Volume 3 of the 1992 QWQTF report on algal bloom problems in Queensland, highlights Case Studies of 16 storages in Queensland having problems with algal blooms. Most of the identified storages (14) are in the bottom area of the state relatively near Brisbane; one was in the Rockhampton area and one was off the coast of Queensland (Palm Island) just north of Townsville. It is now known that weirs, farm dams and reservoirs throughout Queensland have had problem blooms (Gary Jones, pers. comm.). The area of problem blooms extends to waterbodies north of Cairns and to those in the west of the state, such as Lake Julius near Mount Isa (Jones, pers. comm.). It would appear that the only difference between this state and the known wide-spread occurrence of toxic algal blooms in NSW's water systems has been the identification, in tropical Queensland, of a new algal toxin apparently specific to this region (Jones, pers. comm.).

The processes leading to blooms in Queensland (Jones, in press; Harris and Baxter, 1996) are the same as found for much of Australia (see Background), but with probably a more pronounced climate-driven cycle (Harris and Baxter, 1996). Jones (1997) notes that the period between 1991 to 1995 (drought years) was a period where cyanobacterial blooms caused enormous wide-spread problems throughout Australia. Long hot dry years lead to prolonged periods of high surface water temperatures, stable stratification and P-release from anoxic bottom sediments, all of which favour cyanobacterial blooms. Another process noted in the study by Jones (1997), is the effect of the introduction of relatively large loads of nutrients into waterbodies during storm in-flow events. The large bioavailable nutrient load introduced with storm in-flow has been shown to sustain large algal populations, over time, even while a reservoir has undergone hypolimnetic oxygenation (Harris and Baxter, 1996).

The reports of cyanobacterial blooms in Queensland are usually for waterbodies in catchments associated with some land disturbance. Some reports however, come from pristine catchments indicating that bloom formation also occurs naturally. While algal blooms can occur naturally, it must be stressed that continuing catchment degradation will only exacerbate the problem through nutrient inputs in high storm flows. Additionally, to reduce the frequency of algal blooms, some attempt must be made to stop the *in situ* cycling of nutrients from anoxic bottom sediments. In this regard it is suggested that, in catchments with both grazing and agricultural activities, improvement in downstream water quality will come both from decreasing the storm-driven nutrient loads and from decreasing the concentration of sulfate in waterways, derived from fertilizer, to pre-European levels (i.e. <10 mg/L).

Rayment and Neil (1997) noted that cattle are now well distributed over the extensive grazing lands of Queensland. In catchments draining to the Great Barrier Reef, extensive grazing accounts for >85% of total land use, while fertiliser use is dominated by the sugar industry. These authors also suggested that sediment yields were higher (up to four times) under current land use compared with what they would have been for naturally (Rayment and Neil, 1997; see also Hunter *et al.*, 1996). Certainly disturbance leading to loss of riparian vegetation can be a major factor in increasing sediment loads to rivers. As well, Bramley and Johnson (1996) noted in a study of the Herbert River catchment that, irrespective of the land use in the catchment (which included cattle grazing) that: (1) nutrients carried during flood events determined downstream water quality, and (2) nutrient losses, while greatest from the disturbed sub-catchments, were apparently not changed by the different land uses. The message is that all land users (including the cattle industry) should be aiming towards reducing erosion and nutrient loss as a result of their activities.

5.2. Cyanobacterial blooms in the Northern Territory

Water quality officers in the Department of Power and Water in Darwin, indicated that toxic cyanobacterial blooms were not considered a problem in the Northern Territory. As a result very few, if any, of the Department's water monitoring programs were aimed at monitoring the potential for any standing waterbody to develop cyanobacterial blooms and there are no published reports describing the occurrence or distribution of cyanobacteria. The following discussion comes mainly from observations, particularly those of Simon Townsend (Water Resources Division, Power and Water Authority, Darwin). Simon Townsend confirmed that information about the aquatic environment in the semi-arid and wet/dry tropics of the Northern Territory is extremely scant. Hydrographic and hydrological issues have dominated and only recently have issues relating to the aquatic environment been recognised.

5.2.1. Standing waterbodies

There are obviously not many natural standing waterbodies in the arid and semi-arid tropics of the Northern Territory and in general observations of these waterbodies indicate that cyanobacterial blooms are not a water quality issue. The deeper waterbodies occur in gorges and the energy of the wind through the gorges appears sufficient, most time, to provide efficient water column mixing. Most other (saline and non-saline) waterbodies are generally ephemeral and the systems can be efficiently flushed by the next rainfall event. Also, it has been observed in clay-rich areas, that the particle-bound P in waterways is less bioavailable in the wet season if sediments have been previously dried (Baldwin, pers. comm.). In these regions, natural drying for relatively long periods with later flushing rains, could explain why these waterbodies generally remain free of excess phytoplankton growth.

Simon Townsend has observed that where cattle have access to natural waterbodies in the semi-arid tropics during the dry season, the waters can become extremely turbid. He suggests that while the dry season is the time of greatest potential for excess algal growth and P concentrations may be elevated (animal excretion and sediment disturbance), excess algal growth is most probably light limited. The water in 'turkey nests' (i.e. man-made dams) is generally clear and being relatively shallow many of these dams support good macrophyte growth; blue-green algal blooms are not known to be a problem in these dams. It is significant that in one case in central Australia where P and N were added to bore water to supplement cattle nutritional needs, the ponded water developed excess algal growth. The algae were not identified and the practice was discontinued. However, it does suggest that most water systems, at least in this region, are of low trophic status.

Water quality in two impounded waterbodies close to Darwin (the Darwin River and Copperfield Creek Dams) is also of interest in trying to understand the susceptibility of waterbodies in this part of Australia to cyanobacterial blooms. Simon Townsend noted that blooms of *Botryococcus bruani* (a Chlorophyte) occurred a few years after the impoundment of these two waterbodies, but cyanobacteria were not present in any significant numbers during these events. Townsend (1996) indicated that the Darwin River Reservoir normally has a low trophic status. Seasonal water quality measurements show that P concentrations have remained low (i.e. a bias towards high N:P ratios) even though stratification is strong and that there is a significant flux of Fe and nitrogen from the bottom sediments. Even when nutrient levels became high enough to support an algal bloom, N:P ratios still did not favour cyanobacteria. In contrast, water systems in Queensland are dominated by cyanobacterial blooms (Gary Jones, in press) and the algal biomass is generally N limited (i.e. high P:N ratios).

5.2.2. Billabongs

In the wet/dry tropics of the Northern Territory a general practice has been to allow cattle to graze floodplains during the dry season and move them to higher ground in the wet season. There appears to have been no clearing of floodplain vegetation (including riparian vegetation), but generally there are access paths to the billabongs. Normally cattle do not enter the water (steep banks or fear of crocodiles?) and do not defecate in the billabong. Cattle faeces accumulates on the floodplain over the dry season. In the wet season the floodplain billabongs on major water courses are flushed out, but some "back-flow" billabongs may be isolated from storm events.

The first flush of water entering billabongs can be high in nutrients, sediments and organic matter (Mary River floodplain billabong data, Townsend, pers. comm.) suggesting that this is when cattle grazing may have maximum effect on billabong water quality. Algal blooms, however, are unlikely to occur until the following dry season. One blue-green algal bloom has been recorded (Oct/Nov 1995) in a floodplain billabong with cattle access. The bloom was primarily *Anabaena* (90% by biomass) with a significant algal biomass (40 µg/L chlorophyll-a). The *Anabaena* featured heterocysts for nitrogen fixation and this suggests that the phytoplankton biomass was N limited. Simon Townsend states that the sediments in this billabong were mainly sand. If clay sediments were absent, then the absorption capacity of the bottom sediments to buffer inputs of soluble P from the cattle would have been low. The cause of the bloom however is unknown, but may have been due to either: (1) greater access and larger number of cattle entering the waterbody (i.e. nutrient enrichment due to excretion and/or sediment disturbance), or (2) the first flush of storm flow water from the previous wet, priming the system with nutrients, or (3) the result of land clearing and introduction of sediments containing P (i.e. *in situ* P-release from anoxic bottom sediments during the dry season).

The picture which emerges is that, at present, the potentially toxic cyanobacterial blooms, which are causing major water quality problems in large areas of Australia, are largely absent in the wet/dry tropics of the Northern Territory. This is surprising given that all standing waterbodies in tropical Queensland have the potential to develop cyanobacterial blooms. It seem, however, that in some circumstances cyanobacterial blooms can develop in billabongs. Although at this stage the 'key' factors causing these apparently isolated occurrences of cyanobacterial blooms are unknown, it does raise important research questions for future environmental management of waterbodies in the NT. Some of these questions are:

1. Is this an isolated case or another example (like Queensland pre-1991) of a lack of monitoring and reporting water quality problems?
2. If this is an isolated case, and tropical NT does not have problem blooms at present, what are the factors causing this area to be different from other parts of Australia?
3. Is the present management of stock preventing significant influx of nutrients to waterbodies and preserving natural vegetation on the floodplain?
4. Is the hydrology of the region, relatively abundant riparian vegetation and generally good growth of macrophytes within waterbodies, controlling the nutrient status of the water column and preventing excess cyanobacterial growth?

It is important that at least some of these questions are addressed. Water quality may well be buffered by the climatic regime in this region, but there is always the possibility that there are other major factors. At present, NT waterways are free from algal blooms, but without knowledge as to why, it is possible that some anthropogenic change could create the water quality problems now found in Queensland.

5.3. Cyanobacterial blooms in northern Western Australia

As in the Northern Territory, there is very little water quality information available for the northern part of Western Australia. The W.A. Department of Agriculture and Waterways Commission considers that only the southern part of their state has algal bloom problems in either freshwater or marine environments. The following discussion is based on the observations of those who have worked in the area and a few relevant published water quality papers.

The region used by the cattle industry covers most of the top part of the state with a lower boundary which is the northern edge of the Canning Basin and the beginning of the Great Sandy Desert. The only other section of the state, above around the 25° latitude, with a cattle industry is in the region of the Hamersley Ranges, again bounded to the east by the Great Sandy Desert. Observation by workers in the Kimberley region of WA suggests that this region has no algal bloom problems and the freshwater systems are dominantly good water quality; a point stressed by the state authorities contacted for discussions of this region.

There are two reports on the water quality of inland waters in the Pilbara region of WA (Masini, 1983; Masini and Walker, 1984) carried out for the WA EPA as part of a contribution to the State Conservation Strategy. These studies were carried out to examine the quality of water in this region, not because of problems with cyanobacterial blooms. These investigations of wetlands, creeks, springs and stratified waterbodies in the Pilbara region indicated, that of the waterbodies studied (12), all were generally healthy mixed communities. Only one waterbody was dominated by the blue-greens, but for all the systems examined chlorophyll a concentrations only ranged from 0.5 to 5.7 µg/L. The chlorophyll a values were similar to, or less, than those reported along the Harding River (the same region) by Dames and Moore (1975 and 1982) and are generally regarded as low values for freshwater systems.

As part of the Monitoring River Health Initiative in northern Western Australia, Stuart Halse (pers. comm.) comments that, in general, the waterways examined appear to be in good health and support good macrophyte growth. Water quality monitoring in the Gascoyne River, along the 25° latitude, indicated data typical of other waterways in this region with low soluble P concentrations and therefore, low trophic status. Halse *et al.* (in press) have also examined Lake Gregory, a fairly large semi-permanent lake system to the east of the Canning Basin (i.e. just above 20° 22' latitude). This generally freshwater lake system extends from arid into humid regions and has only dried twice in the last 25 years. Over several years of monitoring water quality in this lake, chlorophyll a concentrations have only ranged from 9 to <0.01 µg/L, suggesting a waterbody of low trophic status.

Lake Argyle is a very large, man made, lake situated only some 150 km (ca. 17° latitude) south of Joseph Bonaparte Gulf (Timor Sea); the lake has a very large surface area relative to its water depth. The catchment of Lake Argyle is large (ca. 46,000 km^2) and relatively well stocked with cattle. A review of the effectiveness of an ongoing re-vegetation program in this catchment (Wasson *et al.*, 1994) indicated that the rates of sediment erosion have not been markedly reduced by the re-vegetation program and the lake still experiences relatively high sediment deposition. Lake Argyle and its catchment experiences a strongly seasonal tropical climate with a hot summer wet season and a long warm to hot dry season. However, while there are state agencies which monitor a number of water quality parameters (although no parameters for productivity) officers report no observations of blooms. After a recent visit to this lake, Gary Jones concluded that this waterbody was apparently free of algal bloom problems. While Lake Argyle appears to be continuously of low trophic status, Jones suggested that this system needs further investigation to determine the processes controlling such low water column nutrient levels.

6. Animal Health and Algal Toxins

In a chapter of the report to the Prime Minister's Science and Engineering Council (Cooper *et al.*, 1996), Dr Gary Jones discusses the effect of algal toxins on the beef industry. Although this contains only a summary investigation, it indicated the potential for toxin accumulation in stock wherever stock drink frequently from water with an algal bloom problem. A pilot study has now been carried out by staff from CSIRO Land and Water and the Division of Tropical Agriculture and will be reported on later in 1997 (for details of this report contact either Dr Bob Hunter or Dr Gary Jones).

It is important to keep in mind that while pre-European Australia was susceptible to bloom problems, the recent proliferation of standing waterbodies has lead to a marked increase in the frequency of toxic cyanobacteria blooms. This was apparent in the major drought between 1991 to 1995 during which the wide-spread occurrence of toxic cyanobacterial blooms caused enormous problems to the Australian water industry. Increased algal blooms, coupled with the finding of toxins unique to Australia and with unknown properties, has the potential to affect the beef industry.

7. Summary

This review indicates that many of the standing water systems throughout Queensland are susceptible to cyanobacterial blooms. Blooms in pristine catchments indicate that the tendency towards cyanobacterial blooms is natural. However, there is also good evidence that nutrient loads to waterbodies will increase with increasing disturbance to catchments, and that the increased nutrient loads can contribute to a greater frequency of blooms and significant increases in the algal biomass. It would appear that there are two main processes causing eutrophication and cyanobacterial bloom problems in Queensland's waterbodies; (1) the relatively large nutrient loads carried by storm inflow events, and (2) P-release from anoxic bottom sediments following sustained hot/still dry periods. With respect to the cattle industry and downstream water quality, there is a need to reduce sediment loads reaching waterways. Where toxic algal blooms are common in water used for stock, the potential for algal toxins to accumulate in animals must be considered. Finally, while this does not apply generally to the cattle industry, it is also suggested that the use of sulfate-rich fertilisers in catchments be used with care to try and maintain pre-European soluble sulfate concentrations in Australian waterways and constrain the P-release process.

The data reviewed for the NT and northern WA indicates a similarity between these two states that contrasts with the situation in Queensland. Almost all the data reviewed indicate that waterbodies in these two states are generally in good health and of low trophic status. Management of cattle in these two states has to date had little effect in causing, or exacerbating, cyanobacterial bloom formation. For two large states, however, the amount of data available is very small, a result of algal blooms not being an issue. This was also the picture for Queensland pre 1992, with greater observation and monitoring indicating algal blooms to be a state-wide problem by 1997. It appears unlikely that this could also be the case for the NT and WA. There may be a number of factors which contribute to the generally low trophic status of waterbodies in these two states and, if this is so, then care is needed to not radically change the present status. This includes cattle stocking rates and cattle access to waterbodies.

8. Recommendations

1. In Queensland the cattle industry should aim to decrease sediment (and nutrient) loads to waterways as a long-term process of improving downstream water quality.

2. In Queensland, given the potential for toxic cyanobacterial blooms, the quality of water used in intensive animal industries or wherever stock drink frequently from the same waterbody, should be monitored to prevent toxin accumulation in animals.

3. There is no evidence of the cattle industry in the NT and northern WA causing, or exacerbating, cyanobacterial bloom formation. However, there may be a number of factors involved in preserving the good water quality in these two states and therefore management changes which increase cattle numbers and access to streams, or sediment and nutrient inputs, should not be allowed.

4. Research is needed to understand why cyanobacterial blooms may be uncommon the NT and northern WA, but common in most parts of the other states of Australia, including southern WA and Queensland. The answer may influence how cattle are managed in these two states and lead to a greater understanding of why blooms occur so easily in other parts of Australia.

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ATTACHMENT 1 — RESEARCH WITHIN THE NATIONAL EUTROPHICATION MANAGEMENT PROGRAM

Generic projects

Modelling nutrient release from sediments and lowland rivers and storages

Prof Barry Hart,
Director, Water Studies Centre,
Monash University,
CLAYTON, VIC

Dr Phillip Ford,
CSIRO Land & Water,
GPO Box 821,
CANBERRA, ACT 2601

Objectives:

- Develop a conceptual model of the key microbial and chemical processes involved in nutrient diagenesis in sediments, incorporating the availability (and quality of) organic carbon and of electron acceptor species (ie, 0_2, $N0_3$, Fe (III), SO_4).
- Couple the microbially mediated sediment diagenesis model with a realistic quantitative physical transport model and implement the numerical solution of the resulting coupled partial differential equations.
- From a critical review of the literature, collect values for all parameters required to operate the model under conditions appropriate to Australian waters. Identify cases where adequate parameterization for specific chemical or microbiological processes is not to hand.
- Determine the missing parameters through judicious laboratory experiments.
- Using the model calculate profiles (and flux rates) of N and P species under conditions representative of episodic oxygenation typical of seiching, wind set up, operation of destratification systems, and intermittent flows.
- Apply model to calculate fluxes and nutrient concentrations in specific rivers in NEMP focus catchments.
- Document model.
- Disseminate results and transfer technology as appropriate to river managers and other key target audiences.

The interaction of physics, biology and nutrient regimes on the initiation and development of algal blooms

Dr Susan Blackburn and Dr Peter Thompson,
CSIRO Division of Marine Research,
MARMION, WA 6020

Objectives:

1. Regulation of resting cyst germination:
    - To determine the role of the key environmental factors, light, temperature, salinity, dissolved oxygen and nutrient concentration on resting cyst germination of the bloom-forming dinoflagellate and cyanobacterial species: *Gymnodinium catenatum* (and *G. impudicum* if verified from Wilson Inlet), *Nodularia spumigena*, and *Anabaena circinalis*.
    - To establish endogenous dormancy requirements of resting stages of bloom-forming dinoflagellate and cyanobacterial species (as listed above).

2. Nutrient availability:

   To determine the role of the relative supply of nitrogen, phosphate and silicate (N:P:Si ratios) and rate of supply on phytoplankton species succession using: *G. catenatum*, *Prorocentrum spp.*, *Scrippsiella sp.*, *N. spumigena*, *A. circinalis*, and *Skeletonema costatum*.

   - Interaction of water column stability/turbulence with nutrient gradients (species for objective 3 as listed in objective 2).
   - To establish the relative importance of light attenuation and sedimentation on succession, particularly with respect to development of cyanobacterial blooms.
   - To determine the role of water column stratification due to salinity and temperature on the competitive ability of bloom-forming dinoflagellates and cyanobacteria relative to other phytoplankton groups, both with evenly distributed nutrients and vertical nutrient gradients.
   - To determine the role of variation in the frequency and severity of physical disturbances (simulated turbulence, natural and man-made) on the viability and competitive ability of dinoflagellates and cyanobacteria to initiate and develop blooms.

Retrospective study of nutrient variations in some riverine systems

Dr A Herczeg,
CSIRO Land & Water,
PMB No. 2,
GLEN OSMOND, SA

Objectives:

- Review of literature on stable carbon and nitrogen isotopes in freshwaters, and assess its applicability to interpretation of data from the Murray-Darling Basin and southern WA.
- Analyse C & N isotopes and P/Fe ratios for sediment cores from Lake Alexandrina, Namoi River, Burrinjuck Reservoir, Goulburn-Broken River, Fitzroy River and Wilson inlet (WA).
- Assess the significance of temporal changes in sources and relative fluxes of organic C, N, P inferred from sediment core data, to that of water column and trophic state over the past several hundred years.

Methods:

Sediments will be analysed by continuous flow mass spectrometry. Chronological information will be provided by ^{137}Cs and/or pollen dating. Also, use of existing archival data on algal abundance and nutrient concentrations from the respective catchments.

Movement of phosphorus through soils

Dr Jim Cox,
CRC for Soil & Land Management,
PMB No. 2,
GLEN OSMOND, SA

Objectives:

- To quantify the extent of P movement through a range of soil types.
- To establish the climatic factors (eg storm intensity, seasonal wetting and drying) which influence P movement.
- To quantify the effect of soil properties (eg sodicity, porosity, texture) influencing P movement through soils.
- To devise a P movement index (PMI) to predict the extent of P movement through soil types based on readily measured soil properties.
- To determine the extent to which lime and gypsum reduce the amount of phosphate translocated through the soil profile.

Measurement and treatment of phosphorus and carbon subsoil movement

Dr Jim Cox,
CRC for Soil & Land Management,
PMB No. 2,
GLEN OSMOND, SA

Objectives:

- To quantify the proportion of P and dissolved organic carbon (DOC) moving from soils into streams and water storages by subsurface flow at the hillslope scale.
- To characterise the chemistry, physical and mineralogical properties of the mobile P and DOC.
- To determine the extent to which lime and gypsum reduce the amount of P and DOC translocated through soils and the cost-benefit ratio of their application.
- To transfer results to Land Care officers and water and land management agencies through meetings, field days and the publication of a brochure.

Fitzroy catchment, Queensland

Effects of episodic events on aquatic ecology in tropical and subtropical areas (project still at scoping stage)

Objectives: The project aims to test the hypothesis that algal blooms are part of an aquatic ecosystem response to variations in flow and nutrient loadings and to variations in the cycling of major nutrients within river sections and storages. In particular, the experimental design has been developed to test the hypothesis that gross changes in the biogeochemistry of C, N and P (particularly denitrification) after high flow events are coupled with the dominance of N fixing cyanobacterial blooms.

Proposed methods: The project will study in detail the effects of variations in flow (both high and low flow periods) on the ecology and biogeochemistry of river sections and barrages. An attempt will be made to obtain mass balances for nutrients, algal biomass and species composition in selected river sections which experience large variations in flow on an annual basis. It is suggested that this should be done by selecting a small number (3-5) river reaches in a well gauged catchment and sampling at gauging stations at the upstream end and downstream ends of river reaches and barrages. This will provide inputs and outputs of water, major elements, turbidity, salt and plankton populations for each section. Integrated samples of in-stream concentrations of nutrients are required from stations in the middle of each reach. Phytoplankton biomass and species composition should be measured on all samples. Macrophyte abundance in each reach should be assessed and sediment/water exchanges determined at a range of sites (3-5) in each reach.

Expected outcomes: Expected outcomes include an indication of whether nitrogen plays a role in the growth of cyanobacteria in rivers and storages and about the role of denitrification. The results are not expected to be catchment specific but transportable to other catchments and situations. The results are also expected to have clear management implications in terms of relationships between land use, nutrient loads and algal blooms.

Management strategies for control of cyanobacterial blooms in the Fitzroy river barrage

Dr Myriam Bormans
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GPO Box 821,
CANBERRA, ACT 2601

Objectives:

- To establish the role of flow, stratification, turbidity and nutrient dynamics in the development and persistence of cyanobacterial blooms in the Fitzroy River Barrage (FRB) by a combination of field measurements and modelling.
- To extend an existing predictive model of stratification and algal growth dynamics in rivers by incorporating nutrient dynamics, and to adapt and verify the updated model for the FRB.
- To use the model to investigate and select the best strategies for cyanobacterial control in the FRB.
- To assess the general applicability of the model to other temperate and tropical rivers affected by cyanobacterial problems throughout Australia.

Whole-lake biomanipulation for the reduction of nuisance micro-algae

Dr Vlad Matveev,
CSIRO Land & Water,
GPO Box 821,
CANBERRA, ACT 2601

Objectives:

- To conduct a long-term whole lake biomanipulation experiment by changing the fish community in a small lake or a water storage.
- To perform pre- and post- manipulation analysis of relevant plankton-associated food webs, taking into account seasonal and inter-annual variability.
- To investigate the mechanism of the effect of planktivorous fish on plankton community structure.
- To assess the effect of the manipulation on algal biomass.

Focus catchment projects with objectives or techniques relevant to northern Australian catchments

Algal availability of phosphorus discharges from different catchment sources — Goulburn-broken catchment

Dr Rod Oliver,
Cooperative Research Centre for Freshwater Ecology,
Canberra University,
CANBERRA, ACT

Dr Ian Webster
CSIRO Land & Water,
GPO Box 821,
CANBERRA, ACT 2601

Objectives:

- Describe the chemical compartmentalisation and availability for algal growth of phosphorus contained within the discharge from a STP, an irrigation return drain and an agricultural catchment within the Goulburn-Broken system.
- Describe changes in the quantity of algal available phosphorus associated with suspended sediments from the different sources after laboratory simulation of biogeochemical processing (eg low oxygen/redox conditions).
- Measure longitudinal changes in the particulate and dissolved phosphorus concentrations immediately downstream of the three input sources.

- Determine the algal availability of phosphorus in bottom sediments of the Goulburn River downstream of the three discharge points under oxic and anoxic conditions.
- Develop and test a non-specific sediment transport model incorporating particle settling and resuspension, coupled to a P-speciation model describing transformations between dissolved, particulate, and bottom sediment forms of P, to predict the downstream effects of discharges on streams.

Sources and delivery of suspended sediment and phosphorus to Australian rivers: Part A Radionuclides and geomorphology — Namoi catchment

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Objectives:
- Quantify the relative contributions of topsoil and subsoil to the suspended sediment loads in generic landform/use catchments using atmospherically-derived radionuclides (^{137}Cs, ^{210}Pb, ^{7}Be).
- Link radionuclides results to trace element and ^{143}Nd/^{144}Nd, ^{87}Sr/^{86}Sr data collected and analysed by C. Martin defining natural and anthropogenic sources of phosphorus.
- Assess the relative and absolute magnitudes of the anthropogenic and natural fluxes of phosphorus within the generic catchments. Relate the fluxes to land use and geologic and geomorphic variability in catchments.
- Generate a set of rules governing the behaviour of sources of phosphorus within a set of generic landuse/landscape type catchments.
- Develop a landscape analysis technique that relates the dominant sources of sediment and phosphorus to geomorphic attributes in catchments.
- Determine how geomorphic attributes affect the efficiency of delivery of sediment and P to streams.
- Present this information in a form useful to regional land care and community groups and to State and Federal agencies.

Sources and delivery of suspended sediment and phosphorus to four Australian rivers: Part B Nd and Sr isotopes and trace elements — Namoi catchment

Dr Candace Martin,
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ANU,
CANBERRA, ACT 0200

Objectives:
- Identify the natural and anthropogenic (fertiliser) sources of suspended sediments and associated phosphorus using trace elements and naturally-occurring radiogenic isotope (^{143}Nd/^{144}Nd, ^{87}Sr/^{86}Sr) signatures.
- Assess the relative and absolute magnitudes of the anthropogenic (fertiliser) and natural fluxes of phosphorus. Relate fluxes to land use and geologic and geomorphic variability in catchments, in conjunction with Part A.
- Investigate whether the radiogenic isotope compositions of algae directly monitor the source of bioavailable P, in conjunction with Rod Oliver.
- Present this information in a form useful to regional land care and community groups and to State and Federal agencies together with Part A.

Physical and nutrient factors controlling algal succession and biomass in Burrinjuck Reservoir

Dr Ian Lawrence,
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Canberra University,
CANBERRA, ACT

Objectives:

1. Assess the relationship between reservoir inflow, nutrient loading, mixing and drawdown, sediment desiccation, P and N in the water column, and algal biomass, composition and succession, for Burrinjuck Reservoir for the period 1976 to 1996.
2. Determine if the primary factors controlling nutrient availability are:
   - nutrient loading from river and seepage inflows
   - nutrient losses from discharge and sedimentation
   - nutrient re-mobilisation from the sediment
   - internal nutrient re-distribution due to mixing and flows.
3. Determine if the primary factors controlling algal biomass are:
   - retention time in the surface layer;
   - levels of available nutrients;
   - mixing conditions; and
   - temperature and light.
4. Determine if the primary factors controlling algal composition are:
   - nutrient composition (C/N/P/Si ratios);
   - euphotic to mixed depth ratios.

Review 2

A REVIEW OF THE IMPACTS OF THE NORTHERN AUSTRALIAN GRAZING INDUSTRY ON WETLANDS AND RIPARIAN HABITATS

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Contents

1. Introduction

The effects of the northern Australian grazing industry on wetlands and riparian zones are considered below. They are discussed according to the issues which have been most frequently linked to grazing in previous reviews, and include both the direct effects of grazing, and effects of other practices associated with the industry. These include the effects:

- on water quality
- on riparian biodiversity
- on wetland biodiversity
- of weeds associated with grazing
- of fire management practices

Throughout this review the term riparian will refer to "that part of the landscape which exerts a direct influence on stream channels or lake margins and on water and aquatic ecosystems contained within them" (Bunn and Price 1993) and will specifically exclude floodplains. For the purposes of this review, the large floodplains of many of the rivers in northern Australia are discussed under wetlands rather than riparian areas. The term wetland will broadly follow the definition used by the Ramsar Convention: "areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water depth of which at low tide does not exceed six meters" (Davis 1994). However, the focus will be on natural wetlands and will not include discussion of marine wetlands.

To cover the full range of potential impacts of the northern Australia grazing industry, no attempt will be made to distinguish between the impacts of "grazing" and "overgrazing". The importance of drawing this distinction will, however, be discussed in conclusions and recommendations.

2. Previous reviews

In Australia, there have been numerous studies which refer to the impacts of grazing on native flora and fauna (see Morton 1990). The majority of these studies, however, refer to research into the effects of grazing on terrestrial ecosystems only (e.g. Morton 1990; Landsberg *et al.* 1996). While wetlands and riparian zones exist within the study areas of some projects and monitoring programs, few studies focus specifically on the effects of grazing on these habitats. Furthermore, there is a marked regional bias in the existing literature, with most previous studies having been conducted in southern Australia. These have often been conducted in areas under intensive grazing management, as opposed to rangelands. Despite the overwhelming dominance of grazing as a land use in northern Australia, very little is known about its impacts on wetland and riparian habitats.

Reviews of wetland and riparian management issues have consistently identified grazing effects as both an important threat and an area requiring more research. A national review of the major threats to the conservation of Australian wetlands (McComb and Lake 1988) listed "Grazing of wetland vegetation by stock and watering of stock in wetlands" as a direct threat, while other threats related to grazing included: effects of catchment clearing; river regulation; diversion and extraction of water from rivers and wetlands; weed invasion; wildfires and nutrient enrichment. The National Wetlands R&D Scoping Review (Bunn *et al.* 1997) listed "Grazing in wetlands" under the priority issue of Habitat Modification and noted specific impacts including; selective grazing of macrophytes, damage to banks and wetlands by trampling, contamination of water (e.g. increased turbidity, eutrophication and faecal contamination), and the introduction of weeds. The Habitat Modification background paper in the LWRRDC National Wetlands R&D Scoping Review (Bunn *et al.* 1997) reviewed the national literature on grazing impacts and included specific recommendations for future research and development. Aspects from this paper which are relevant to northern Australia have been included in this overview. At a national workshop on the ecology and management of riparian zones, degradation of riparian zones through grazing was ranked highly as an issue for research and management (Bunn and Pusey 1993).

Reviews relating specifically to northern Australia have also stressed the importance of grazing impacts as a threat to wetlands and riparian zones. In Queensland, the impact of grazing in wetlands has been described as varying from beneficial in some instances, to severely degrading in others. Inland areas are worst affected with the most widespread source of disturbance to wetland systems being erosion, siltation and plant invasions associated with over grazing, especially along watercourses, drainage lines and seasonal swamps (Blackman *et al.* 1993). The Western Australian chapter of "A Directory of Important Wetlands In Australia" (Jaencsh and Lane 1993) lists grazing as having a deleterious effect on wetlands through damage to river banks and riparian vegetation, degradation of catchments and associated increases in erosion, runoff and siltation. Recent reviews of the conservation status of wetlands in the NT (Finlayson *et al.* in press; Storrs and Finlayson 1997) include considerable discussion of the direct and indirect effects of grazing (i.e. impacts of weeds, fire regime, water regime and physical modifications) on wetlands and riparian habitats.

Recent reviews of riparian zone management in northern Australia have also placed particular emphasis on the effects of the grazing industry. Halse and Jensen (1993) reviewed the current ecological condition of the four drainage divisions recognised by the Water Resources Council in Western Australia. The Indian Ocean drainage division was found to have moderate to high levels of riparian zone disturbance which was attributed largely to grazing and subsequent erosion caused by cattle moving in and out of stream beds. The southern and eastern Kimberley (Timor Sea drainage division) has extensive land degradation due to grazing, especially on the river floodplains and stream banks. By comparison, in the north western Kimberley, where there is no pastoral industry, riparian zones are mostly undisturbed. Sattler's (1993) review of riparian zone management in Queensland and the Northern Territory highlights inadequate management practices resulting in overgrazing as having caused considerable damage to riparian zones in these states.

A recurrent theme in all these reviews—riparian or wetland; national or regional—is the lack of information on the effects of grazing. It is clear that while grazing is invariably considered a *potential* threat to wetlands and riparian areas, the lack of research effort makes it extremely difficult to assess the magnitude and extent of the threat.

3. Water quality

Removal of catchment vegetation through grazing, soil exposure, trampling and soil compaction leads to increased run-off, erosion and transport of sediments into rivers and wetlands. Increased levels of sediment and silt in rivers and wetlands from erosion and slumping of banks, has severe implications for vertebrate and invertebrate animals in addition to causing changes in river morphology. In extreme cases increased sediment loads can fill in water holes, totally destroying both in-stream and riparian habitat.

Riparian vegetation plays an important role in stabilising river banks and influencing water quality. The impacts of disturbances on water quality within a catchment may be reduced if wetlands are surrounded by a "healthy" riparian zone. However, as cattle have natural tendency to focus on riparian areas, this compounds the effects of degradation elsewhere in the catchment. Cattle may also have direct effects on water quality through trampling of stream beds and the addition of urine and faecal material.

Observations on the effect of cattle on water quality come from studies of streams draining the Australian Army's Townsville Field Training Area (TFTA) conducted by the Australian Centre for Tropical Freshwater Research (ACTFR). They have undertaken several surveys of the water quality (and fauna) of the area over a period of several years. Water quality is known to have deteriorated during this time with the main direct effect being attributed to the pressures of cattle grazing (Pearson 1996). It was found that cattle wallowing and the addition of faeces and urine caused microbial contamination and elevated nutrient levels leading to eutrophication, particularly during extended dry seasons (Butler and Faithfull 1991); cattle faeces were a significant source of organic matter to the streams; cattle movement around streams has caused stream bank damage and increased turbidity; and re-suspension of sediments and nutrient elevation is also believed to have resulted from disturbance of the stream bed by cattle (Pearson 1996).

The TFTA is currently the site for several research projects related to impacts of military activities and grazing (J. Brown, pers. comm.). While these projects deal primarily with terrestrial systems, one project will investigate the effects of grazing on flora and fauna in riparian zones, and the downstream effects on water quality. This project is notable in that it uses very large plot sizes and is complemented by an additional project undertaking detailed catchment land mapping.

Grazing effects on water quality have been reported from elsewhere in Queensland. Lucaks (1995) described the poor water quality of grazed wetlands of the Lower Burdekin region, North Queensland.

The potential for cattle to affect water quality has also been noted in the NT (Fulton 1995; Finlayson *et al.* in press; Storrs and Finlayson 1997) but no data have been published. A study is currently underway to assess the water quality of three floodplain billabongs, with various degrees of cattle access, on the Reynolds River, NT (S. Townsend, pers. comm.). Findings so far indicate that the billabong with the greatest cattle access also had the highest nutrient and blue-green algae concentrations. However, not enough is known about the baseline water quality of the billabongs to attribute these effects to cattle access.

There are also reports from the Pilbara, WA, of how normally clear waters of dry season pools may become highly turbid as a result of trampling cattle (P. Davies, pers. comm.)

4. Riparian biodiversity

Riparian zones are recognised as critical habitats which link wetland ecosystems with their catchments. In northern Australia these habitats may represent only a small proportion of the landscape but are important for native wildlife, acting as corridors for movement and refugia during dry periods (Braithwaite 1985; Braithwaite 1990; Catteral 1990; Morton 1990; Braithwaite and Muller 1997). Unfortunately, riparian zones are also particularly prone to intense grazing pressures as they offer water for stock, shade and more palatable pasture species (Wilson 1990; Sattler 1993; McIvor *et al.* 1995). This intense grazing pressure may result in a loss of vegetation, particularly ground cover, trampling and soil compaction, stream bank erosion and the introduction and spread of weeds. This in turn can lead to high nutrient and soil inputs into wetlands, causing reduced water quality, increased sedimentation, silting of waterholes and stream channels, increased flood potential and loss of both in-stream and riparian habitat (Sattler 1993). Although these potential impacts, are widely reported in the literature, they are rarely supported by experimental evidence. Rather, they appear to be based mostly on casual observations.

The Cooperative Research Centre for Sustainable Development of Tropical Savannas (CRC SDTS) has a Riparian Habitats project proposed within its Biodiversity sub-program. Project details are still being finalised but the impacts of grazing management on riparian habitats, and subsequent effects on the aquatic biota will be a major focus of research (M. Douglas pers. comm). Study sites will include the VRD Region in the NT, but may also include areas in WA and QLD.

A study recently commenced through the CRC SDTS will involve the sampling of birds, adult dragonflies and plants (including weeds) in riparian and adjacent non-riparian areas from 120 sites throughout the NT (J.

Woinarski, pers. comm.). Sites will be sampled once during the next two years and will include all the sites sampled for the Monitoring River Health Initiative (see below), which experience a range of grazing pressures.

The CRC SDTS will also be undertaking an assessment of the vertebrate fauna associated with chenopod shrublands within the northern savannas. In this region, Chenopod shrublands are usually associated with intermittent wetlands and are highly sought by cattle, but are readily degraded by excessive grazing pressure. The project aims are to: document the conservation value of these blue bush swamps, examine the distributional patterning of their associated vertebrate fauna and briefly investigate the effect of grazing (J. Woinarski, pers. comm.).

4.1. Riparian flora

Plants are particularly useful indicators of grazing disturbance as they are abundant and diverse, and are the taxon most directly affected by grazing (Landsberg *et al.* 1996). Few studies have examined the effects of grazing on riparian vegetation in northern Australia, although the scant information currently available clearly indicates that cattle grazing has a negative effect on riparian vegetation.

A study is currently underway to determine the effects of grazing on the regeneration and persistence of riparian vegetation of the Ord River in the Kimberley, WA (N. Pettit, pers. comm.). The project aims to provide information which can be used for the restoration of degraded riparian zones. This project will use field surveys, soil seed bank studies and cattle exclosure plots and is complemented by additional field work on riparian vegetation in south west Western Australia. Preliminary results indicate a large effect of cattle grazing on species richness and structural diversity of the riparian zone, although there appears to be a less significant effect on the recruitment of overstorey species.

In the lower Burdekin region, continued grazing pressure also appears to be restricting forest re-growth in the lower floodplain areas of the East Barratta Creek (Lukacs 1995). Severe damage to riparian vegetation as a result of cattle access to water courses, has also been observed in streams within the Townsville Field Training Area (Pearson 1996)

4.2. Riparian fauna

Compared with riparian vegetation, slightly more is known about the effect of grazing on riparian fauna. However, given the small number of studies on vegetation, this is hardly reassuring.

4.2.1. Invertebrates

No past studies were found which dealt with the effects of grazing on invertebrate communities within riparian habitats. Whilst the CRC SDTS is currently using a range of invertebrate fauna as indicators of land condition in northern Australia, these study sites do not include riparian habitats (A. Andersen, pers. comm.). Previous investigations have found ants to be the most useful invertebrate indicators of grazing effects due largely to their relatively high abundance and diversity (Landsberg *et al.* 1996). Expertise is available for the identification of ants throughout northern Australia (A. Andersen, pers. comm.), and ants have already been used to examine the effects of other disturbances (e.g. introduced invertebrates) in riparian zones (B. Hoffman, unpubl. data). Ants may therefore also have potential as indicators of the effects of grazing in riparian habitats.

4.2.2. Birds

The vulnerability of birds associated with riparian zones in tropical savannas has been highlighted in a review of the conservation status and threats to savanna avifauna (Woinarski 1993). Although Woinarski laments the lack of information on which to determine the impact of grazing, it is worth noting that there is more documentation on the decline of birds in riparian zones than for other faunal groups.

Tidemann (1990) showed that the abundance of finches in tropical woodland in the NT declined with increasing grazing pressure. Although the study did not specifically examine riparian habitats, the results are relevant to this review as riparian zones appear to be important areas for granivorous (and nectarivorous) birds (Braithwaite 1985). Woinarski (1993) considers two other finches associated with riparian habitats — the Crimson finch and the Star finch — as species of conservation concern, again due to the potential effects of grazing in these habitats.

Observations of the link between the decline in riparian birds and drought and grazing, were first described by Barnard (1925) for the riparian grasslands in Queensland. However, the most well documented impacts of grazing have been on the Purple-crowned Fairy-wren and the White-browed Robin (Smith and Johnstone 1977; Boekel 1980; Rowley 1988; Woinarski 1992; Rowley 1993). These insectivorous species have disappeared from the riparian grasslands and fringing Pandanus from many areas in the Kimberley following the loss of this vegetation through overgrazing. The Western sub-species of the Purple-crowned Fairy-wren (*Malurus coronatus coronatus*) is now listed as vulnerable (Garnett 1992).

In a review of the conservation of birds in arid Australia, Reid and Fleming (1992) concluded that vegetation modification as a result of overgrazing had been the principal agent causing the decline of bird species within the arid zone, and that birds with a preference for grassy riparian environments and chenopod shrublands had been disproportionately affected.

4.2.3. Mammals

Morton (1990) constructed a conceptual model to account for the recent high extinction rates and dramatic range contractions of arid zone mammals. Although the model included several contributing factors, Morton (1990) argued that the primary cause for extinction of medium sized mammals from central Australia was habitat modification due to grazing by a range of introduced herbivores, including cattle. Medium-sized mammals were prone to decline because they were particularly dependent on moist and fertile patches in the landscape (including riparian habitats) during droughts. These habitats are also a natural foci for introduced herbivores and have experienced severe degradation through overgrazing (Curry and Hacker 1990). Cattle and sheep in particular have had the greatest effect on these habitats due to their reliance on water (Reid and Fleming 1992) and their greater weight and harder hooves (Harrington *et al.* 1979).

The savannas of northern Australia have not experienced the high rates of mammal extinctions recorded in the arid zone, and have suffered less, in terms of range contractions, than any other region (Braithwaite 1985; Braithwaite and Werner 1987). Riparian zones in savannas are however, considered to be centres of diversity of non-volant mammals less than 5 kg (Braithwaite 1990); many species occur in higher abundance in riparian areas (Braithwaite 1990) and there is evidence that most reproduction and the most dominant individuals, occur with them (Braithwaite and Griffiths 1994). Braithwaite and Muller (1997) examined declines in several mammal populations in Kakadu National Park, NT. They derived an index of vulnerability and concluded that the species which appear to be most vulnerable are those with annual life histories and a strong preference for riparian areas. As their study was conducted in an area free of cattle, it did not examine the effects of grazing directly, but the authors noted that many of the positive features of riparian areas would be compromised by introduced grazers. The authors suggest that while grazing may be an important threat to the mammals reliant on these refuge areas, their observed decline in the absence of exotic herbivores suggests that other factors, in particular, long term changes in groundwater levels may also be important.

Probably the most important and dependent mammalian users of riparian zones in northern Australia are flying foxes (Woinarski, pers.comm.). Several species of flying foxes roost in and feed on, riparian vegetation and contribute to its maintenance through seed dispersal and pollination.

4.2.4. Reptiles and amphibians

There is a growing body of literature documenting the dependence of freshwater turtles on their riparian communities. Research in the Daly River, NT has shown that the Snapping Turtle (*Elsya dentata)* is far more dependent on riparian zones than previously thought. As well as relying on fruit inputs (particularly *Ficus* spp.) to the river as a major food source, high densities of turtles have also been found to forage in the riparian zones during the wet season (A. Georges pers.com). Turtles may also play an important role in the seed dispersal of riparian plants (R. Kennett, pers.comm.). Pig-nose turtles (*Caranettochelys insculpta*) lay eggs in shallow nests in riparian sand banks and as a result are especially vulnerable to trampling by stock (Georges and Kennett 1989).

There is also evidence that grazing may assist in the spread of cane toads (*Bufo marinus*). Cattle hoofprints can provide a favourable microclimate for toads, thus increasing their chances of survival during the dry season (R. Alford, pers. comm.). It has also been noted that borrow pits excavated for the construction of access roads for the pastoral industry has provided additional breeding sites for native frogs (M. Tyler, pers. comm.), although these sites may also assist the spread of the cane toad.

5. Wetland biodiversity

5.1. Aquatic macrophytes

Recent reviews of grazing in wetlands emphasise the lack of knowledge of grazing effects on wetland vegetation (Bunn *et al.* 1997; Finlayson *et al.* in press; Storrs and Finlayson 1997). Bunn *et al.* (1997) state that selective grazing of macrophytes, particularly in arid and northern Australia, is unchecked and that the repercussions for community dynamics and wetland succession are unknown. It has also been suggested that northern Australian wetlands may be more vulnerable to grazing than those in southern Australia, due to the massive concentrations of cattle around wetlands at the end of the dry season (Bunn *et al.* 1997). Furthermore, the highly seasonal nature of many wetlands in northern Australia means that cattle have greater access to a wetland as it dries out, exposing more of the wetland area to grazing and trampling disturbance.

A survey and classification of wetlands in the lower Burdekin region of north Queensland (Lukacs 1995) identified trampling and grazing and their subsequent effects as a current threat to vegetation of the Burdekin floodplain. Lukacs noted that the aquatic vegetation of the seasonal wetlands, particularly emergent plants, were especially prone to cattle damage as they were often grazed heavily during the dry season. Peripheral wetland vegetation is subjected to continual grazing pressure throughout the year.

Much research on the impacts of grazing on wetland vegetation in the NT has focused on the water buffalo. As these animals may use the land differently to cattle, their effects are summarised separately below. Effects of buffalo and cattle grazing on vegetation are being investigated in a long-term exclosure experiment on the floodplain of the Mary River, NT (D. Liddle, pers. comm.). This study is examining three different vegetation types with four replicates of grazed and ungrazed plots in each.

In a survey of the importance of black soil lakes of the Barkly and Sturt drainages as waterbird habitat, Jaensch *et al.* (1995) noted that lignum (*Muehlenbeckia cunninghammi)* and other plant species such as wild rice (Oryza spp) had declined or disappeared from parts of the wetlands where grazing had occurred. The disappearance of these plants from the Barkly wetlands is significant as Jaensch *et al.* (1995) found lignum to be the most important vegetation for waterbirds.

Other effects of pastoralism on native vegetation relate to the introduction of improved pasture species and are discussed below.

5.2. Algae

Current research on the Cooper Creek in western Queensland has revealed that food webs in these turbid river systems may be largely based on in-stream production of benthic blue-green algae (S. Bunn, pers. comm.). The high turbidity means that the algae can only grow in the shallow margins of the wetlands, making these systems highly susceptible to the effects of cattle trampling and to water drawdown.

5.3. In-stream fauna

Many aquatic vertebrates and invertebrates depend on riparian inputs (e.g. leaves, fruits etc.) for their survival. In addition to providing organic material which serves as habitat and food for aquatic fauna, riparian vegetation plays a crucial role in shading streams. Shading reduces both light and heat reaching the stream, which can lead to elevated plant growth and increases in water temperature – both of which may have detrimental effects on stream fauna. Consequently the effects of grazing on riparian habitat discussed previously, can also affect aquatic biota.

5.3.1. Aquatic invertebrates

Invertebrates are an important component of the aquatic ecosystem and are a potentially valuable group to use as indicators of river health (Schofield and Davies 1996). Although information on the effects of grazing on aquatic invertebrates is currently poor, it is likely to improve with the publication of results from the Monitoring River Health Initiative. This national program coordinates the sampling of macroinvertebrates from hundreds of sites across Australia (including northern Australia) and will greatly expand existing knowledge of this group (Schofield and Davies 1996). In the NT, the Monitoring River Health Program has over 120 sites located across the Top End. Macroinvcertebrate samples and a range of physical and chemical measurements are taken at each site. Approximately 50% of these sites are subjected to a range of grazing pressures from cattle. Some of them show the effects of heavy cattle use with loss of vegetation ground cover, bank destabilisation, local catchment erosion and accumulation faeces (J. Suggitt, pers. comm.).

At present, there appears to be very little research in northern Australia specifically documenting the effects of grazing on invertebrate fauna in wetlands. Results of monitoring programs in the TFTA in Townsville revealed that while these streams have high macroinvertebrate biodiversity, reductions in diversity and abundance over time were correlated with increases in stream-bank degradation and turbidity due to grazing pressure (Pearson, 1996).

A recent study conducted in the Upper Brisbane River compared the chironomid fauna (midge larvae and pupae) and water quality of two sub-catchments with different levels of grazing (A. Arthington, pers. comm.). The more disturbed sub-catchment had five or six times higher electrical conductivity and concentrations of many inorganic ions, and twice the levels of suspended solids. The chironomid communities were also markedly different in the two catchments. Fewer species occurred in the more disturbed catchment, and it contained taxa usually associated with poor water quality. These taxa were absent from the less disturbed catchment. The faunal differences reflect the differences in the water quality of the two catchments and highlight the potential of these taxa to act as indicators of catchment disturbance.

Not all effects of grazing result in reductions of invertebrate richness or abundance. The presence of cattle hoofprints in the shallow wetlands of the Burdekin region increases available breeding sites for mosquitoes, especially *Aedes* spp. (Hearnden pers. comm. *cited in* Lucaks, 1995). However, this increase in mosquito abundance may not be desirable, particularly given the prevalence of arboviruses in northern Australia.

Literature from elsewhere in Australia has shown that many fish and invertebrates are susceptible to sedimentation, either through loss of interstitial habitat, suffocation (in gill breathing animals) or smothering of eggs. Given that several studies have described increased sediment inputs to wetlands as a result of grazing, it is likely that grazing induced sediment effects are widespread in northern Australia. This view is supported by a recent study conducted in Kakadu National Park, NT comparing two streams, one of which had undergone sedimentation in association with construction of a road crossing (Stowar *et al.* 1997.). The study found strong turbidity-related effects for macroinvertebrate communities inhabiting rootmat habitats. The communities from the sedimented sites were characterised by lower abundance of macroinvertebrates, particularly Chironomidae. Effects were not detected in sand habitats, probably due to the greater temporal and spatial variability in these communities.

5.3.2. Fish

The only direct evidence of grazing effects on fish relate to the decline of Red-finned Blue-eye (*Scaturiginichthys vermeilipinnis*) from the Edgbaston Spring complex in central Queensland. This species was described from six artesian springs in 1991. Since then it has disappeared from two springs and is now listed as endangered. The Action Plan for Freshwater Fishes (Wagner and Jackson 1993) identifies habitat destruction due to trampling, watering and grazing of cattle, and the excavation of the springs to increase water storage for stock watering, as factors that may have contributed to the decline of Red-finned Blue-eye.

6. Weeds

6.1. The link between grazing and weeds

The spread of weeds is one of the greatest threats to Australia's biodiversity (Humphries *et al.* 1991). The current and potential distribution of environmental weed species is discussed in detail in Humphries *et al.* (1991). Tropical wetlands and riparian habitats are particularly susceptible to weed invasion and of the top 18 environmental weeds, Humphries *et al.* (1991) list 14 as occuring in wetlands or riparian areas in northern Australia. Eight of these are clearly linked to aspects of cattle grazing, as discussed below, although other land management practices may also be involved with their spread and dispersal.

Grazing may influence the effects of weeds in riparian areas and wetlands in a number of ways. Grazing can result in trampling and erosion of riparian and wetland areas and this physical disturbance may make these areas more susceptible to weed invasion. Furthermore, selective grazing may prevent the regeneration of native species and facilitate the establishment of weeds. For example, preliminary observations indicate that grazing promotes the invasion of Rubber Vine (*Cryptostegia grandiflora*), which is a major threat to riparian habitats in Queensland (Stanton pers. comm., cited in Humphries *et al.* 1991). The interaction between grazing, fire and Rubber Vine establishment, however, needs further investigation to determine the mechanism by which grazing appears to promote weed invasion (Humphries *et al.* 1991).

In northern Australia, many of the weed species listed as threats to wetland and riparian areas are spread by cattle. Cattle can assist in the dispersal of weeds into wetlands and riparian areas by transporting seeds either through their faeces or attached to their skin. Species spread by cattle include Parkinsonia (*Parkinsonia aculeata*), Rubber Vine (*Cryptostegia grandiflora*), Prickly Acacia (*Acacia nilotica*), Mesquite (*Prosopis* spp.) (Grice 1996), Noogoora Burr (*Xanthium pungens*) and possibly Buffel grass (*Cenchrus ciliaris*) (Humphries *et al.* 1991). In addition to dispersal by cattle themselves, Prickly Acacia seedlings are becoming increasingly common along roadsides, probably as a result of cattle dung falling from roadtrains (Humphries *et al.* 1991).

Pastoral managers may actively introduce and spread exotic species in wetland and riparian areas in an effort to reduce land degradation or to provide shade or fodder for stock. Mesquite, which is currently a problem in flood-prone habitats of semi-arid rangelands in northern Australia, was originally introduced to provide shade and fodder for cattle and as a garden ornamental around homesteads. It forms dense stands around watercourses and although infestations in Australia are currently contained, it has the potential to cause great economic losses for graziers (Humphries *et al.* 1991). Buffel grass was introduced to the NT and the Kimberley as a pasture species and to ameliorate the impacts of erosion from overgrazing. The species is now well established in riparian and other mesic habitats throughout the arid and semi-arid zone.

Some species considered to be environmental weeds are still being actively spread by pastoralists to improve productivity in riparian and, in particular, wetland areas. Pasture grasses were introduced to northern Australia by pastoralists in an attempt to overcome cattle weight losses associated with declining nutritional value of native pastures during the progression of the dry season (Clarkson 1995). The benefits of ponded pastures to the grazing industry were recently summarised as: "nutritional, management flexibility, drought proofing and nature conservation" (Ponded Pastures Steering Committee 1997).

Three species introduced for grazing in wetland areas, Para grass (*Brachiaria mutica*), Aleman grass (*Echinochloa polystachya*) and Hymenachne (*Hymenachne amplexicaulis*) are included on the list of nationally important weeds. To provide an environment for these pasture species to grow, wetlands have been artificially constructed or existing wetlands "ponded" for water retention, by the construction of earth banks and levees. The practice is most widespread in Queensland, where in central Queensland alone, close to 22,000 ha of grazing land has been ponded (Coffey 1991).

6.2. The impacts of weeds associated with grazing

6.2.1. Riparian species

The environmental effects of weeds in general, are very poorly understood and this includes the effects of weeds linked with grazing (Humphries *et al.* 1991). Several posssible effects arising from wetland and riparian species which are spread by cattle, however, have been identified. Mesquite, and Parkinsonia, for example, have the ability to alter the hydrology of wetlands by using significant amounts of water, making them even more susceptible to further invasion (Humphries *et al.* 1991). Both species threaten the ephemeral wetlands on the Barkly Tablelands, NT and in central Queensland. These are nationally significant wetlands of great importance to waterfowl. Both weed species can grow in very dense stands around riparian areas, inhibiting wildlife movement and access. On the Barkly Tablelands, for instance, Parkinsonia is believed to limit water bird access to wetland edges which serve as important feeding areas (Jaensch *et al.* 1995). Rubbervine is also known to choke native vegetation in riparian areas (Humphries *et al.* 1991) and thus remove important habitat for birds (Humphries *et al.* 1991).

Another impact of weeds able to grow in riparian areas is their potential to modify fire regimes. For example, it has been suggested that Buffel grass has displaced native vegetation in key riparian habitats in central Australia, making these areas more susceptible to hotter and potentially more damaging fires (Humphries *et al.* 1991).

6.2.2. Ponded pastures

The widespread and increasing use of ponded pasture species has become a contentious issue. This has lead to the formation of the Ponded Pastures Steering Committee which recently released the Ponded Pastures Policy Options Paper (1997) for public comment. This report documents major concerns associated with ponded pastures and presents policy options to address these issues.

One of the major concerns with ponded pasture species is that they can spread from grazing areas to become weeds in native wetlands (Cowie and Werner 1993; Clarkson 1991; Clarkson 1995). The propensity for ponded pasture species to spread is exacerbated by the presence of water as flooding can break up plant material and distribute it to new areas (Clarkson 1991). The spread of ponded pasture plants into wetlands outside the pasture system, poses a potentially serious threat as the plants may compete with native vegetation species, reduce biodiversity and affect ecosystem dynamics (Clarkson 1995). Ponded pasture species also have the potential to smother banks and inhibit natural recruitment of riparian species (Humphries *et al.* 1991).

Altering existing wetlands or creating new ones also has the potential to significantly affect marine, aquatic and terrestrial wildlife (Chuk 1991). The capacity of wetlands to support a diversity of wildlife depends on the diversity of wetland habitats. Whitehead *et al.* (1992) suggest that widespread modification of wetlands to achieve pastoral objectives will probably reduce the range of wetland habitats. They suggest that the homogeneous and regulated floodplains will lack the idiosyncratic response to variable rainfall that currently maintains habitat diversity.

Para grass is one of the more well-known ponded pasture species to become a serious weed in Queensland and the Northern Territory. This species is known to displace a range of native species, particularly those that occur along the margins of wetlands where the greatest diversity of vegetation occurs. As monospecific vegetation displaces the diverse natural vegetation on these fringes, many of the dependent faunal species, such as wading birds, are also displaced (Clarkson 1995). For example, in Eubanangee National Park and Townsville Town Common Environmental Park in Queensland, Fisk (1991) notes that fauna dependent on vegetation growing along wetland margins, such as brolgas which feed on Bulkuru bulbs, suffer a serious decline in food resources. He also notes that Para grass produces large amounts of dead organic matter which alters the hydrological system by restricting flow and changing the topography. This subsequently affects plant assemblages. A recent study in the NT showed that Para grass had displaced large areas of wild rice (*Oryza rufipogon*) on the Magela Creek floodplains of Kakadu National Park (Finlayson pers. comm.). This displacement of wild rice is thought to adversely affect the Magpie Goose (*Anseranas semipalmata*) as it relies on seeds of wild rice at critical periods of its life-cycle (Frith and Davies 1966).

There is also widespread concern that construction of levees and barriers to retain water for ponded pastures, may significantly affect the passage of migratory fish. Fisherman in Queensland have expressed concern about the potential effects on fish stocks that may result from creating artificial barriers to fish movement. The inhibitory effect on fish movement, of barriers arising from river and wetland regulation, has been well documented in the southern states. Barriers to fish passage can cause high concentrations of fish in a given area, leading to a deterioration in water quality and consequent increases in mortality. Fish mortality is known to increase when water quality fluctuates, especially in shallow, heavily vegetated locations. In the NT, fishery managers are also concerned that ponded pastures will prevent freshwater runoff to estuaries, reduce primary productivity in these habitats, and prevent migration of juvenile barramundi (Griffin 1995). Garrett (1991) points out that barriers can interfere with the role of marine plains as nursery areas and refuges for the juvenile stages of many estuarine species.

McCabe (1991) outlines other potentially negative effects of ponded pastures including:
- the alteration of tidal flow and freshwater/saltwater interactions;
- the potential for diversion of freshwater from rivers and streams leading to loss of water quality in freshwater systems;
- the provision of major mosquito breeding areas where natural controls may be ineffective;
- disruption to natural equilibria between native wildlife species, potentially displacing some while concentrating others in areas rated as prime stock production sites — this may ultimately result in pressure to cull wildlife; and
- where ponding occurs in tidal locations, restriction to movement and breeding of fish and crustacea, and elimination of habitat significant for a range of waterbirds, particularly those that prefer shallow saline water to deeper freshwater (Chuk 1991).

To date, the spread of ponded pastures into native wetlands is a more contentious issue in Queensland than in the Northern Territory. While para grass is the only ponded pasture species to have become a widespread weed in coastal Queensland, there is concern that other more recently introduced ponded species will follow a similar pattern (Clarkson 1991). Clarkson (1991) cites an example of the proposed introduction of new ponded pasture species in the Kennedy and Normanby Rivers catchment in the southern Cape York Peninsula. This proposed introduction, despite known information on the behaviour of these species and their potential to become serious weeds, highlights shortcomings in the guidelines for, and process of, the introduction of pasture species to Australia.

In Australia, knowledge about weeds which pose a threat to the natural environment is extremely poor (Adair 1995). In many cases even the most basic information about these weeds, such as their distribution, abundance and basic control options, is lacking (Humphries *et al,* 1991). Humphries *et al.* (1991) recommend that the first and urgent step is to provide formal documentation of the potential threat to conservation of the various species. Although ponded pasture species have been identified as posing an acute risk to ecosystems over their continental range, there have been few investigations of their effect on wetland biodiversity or ecosystem processes. Most of the potential effects, listed above, of ponded pastures species are based on casual observation with few studies having attempted to quantify the threat they pose.

Research conducted in Bamboo Creek in far north Queensland, showed that although Para grass was very abundant in stream and riparian areas, it contributed little to aquatic food webs (Bunn *et al.* 1997). A project is currently underway in wetlands of the Townsville area, to assess the effect of grazing on the density of Para grass and native plant and bird species (P. Williams pers. comm.). A second project to assess herbicide control measures for the spread of *Hymenachne amplexicaulis,* which is considered to be even more invasive than Para grass (P. Williams pers. comm.), is being undertaken in the Tully area. In the NT, a project has recently commenced which will compare the fauna and ecosystem processes on floodplains in Kakadu National Park, in areas with and without Para grass (M. Douglas, pers. comm.). The project aims to determine the effect of Para grass on biodiversity and wetland processes and to assess the effectiveness of chemical control methods. Similar studies in other areas and with other species are urgently required to enable adequate assessment of the potential threat of ponded pasture species and to determine management priorities.

It should also be noted that while ponded pastures are considered by many to be one of the most significant effects of grazing on wetlands, others have highlighted the beneficial aspects of these pastures. Also, once ponded pasture species have been introduced, it may be beneficial to maintain grazing of the wetlands to keep these plants in check. Removal of grazing from seasonal wetlands in the coastal sedge swamps of the

Burdekin-Townsville area, for example, has had catastrophic effects with respect to changes to vegetation dynamics (G. Blackman, pers. comm.). The Townsville town common, for example, previously regarded as an important wetland of high conservation value, has been overrun with para grass since the removal of cattle. This highlights the complexity of the relationships between grazing and wetland vegetation in northern Australia, and also shows the need for more research.

7. Fire management

Fire is widely used to manage native pastures in northern Australia (Anderson *et al.* 1988). While the type of fire regime varies between regions and individual pastoralists, it is worth reporting some recent evidence which shows a clear link between this form of land management and riparian and aquatic biota. A study carried out in Kakadu National Park, NT, compared replicate catchments subjected to two contrasting fire regimes - no burning versus annual late-dry season burning (Douglas and Lake 1996). Burning had a detrimental effect on riparian vegetation, resulting in decreased richness and abundance of woody species and vines. In contrast, burning lead to increased species richness and abundance of aquatic macrophytes and increased richness (though not abundance) of aquatic invertebrates (Douglas and Lake 1996). Research is continuing to look at the effects of other fire regimes and recovery after the removal of fire (M. Douglas, pers. comm.). While this study demonstrates that there are links between fire and wetland and riparian habitats, further research is needed into the effect of other fire management regimes and on the effects of interaction between grazing and fire.

There are also a number of reports on fire regimes and weeds linked to grazing. Observations suggest that there is an interrelationship between burning on floodplains and areas of introduced pasture species and native vegetation in the Northern Territory (P. Whitehead, pers. comm.). As mentioned above, Buffel grass has the ability to invade riparian habitats in central Australia and can increase the intensity of fires and the extent of areas burnt. Consequently Buffel grass has probably altered the fire regime of riparian habitats, possibly to the detriment of the birds and mammals that rely on these areas (Humphries *et al.* 1991). In contrast, grazing in riparian areas Queensland has kept fuel loads at low levels and helped to facilitate the establishment of rubber vine. Following the removal of stock, fuel loads have increased allowing the use of more intense fires which can help to control the weed (Humphries *et al.* 1991; Grice 1997 and references therein).

8. Effects of buffalo on wetlands and riparian zones

Although buffalo were considered to be outside the scope of this review, they are mentioned briefly as they illustrate the effects that heavy grazing can have on wetland and riparian habitats in northern Australia. It is acknowledged, however, that buffalo differ from cattle in the way they graze and use the landscape and hence, many reported effects of buffalo may not be applicable to cattle grazing.

Small herds of buffalo were introduced into the Northern Territory in the late 1820's during early settlement attempts (Skeat *et al.* 1995). By the 1970's buffalo numbers were estimated to be over 280, 000 animals (Skeat *et al.* 1995). In recent years their numbers been dramatically reduced through the brucellosis and tuberculosis eradication and control (BTEC) program and now very few wild buffalo remain.

The most comprehensive review of the impact of feral water buffalo in northern Australia, is by Skeat *et al.* (1995). They summarise the primary effects of buffalo grazing as:

1. a reduction in vegetation biomass, changes in species composition, weed dispersal, and, locally, complete removal of vegetation;
2. compaction of soils and soil erosion;
3. changes to surface hydrology including reduced retention of water in flood basins and intrusion of saltwater into freshwater swamps; and
4. increased turbidity in water bodies due to trampling, wallowing and grazing, as well as contamination by buffalo faeces and urine.

Effects on native fauna include:

1. suppression of small vertebrate populations on the flood plains, probably related to removal of ground cover;
2. no effect on the number of magpie goose nests, but a shift in distribution away from floodplain margins and possible adverse effects on dry season swamp refugia contributing to population decline; and
3. adverse effects on pig-nose turtle populations through trampling of nest sites and habitat destruction, resulting in negligible recruitment (Georges and Kennett 1989).

Most of these reported impacts are qualitatively similar to those discussed for cattle grazing. Certainly the observation by Skeat *et al.* (1995), that the effects of buffalo on one part of the ecosystem often compounded effects on others, is directly applicable to cattle. For example, in both cases, loss of vegetation and soil compaction both contribute to accelerated soil erosion, while soil compaction and changes in surface hydrology will affect the composition of the vegetation. However, perhaps the most devastating impact of buffalo — the creation of swim channels linking freshwater wetlands to tidal creeks that result in saltwater intrusion — is also the least likely to occur as a result of cattle grazing.

9. Repair of degradation

There appear to be few data available that enable assessment of the effectiveness of management practices to repair wetland and riparian habitats damaged by cattle grazing and use. Although there are a range of methods which may be useful in rehabilitation — from simply reducing stocking rates to reseeding and replanting — we do not know whether these procedures will be successful in allowing re-establishment of the ecosystem processes and landscape functions have been disturbed. Restoration of such processes is necessary for complete rehabilitation (Ludwig and Tongway 1996). As discussed elsewhere in this report, we have only a fragmented understanding of the effects of grazing on the ecological processes in wetlands and riparian areas of northern Australia.

In addition, successful and cost-effective vegetation re-establishment requires an understanding of the regeneration ecology of desired species (Ray and Brown 1994). For many species in northern Australia however, this basic information is very limited. For instance, the factors restricting regeneration of one of the most widespread trees in northern Australian savannas (*Eucalyptus miniata*), were only recently identified (Setterfield *et al.* 1993). This research has provided a basis for developing restoration guidelines for degraded savannas (Setterfield *et al.* 1993). There is no indication that restoration techniques necessary for wetland (or riparian) habitats are any better known (Cook and Setterfield 1995). The challenge is even greater for the re-establishment of fauna as this requires an understanding of the habitat requirements pf particular species as well as the successful re-establishment of such habitat.

Efforts to mitigate erosion in riparian areas, and elsewhere in catchments, have received most attention. A study which monitored the effectiveness of erosion control measures in the Ord River Catchment (P. Novelly, pers. comm.) found that while revegetation had been effective in much of the catchment, complete removal of stock was the only way to allow sufficient vegetation regrowth to control gully and streambank erosion. A study currently underway in the Desert Uplands (M. Lorimer, pers. comm.) will use experimental exclosures to examine how different land types can withstand grazing pressure and the management needed to restore degraded land to a useful level of productivity. The study is relevant to this review as it is being conducted in an area with soils susceptible to degradation, and in a catchment containing two significant wetlands — Lake Buchanan and Lake Galilee.

A noteworthy example of a cost-effective management technique for the protection of riparian zones was reported by Sattler (1993). The Heytsbury Pastoral Group have undertaken extensive fencing of riparian areas along the Victoria River, in the Northern Territory. Areas up to one kilometer wide have been fenced off from the river and off-stream watering provided. Stock are excluded from the riparian area except in times of drought, when the area is used to provide relief grazing. The company considers this management practice to have been cost neutral, with the initial expense being offset by savings in fewer bogged cattle, reduced time spent checking the river for stock and more efficient helicopter mustering. It is recognized, however, that fencing off large areas of riparian habitat may not be an option for much of the rangelands in northern Australia.

Research is needed on the practical application of restoration techniques. Experimental trials and assessment of the success of different techniques, are essential for evaluating the costs and benefits of alternative methods.

10. Current and proposed research

A summary of current and proposed research into the effects of grazing on wetland and riparian biota and water quality is given in Attachment 1. Most of the studies listed have been undertaken in the Northern Territory and Queensland, with far fewer studies carried out in northern Western Australia. In the NT, the majority of listed studies are in the Alligator Rivers region, though few of the studies relate directly to grazing impacts. Most of these projects have been carried out by either the Parks and Wildlife Commission of the Northern Territory (under the auspices of the CRCSDTS) or the Northern Territory University. Most of the studies listed for Queensland have been around Townsville or in the Burdekin River Region. These have been carried out predominantly by the Australian Centre for Tropical Freshwater Research at James Cook University or through the Queensland Department of Environment and Heritage. Some projects have been carried out by the Centre for Catchment and In-Stream Research at Griffith University or the CSIRO.

In riparian habitats, most research has focussed on birds, while macroinvertebrates are the most commonly investigated taxa in wetland habitats. There have been surprisingly few investigations of the direct effects of grazing on riparian or wetland vegetation and very limited research into the effectiveness of different rehabilitation techniques.

It should be remembered that this is not an exhaustive summary of current and proposed research as not all organisations were able to respond within the time-frame of this overview. Therefore, these trends should be interpreted with some caution.

11. Conclusions

Clearly this report cannot provide a comprehensive assessment of the effects of the northern Australian grazing industry on wetland and riparian habitats. The extreme paucity of information means that it is only possible to highlight the potential effects of grazing and note those (few) studies where these effects have been demonstrated. Many of the studies reporting effects of grazing relate to situations where stocking rates were clearly unsustainable and overgrazing had occurred. There possibly are levels of grazing at which none of the potential deleterious effects are realised, or, there may be levels of grazing at which the benefits (such consumption of weeds) outweigh the adverse effects. However, on the basis of available information, it is impossible to determine whether this is the case. We therefore reiterate the recommendation of Bunn *et al.* (1997) that a priority for future research should be determining sustainable levels of grazing and cattle use in riparian areas. Levels should be such as to ensure the maintenance of biodiversity and ecosystem function.

Much of the literature on this topic is speculative or at best, based on casual observation. More effort needs to be placed on quantitative and preferably experimental approaches. Studies will often need to be conducted over large areas, as many of the potential effects of grazing on wetlands arise from use in other parts of the catchment. Of particular importance is the need for studies to be conducted not only over a year, so as to incorporate the marked seasonal variation within the wet-dry tropics, but for sufficiently long periods to include the considerable interannual variation in rainfall, particularly in arid and semi-arid areas. Encompassing the annual variation in rainfall is necessary as it determines the patterns of movement of both stock and native biota and their degree of dependence on wetland and riparian areas. It is essential to obtain information during the critical dry periods, when these habitats act as refugia for native fauna.

Every effort should be made to integrate studies on the effect of grazing on the physical and biological components of ecosystems. The expense of experimental work, particularly where it involves manipulation of grazing over large areas, is invariably high. Multidisciplinary approaches should be pursued, not only to maximize the use made of experimental procedures, but also to allow interactions between physical and biological components to be investigated.

Very often we do not know the most effective techniques for restoring or rehabilitating particular riparian areas and wetlands. Often we do not know the important characteristics, and their quantity and spatial arrangement, that need to be re-established (for example, the particular vegetation composition and structure required for particular animal species). While many Landcare and other restorative programmes are underway, research is needed to provide a sound scientific basis for these schemes. Monitoring and assessment of the success of these programmes should also be a priority.

While any new research should be targeted to the specific needs of northern Australia, it should be done in the context of the relevant national R&D Programs — the National Wetlands R&D Program, the National Riparian R&D Program and the National River Health Program. In particular, new research should be consistent with the specific recommendations in the National Wetlands R& D Program Scoping Review (Bunn *et al.* 1997) for future R&D relating to grazing and weeds. Their recommendations are that R & D should: determine the effect of different levels of grazing on wetland structure and function; plan and develop integrated grazing systems; and determine sustainable stocking rates in different wetland types.

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ATTACHMENT 1 — CURRENT AND PROPOSED RESEARCH

Contact	State	Catchment/Region	Issue	Status	Organisation	Division
Douglas	NT	Alligator Rivers Region	Fire and aquatic vegetation	Current	NTU	CTWM
Douglas	NT	Alligator Rivers Region	Fire and macroinvertebrates	Current	NTU	CTWM
Douglas	NT	Alligator Rivers Region	Fire and riparian vegetation	Current	NTU	CTWM
Stowar *et al.*	NT	Alligator Rivers Region	Fish and erosion	Completed	ERISS	
Stowar *et al.*	NT	Alligator Rivers Region	Macroinvertebrates and erosion	Completed	ERISS	
Douglas *et al.*	NT	Alligator Rivers Region	Para grass	Proposed	NTU	CTWM
Jaensch	NT	Barkly Tablelands	Birds in Riparian	Completed	PWCNT	
Reid	NT	Central Australia	Birds in Riparian	Completed	CSIRO	
Whitehead	NT	Mary River	Grazing of wetland vegetation	Current	PWCNT	
Woinarski	NT	Micthell Grasslands	Birds in Riparian	Proposed	PWCNT	CRCSDTS
Woinarski	NT	Various	Birds in Riparian	Current	PWCNT	CRCSDTS
MRHI	NT	Various	Macroinvertebrates	Current	DLPE	
Dostine	NT	Various	Macroinvertebrates in Riparian	Current	PWCNT	CRCSDTS
Cheal	NT	Various	Plants in Riparian	Current	PWCNT	CRCSDTS
Haytesbury	NT	Victoria River District	Rehabilitation	Current		
Boekel	NT	VRD	Birds in Riparian	Completed	?	
Douglas		Various			NTU	CRCSDTS
Bunn and Davies	QLD	Bamboo Creek, Innisfail	Para grass	Completed	GU	CCISR
Arthington	QLD	Brisbane River	Macroinvertebrates	Completed	GU	CCISR
Arthington	QLD	Brisbane River	Water quality	Completed	GU	CCISR
Brown	QLD	Burdekin	Landscape restoration*	?	CSIRO	CRCSDTS
Lucaks	QLD	Burdekin	Grazing of riparian vegetation	Completed	JCU	ACTFR
Lukacs	QLD	Burdekin	Grazing of wetland vegetation	Completed	JCU	ACTFR
Lucaks	QLD	Burdekin	Water quality	Completed	JCU	ACTFR
Bunn and Davies	QLD	Cooper Creek	Algae trampling	Current	JCU/UWA	CCISR
Lorimer	QLD	Desert Uplands	Rehabilitation	Current	QDEH	
Rowley	QLD	Gulf	Birds in Riparian	Completed	CSIRO	
Williams	QLD	Townsville	Hymenachne	Current	QDEH	
Pearson	QLD	Townsville	Macroinvertebrates	Completed	JCU	ACTFR
Williams	QLD	Townsville	Para grass	Current	QDEH	QNPWS
Brown	QLD	Townsville	Riparian biota/water quality	Current	CSIRO	TA
Pearson	QLD	Townsville	Water quality	Completed	JCU	ACTFR
MRHI	QLD	Various	Macroinvertebrates	Current	QDPI	
Rowley	WA	Kimberley,	Birds in Riparian	Completed	CSIRO	
Woinarski	WA	Kimberley, Purnululu	Birds in Riparian	Completed	PWCNT	
Pettit	WA	Ord River	Riparian vegetation	Current	ECU	
Davies	WA	Pilbara	Water quality	Completed	UWA	
MRHI	WA	Various	Macroinvertebrates	Current	WAWA	

List of organisations and divisions

ACTFR	Australian Centre for Tropical Freshwater Research
CCISR	Centre for Catchment and Instream Research
CCNT	Conservation Commmission of the Northern Territory
CRCSDTS	CRC for the Sustainable Development of Tropical Savannas
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CTWM	Centre for Tropical Wetlands Management
DLPE	Department of Lands Planning and Environment
ECU	Edith Cowan University
ERISS	Environmental Research Institute of the Supervising Scientist
GU	Griffith University
JCU	James Cook University
NTU	Northern Territory University
PWCNT	Parks and Wildlife Commission, NT
QDPI	Queensland Department of Primary Industry
QNPWS	Queensland National Parks and Wildlife Service
TA	Tropical Agriculture
UWA	University of Western Australia
WAWA	Western Australian Water Authority
WRD	Water Resources Division

* see description on next page

Landscape Restoration (Indicators of Sustainable Landuse Program)

Dr Joel Brown,
CRC for the Sustainable Development of Tropical Savannas,

Background: Exotic weeds are a major threat to both the productive capacity and the native ecosystems of northern Australia. Because these invasions are recent in origin, much of the potential range has yet to be occupied. Even within the current range, many landscapes are occupied only by discrete subpopulations. There is a genuine opportunity for focussed management to both limit the spread and reclaim landscapes already invaded.

Over the past ten years, work by state and federal research agencies has identified techniques for both containing invasions at current levels and removing weeds from small areas. However, the application of these techniques is only sporadic because of high treatment cost/land value ratios and climatic variability. One way to improve the economic effectiveness is to lengthen the time-frame across which treatments are applied. By extending the time-frame, the cost in any one year can be reduced and risk can be minimised. However, by applying treatments to selected portions of the landscape over a longer period of time, reinfestation is a risk. This project seeks to overcome these problems by developing a new approach to planning and implementing landscape restoration strategies, tactics and operations by considering both ecosystem and invasive plant attributes and the technologies available. The project will use research theory and techniques developed from landscape ecology and spatial analysis to develop a better understanding of the impact of degrading processes and what are the most cost effective restoration techniques using weeds as a model.

Objectives:
1. Develop a computer based Geographic Information System of *Cryptostegia grandiflora* distribution, soil property distribution, infrastructure and topography in two subcatchments by June 1997.
2. Develop a mechanistic model of *Cryptostegia* invasion patterns based on dispersal attributes, habitat suitability and climatic patterns by June 1997.
3. Using the models developed in 1 and 2, test alternatives for management of *Cryptostegia* at the subcatchment (<500,00 ha) scale in two areas by December 1997.
4. In collaboration with local land managers in the test catchments, implement a program of field experiments to validate the model by March 1998.
5. Test the model with other weed species in other catchments by December 1998

Methods: The application of mathematical models to determine where and when woody weed populations are most vulnerable offers an opportunity to improve the basis for managing weed populations. This project will use mathematical models in conjunction with field-based research programs to parameterize and validate the models. Population biology (dispersal, seed ecology, seedling ecology, life histories) data has largely been collected and working models are available. Information on the local impact of various control technologies (mechanical, biological, chemical, fire) is also available and disturbance—population relationships are quantified. A collaborative project between CSIRO-DTCP, UQ and CRC-TPM is currently underway to use GENSECT to predict large scale (5 km^2) patterns of weed spread across the tropics in response to different temperature, precipitation, atmospheric chemistry and land management change scenarios. RIRDC has funded the work for three years (1995-1998).

The next task is to apply spatially explicit models to provide testable hypotheses for applying control technologies at the landscape scale. There has been success in the area of conservation biology via the application of meta-population models to identify the most vulnerable sub-populations of endangered species. The output of these models has been used to predict which sub-populations are most critical to maintenance of the meta-population. As yet, there have been no attempts to apply this modelling technique to local eradication of undesirable species. In addition, other models of the impact of the spatial distribution of disturbance (percolation, diffusion, semivariance etc) and the impact on ecosystems may provide improvements in the design and implementation of land restoration programs. Using these techniques has much potential as the weed species in question have relatively long lifespans, short seedbank lives, restricted dispersal ranges, recruit only episodically, and are reasonably easy to detect remotely.

Potential Outcomes:

1. Field tests of metapopulation theory as an organising principle for weed and pest management programs.
2. Design procedures for optimising public investment in weed and pest management programs.
3. Improved decision making aids for individual land managers and Landcare organisations.

Review 3

SALINITY AND NITRATE CONTAMINATION OF GROUNDWATER

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Contents

1. Summary

This review broadly assesses the potential for salinization of soil and surface water, and for nitrate contamination of groundwater, as a result of tree clearing and the establishment of introduced pasture. In the case of nitrate contamination of groundwater, potential for contamination would mainly be associated with introduction of leguminous species, nitrate fertilizer not having had very much use in the grazing industry.

Potential for soil and water salinisation is regarded as existing in both Queensland and the Northern Territory and broad assessments of areas which are susceptible to salinization have been carried out but these represent only a first approximation. No relevant literature on the potential for salinity was found for north-west Western Australia. The major issue seems to be the extent to which groundwater recharge is likely to increase following clearing and/or the establishment of introduced grasses. Modelling work carried out to date suggests any increase in recharge is likely to be episodic. The potential for increased recharge is also likely to be highly variable for the different climatic regimes and landscapes across northern Australia, and further work to determine the variation in this potential is necessary to ensure development of sustainable land use practices. However, given that salinity can only occur where there is significant salt storage in the landscape, studies to determine the land types likely to be associated with such storages should not be ignored.

With respect to nitrate contamination of groundwater, some groundwaters in the arid zone and in Queensland have been found to have nitrate-N in excess of recommended levels set for drinking water quality. In one area of the arid zone, this contamination was attributed to nitrate leaching from termite mounds. The potential for nitrate contamination of groundwater under leguminous pasture does not appear to have been investigated. While it is considered unlikely to be a problem, the current study on *Stylosanthes* pastures being funded by the MRC will probably provide data that indicate whether there is potential for such contamination for several soils and climatic regions.

2. Potential for soil and water salinization

The potential for soil salinization occurs where salt is stored in the regolith (including aquifers) and where the hydrological regime is such that changes to the vegetation can so alter components of the water balance that there is an increase in groundwater recharge and rise in saline watertables. Of interest here are the changes that can be produced in the hydrological regime by practices associated with grazing management, in particular, tree clearing and the establishment of introduced pasture species.

Dryland salinity as a result of replacing perennial deep rooted trees and shrubs with generally shallow rooted and often annual plants, is widespread in southern Australia. The extent and severity of the problem is such that millions of dollars are now being spent in research, extension and on-ground remediation programs to prevent further degradation and to reinstate the productive capacity of now saline land. To date, dryland salinity in northern Australia has not developed to anywhere near the same extent as in the south. There are differing views as to whether this is purely because tree clearing has not yet occurred on the same scale in the north, or whether it is because the potential for dryland salinisation is much lower. One view is that the dominance of summer rainfall results in a reduced risk of increased recharge compared with the winter dominant rainfall of the south. This line of reasoning assumes that the high evapotranspiration rates in summer result in most rainfall being taken up by plants even if there is a change to a shallower rooting system. Other scientists, however, point out that factors in addition to evapotranspiration, influence soil water regime following clearing. In particular, rainfall regime (the amount of rainfall and sequence of rainfall events), soil permeability and soil water holding capacity are also important.

This section reviews what is known of the current distribution of dryland salinity in northern Australia and work that aims to determine the potential for development of dryland salinity in northern Australian environments. This work covers that investigating extent and distribution of salt storages, as well as that concerned with the distribution of landscape characteristics likely to increase the potential for increased recharge and rise in watertables. Specific investigations of changes in components of the water balance are discussed in detail in Review 4, although reference is made here to the relevant work.

2.1. Queensland

2.1.1. Distribution of saline soils and areas with secondary salinity

In 1990, the Queensland Department of Primary Industries (QDPI) undertook a survey of the known area of land affected by salinity resulting from dryland and irrigated agriculture, via a questionnaire sent to government bodies associated with primary production (Gordon, 1991). A total of 10 000 ha were reported as being affected by secondary salinity (both dryland and irrigation) throughout Queensland, with a further 73 000 ha regarded as susceptible. Areas of secondary salinity were reported from all regions although their greatest prevalence was in Central, South-east and South Queensland (Figure 1).

1. North Queensland: in this region, dryland salinity was associated with colluvial and alluvial materials, with outbreaks along toe slopes. Soils identified as susceptible to salinity were those with large salt storages in the lower profile and situated in landscape positions vulnerable to water balance changes. Assessment of the probability of secondary salinization following development was highly recommended for this region.

2. Western Queensland: only 26 ha were identified as being affected by secondary salinity. Saline areas were associated with light or medium clay alluvial soils. The low area affected was attributed to the low rainfall which is considered to reduce the opportunity for recharge and the development of hydrologically driven salinity problems in the region.. More information on depth to watertables was considered necessary to further evaluate the potential for future development of salinity.

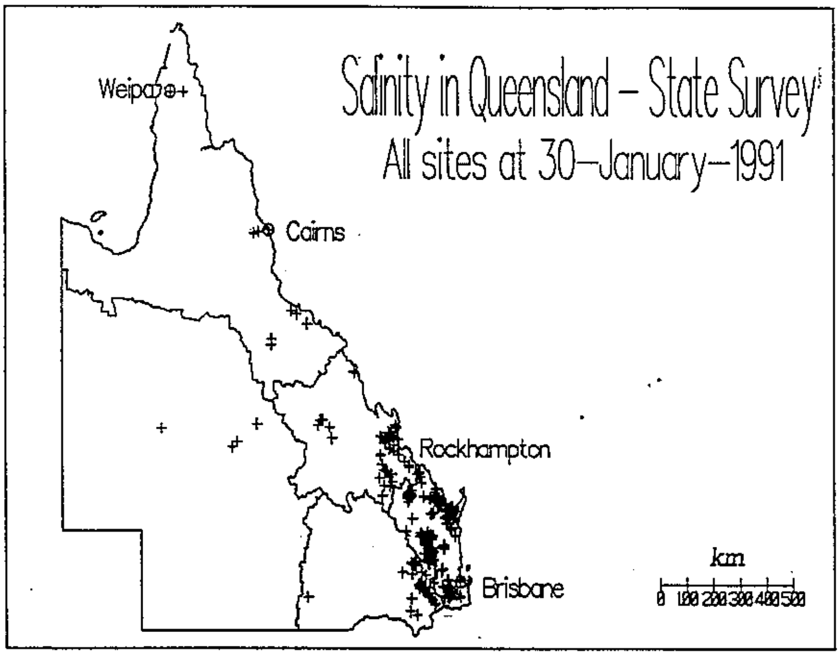

Figure 1. The distribution of areas with secondary salinity identified in the 1990 survey in Queensland (From Gordon 1991)

3. South Queensland: 2400 ha of salt affected land were identified, with the major occurrences located on the Eastern Downs and some in the traprock country around Stanthorpe and Inglewood. Most of this salinity occurs as seepage or watertable forms in areas where clay soils (mostly derived from basalt)

overlie sandstone. A further 3200 ha were regarded as susceptible to salinity, with most of this area also associated with landscapes where basalt overlies sandstone.

4. Central Queensland: This region had the second largest area of recorded secondary salinity, with most of the 3500 ha affected being in the Rockhampton, Biloela and Emerald regions with a small area near Mackay. Salting in the Rockhampton area was primarily associated with clearing on the more permeable basalt soils and subsequent watertable elevation. The low slopes associated with these soils result in large areas of land being affected when the watertable rises to near the surface. In the upland areas, salinity occurs on a variety of soils in response to a geomorphological restriction to catchment outflow of water. Around Biloela and Emerald, salting often occurs on soils on sandstone, with the excess water causing the problem derived from clearing of adjacent permeable basaltic soils.

5. South East Queensland: The largest area of salt affected land in Queensland occurs in the South-east. Although the survey report gives only 3344 ha affected, this documents only major outbreaks. Numerous small areas affected by salinity takes the total area affected to nearer to 9665 ha. The localities most affected are the Lockyer valley, the Ipswich/Boonah Shires, the Monto/Eisvold district and the Bundaberg area (associated with sugar cane). The area of land regarded as susceptible to secondary salinity is 57 000 ha. In this region, irrigation as well as dryland salinity is important.

More recently, the CSIRO Division of Soils and QDPI have completed a survey of the soil and land resources of the Dalrymple Shire. The report is not yet available and hence areas identified by this survey as being affected by dryland salinity could not be determined. As part of the survey, soils at 1000 sites were sampled to 2 m and were analysed for pH and EC on 1:5 soil solution extracts. These data were used in the assessment of potential for dryland salinity development, described in Section 2.1.3. below.

There have been several land system surveys covering relatively extensive areas of Queensland but these have not been assessed for the information they contain relevant to salinity. Adrian Webb (cited in Yule 1989) found changes in soil salinity associated with clearing Brigalow where virtually all soils had high salinity levels at shallow depths under the native vegetation.

2.1.2. Salinity of ground and surface waters

No attempt was made during this review to obtain information on the salinity of the groundwater resources of Queensland though, from the work on salinity risk mapping in the Upper Burdekin, it is apparent such data are available. Moss *et al.* (1996) note that the Queensland Water Quality Atlas (QDPI 1994) shows an increasing trend in surface water salinity for much of Queensland with deceases only in undeveloped areas or where land use has reverted to less intensive agricultural practices. Gordon (1991) also noted the development of stream salinity problems in the traprock country near Inglewood.

2.1.3. Assessments of potential for development of dryland salinity

There have been several projects investigating the inherent susceptibility of different landscapes to salinization. Two of these, the study in the Upper Burdekin and that in the Ipswich—Kingaroy area, have been based on approaches which combine landscape attributes within a Geographical Information System (GIS). A small catchment study to investigate recharge changes following clearing of brigalow (*Acacia harpophylla*) has been undertaken at the Brigalow Research Station.

(*Note on the use of the terms susceptibility, risk and hazard.* These terms are commonly used in land resource assessments though often with slightly different meanings. It is therefore appropriate to comment on how these terms are used in this review. Dictionary definitions of risk and hazard indicate both involve the connotation of an element of chance. This author considers that, with respect to degradation, the chance of (or risk, hazard of) a particular form of degradation occurring in a landscape depends both on the characteristics of the land and on the probability that the changes necessary to set particular processes in train, will occur. So for example, the risk (hazard) of dryland salinity depends both on the presence of a landscape *susceptible* to salinisation as well as on changes being made to the vegetation which can cause an increase in recharge and groundwater rise.

In this review, susceptibility to salinization is used to denote the inherent tendency of the land to become saline, and hazard and risk are both used where the likelihood of changes to the perenniality and/or rooting depth of vegetation are also considered, irrespective of how these terms may have been used in the reports from which the information has been taken. In Attachment 1, however, the terminology used is that of the project being described. For a fuller discussion of the concept of the inherent susceptibility of land to degradation see Aldrick *et al.* 1988)

1. Upper Burdekin — Dalrymple Shire

The susceptibility to salinisation of catchments in the Upper Burdekin catchment was determined in a project undertaken by the CSIRO Land and Water (Bui 1995). Catchments were found to encompass the range of possible susceptibility ratings of high, moderate and low. Definition of susceptibility ratings were:

- **high susceptibility**: groundwater depth $\leq$ 6 m and TSS $\geq$ 0.25%;
- **moderate susceptibility**: either groundwater depth < 6 m or TSS > 0.25%;
- **low susceptibility**: groundwater depth $\geq$ 6 m and TSS $\leq$ 0.25%.

Susceptibility of the landscape to salinization was determined by combining data from a number of information sources in a Geographical Information System (GIS). The data sources were:

- the digital Atlas of Australian soils (1: 2M);
- the digital geology of Australia (1: 2.5M);
- a grid digital elevation model with drainage (1: 1M);
- point observations and measurements of pH and EC from Dalrymple Shire Survey;
- borehole data with depth to aquifer, EC and major ions;
- the Queensland groundwater resources map (1: 2.5M) with information on aquifers and salinity levels.

Several assumptions were made for this assessment.

- Recharge areas were defined on the basis of permeability and drainage classes assigned to map units in the Atlas of Australian Soils. These classes were inferred from dominant principle profile forms, soil thickness, underlying bedrock and topographic position.
- Conversely, groundwater discharge areas were assumed to be topographic lows that had poor drainage and low permeability.
- Saline soils were defined on the basis of $EC_{1:5}$ > 0.7 dS/m, with no allowance made for clay content. In parts of southern Australia, soils with a lower EC value have resulted in the growth of salt tolerant plants only and bare surfaces.

Since the initial assessment, in which likelihood of increased recharge was based on an interpretation of soil profile characteristics, soil water balance modelling has been undertaken to help determine whether increased drainage beyond the root zone is in fact probable. Water balance measurements, extended by the use of the SWIM and PERFECT models (see section *Water, nutrient and sediment fluxes —plot and small catchment scale*) indicated the potential for an increase in recharge following clearing (Williams *et al.* 1997).

Williams *et al.* (1997) concluded that both factors necessary for development of salinisation (namely potential for increased recharge and high amounts of salt in the groundwater/regolith) were present in some catchments within the Upper Burdekin. The assessment of susceptibility of different landscapes to salinisation, however, was considered to be limited, requiring a better knowledge of groundwater depths and relationships between increases in deep drainage and groundwater response. This relationship depends on factors such as catchment shape, regolith stratigraphy and geological structure, aquifer properties and slope of the land surface.

2. Brigalow Experimental Catchment Study (Near Theodore)

An objective of the paired catchment study at the Brigalow Research Station was to determine the effects on catchment hydrology of clearing brigalow (*Acacia harpophylla*) and establishing pasture. Increased soil salinization was considered to be a potential problem if deep drainage increased because of the high salt storages in the regolith. The study concluded that there was little increase in recharge following clearing and hence little risk of rising watertables and development of soil salinisation (Lawrence and Thorburn 1989).

3. Ipswich and Kingaroy areas of SE Queensland

The Department of Natural Resources in Queensland has undertaken a twelve month trial, supported by funding from the National Landcare Program, to assess the potential of a technique which combines landscape attributes within a GIS, for mapping susceptibility of landscapes to salinization at 1:250 000 scale (Searle and Baillie, in prep). If successful, the intention is to use a similar approach to map susceptibility of land to dryland salinity in other areas of the State within the 700 - 1100 mm rainfall zone; the area with rainfall < 500 mm is not considered to be susceptible to salinization because of insufficient water but this has not been investigated.

Emphasis is given to identifying areas with potential for development of shallow watertables and waterlogging rather than areas with high salt storages in the soil, regolith or groundwater. Consequently features incorporated in the GIS include climate; topography; and soil characteristics such as texture, which is used as an indicator of permeability. The method involves the use of the TAPES-G program to calculate a wetness index. Where salt profile data are available, these are used to provide a recharge rating. The map developed was checked against known areas of salinity, including those identified through the Salt Watch program. If the method is extended to different regions, the information incorporated within the GIS will be adapted to include local features thought to be controlling the movement of water. This may include, for example, the presence of dykes or highly impermeable layers which result in the lateral movement of groundwater above them.

2.2. Northern Territory

The only salinity information obtained for the Northern Territory was a map of the Territory indicating the susceptibility of different landscapes to salinisation and the associated report (Tickell 1994). This report, in deriving an assessment of susceptibility of land, summarized the relevant data.

2.2.1. Available data

Unsaturated zone salt contents: other than for analyses of relatively shallow soil samples taken during soil surveys, there were virtually no data on unsaturated zone salt content. A sampling program was undertaken for the study and involved drilling to depths of up to 21 m at 116 sites spread throughout the Territory. From these sites, a very broad trend of increasing salt storage with decreasing rainfall was recognized though it was noted that the paucity of data prevented too much reliability being placed on the observation.

Groundwater salinity: The Territory has about 22 000 registered water bores. Groundwater analyses from about 9000 of these were used to obtain broad trends in groundwater chemistry. These data also showed an increasing trend in salinity from north to south. In addition, groundwater salinity classes were mapped at 1: 250 000 scale, were class values were 0-500 mg/L, 500-1500 mg/L, 1500-3000 mg/L and greater than 3000 mg/L.

2.2.2. Assessment of potential for development of dryland salinity

Assessment of the potential for different areas to become salinized was based on a Territory wide evaluation of environmental characteristics that have been found to be associated with dryland salinity. The characteristics or indicators used to construct the susceptibility map were groundwater salinity, vegetation type, median annual rainfall, aquifer yield and the presence or absence of laterite. For each indicator, a range of classes were defined which were considered to indicate different degrees of susceptibility and values were assigned to each class. The definitions of the four susceptibility categories used are given below.

High susceptibility: areas of high susceptibility require groundwater TDS ≥ 3000 mg/L; median annual rainfall between 600 and 1400 mm; vegetation of low open woodland to forest; aquifer yields of < 0.5 L/s; and laterite to be present. Salinity susceptibility indices range from 43-50.

Moderate susceptibility: a combination of physical features giving a susceptibility index in the range 33-42.

Low susceptibility: TDS < 1500 mg/L, median annual rainfall < 600 mm or > 1400 mm, and aquifer yields > 0.5 L/s; susceptibility index is 32 or less.

Very low susceptibility: areas with grassland or aquifer yields > 5 L/s were automatically rated as having very low susceptibility to salinity as there is little potential for an increase in groundwater recharge as a result of land management practices.

The report notes the very broad nature of the assessment and obvious inadequacies. For example, areas with deeply weathered profiles, which have been correlated with high salt storages, were identified from soil maps on the basis of the presence of laterite. In some areas, the laterite cappings have been removed but the weathered material underneath remains — these areas were not assigned high salt storages.

On the basis of the assessment techniques used, no areas of high susceptibility to salinisation were identified, while landscapes with moderate susceptibility are in the semi-arid areas, particularly the Sturt Plateau region. The areas with a moderate potential for becoming saline are almost entirely underlain by Cretaceous claystone with a laterite capping. The samples taken by drilling during the survey confirmed that these regoliths had relatively high salt storages.

Overall, about 6% of the Territory is regarded as having a moderate potential for dryland salinity following clearing, 34% low and 60% very low.

2.3. Western Australia

No specific studies examining potential for salinization were found for Western Australia during this review. Land resource assessment surveys were not examined to determine what information is collected about the potential for salinization, on a routine basis.

2.4. Current and proposed research

Details of current research projects are given in Attachment 1. Much of the current research is in the Balfes Creek area to the west of Charters Towers in the Burdekin catchment, the Burdekin catchment being one of the focus catchments in the National Dryland Salinity Program. Relevant projects measuring components of the water balance and changes within them as a result of land management practices, are given in Attachment 1 in Review 4.

3. Potential for nitrate contamination of groundwater

Groundwater quality has become an issue of increasing importance, with most concern about groundwater quality in agricultural areas relating to contamination by pesticides. Increased use of nitrate fertilizers for crops and the resultant increased potential for nitrate leaching to groundwater, however, has resulted in nitrate contamination of groundwater also becoming an issue in some cropping areas. Nitrates in water are toxic to humans and animals. The USA drinking water limit for nitrate-N is 10 mg/L (45g/L nitrate); the draft Australian drinking water guidelines give a limit of 50 mg/L nitrate for infants under three months, and 100 mg/L nitrate for the rest of the population. Reviewed here are investigations of nitrate contamination of groundwater within northern Australia, that were obtained during this project.

3.1. Central Australian arid-zone

Barnes *et al.* (1992) note that high nitrate-N concentrations are common in shallow aquifers of the Australian arid zone and report values of 80 mg/L in Cainozoic aquifers in the Ti-Tree Basin, Northern Territory (from McDonald 1988) and of up to 50 mg/L in Cainozoic aquifers at Ayers Rock (Yulara) (from Knott 1981).

Potential sources for high nitrate levels in arid zones have been identified as: anthropogenic, including leaching of fertilizers and animal wastes; dissolution of evaporite deposits in groundwater; and leaching of nitrate fixed by bacteria. As a result of the dependence of local aboriginal populations on groundwater resources in the Yulara region, Barnes *et al.* (1992) undertook a study that investigated the cause for the high groundwater nitrate levels in this area. Specifically, this study aimed:

- to test the hypothesis that the major source of nitrate was from biological fixation near the soil surface;
- to quantify the distribution of nitrate in surface soil layers; and
- to describe the pathways by which this nitrate may reach the watertable.

Bore-water data indicated a correlation of high-nitrate groundwaters with shallow unconfined aquifers, while aquifer hydrochemistry indicated the waters of these shallow aquifers were emplaced by episodic Holocene recharge events. The origin of nitrate was found to be near-surface biological fixation associated with cyanobacteria in soil crusts and bacteria in termite mounds. The highest soil nitrate concentrations were found in the outer skin of the termite mounds. It appears that bacteria associated with the termites fix nitrogen and that nitrate, derived from this source by a number of processes, is leached to the outside of the mound by capillary action. From there, the nitrate is flushed during large rainfall events through the unsaturated zone, which apparently lacks denitrification activity, to the watertable.

3.2. Groundwater resources of Queensland

An analysis of the QDNR groundwater quality database was recently carried out to determine the nitrate status of Queensland groundwaters (Keating *et al.* 1996). The most recent nitrate data from 15 000 bores showed 1.3% of bores exceeded the 100 mg/L nitrate limit and 2.0% exceeded the 50 mg/L limit. Bores exceeding the limit were scattered throughout Queensland although in that study there was a particular concentration on the Darling Downs and around Bundaberg. The causes for high groundwater nitrate concentrations in the non-coastal areas and away from the Darling Downs were not identified.

The importance of nitrate leaching below sugarcane, bananas and dairy pastures growing on ferrosol soils is being investigated on the north Queensland coast (Moody *et al.* 1996), though here the association is with the use of nitrate fertilizers. The episodic recharge that is considered to occur in various environments in northern Australia (see Review 4 *Water, sediment and nutrient fluxes — local and small catchment scales*) suggests that nitrate leaching to groundwater is a potential problem wherever sufficient nitrate is able to accumulate in the soil profile prior to rainfalls large enough to leach the nitrate beyond the root zone. This raises the issue of whether legume-based pasture systems have the potential to accumulate sufficient nitrate to cause nitrate contamination of groundwater. While not considered likely, the current project "*Sustainability of* Stylosanthes *based pasture systems in northern Australia: managing soil acidity*" being undertaken by Andrew Noble (see Attachment 1) should provide data that can be used to assess the potential for such leaching.

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ATTACHMENT 1 — CURRENT RESEARCH RELEVANT TO SALINITY AND NITRATE LEACHING

Salinity

See also projects relating to measurement of components of the water balance in Review 4

Groundwater resources of Balfes Creek catchment

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Objectives:

1. Locate, sample and chemically analyse all bores in the Balfes Creek catchment to define areas with saline groundwater.
2. Determine a source, concentrating and transport mechanisms for these saline waters.
3. Locate any major palaeochannels that may serve as a significant water source.
4. Describe features or types of aquifers that may be found, and help increase the success rate in drilling for water.
5. Develop a relationship between geology, soils, topography and vegetation and salinity.
6. Determine the success in predicting palaeochannels and the occurrence of salinity using Landsat imagery.
7. Promote involvement of landholders to increase awareness of salinity problems and encourage the adoption of appropriate land management practices that will lower the outbreak of salinity in high risk areas.
8. Determine if the clearing of native vegetation has contributed to the development of salinity.

Methods:

1. Bores will be located in the catchment with a GPS. Data on water level, pH, conductivity, temperature, and chemical analyses will be recorded. Bores drawing water from the same source will be defined by comparing the chemical analyses of adjacent bores. This will enable the definition of areas with saline groundwater.
2. Landsat imagery will be studied to determine if it is useful in defining features that confine saline water (eg palaeochannels). Collaborative work with soil scientists will be undertaken to aid in determining the influence of soils on the salinity. The geology will be considered as a possible source of salinity. Logs of mineral exploration holes will be used to identify major aquifers in the area. The Landsat images will be used to map known aquifers using existing bores.
3. Water balances will be modelled using PERFECT to help determine watertable rise with tree clearing.
4. A comparative study on the evapotranspiration of natural vegetation and regrowth will be undertaken to determine the water usage of each and study the influence of clearing on accessions of water to the water table, and the effect of clearing on salinity.
5. The Balfes Creek Catchment Group meets every three months to discuss the progress and future direction of the project, to keep the landholders informed and to gain information from them.

Status: Most bores have been located and sampled. An Arcview GIS including soils, geology, vegetation, cadastral, drainage, relief, and Landsat has been established. The main aquifers in the catchment are in the form of palaeochannels. Much of the saline water encountered so far has been located beneath a shallow freshwater ephemeral lake (Lake Powlathanga).

Funding sources: Land and Water Resources Research and Development Corporation; CSIRO; Queensland Department of Natural Resources/Queensland Department of Primary Industries; Balfes Creek Catchment Committee.

Upper Alice River Catchment Project — dryland salinity assessment & tree clearing guidelines

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Objectives: To investigate the landscape characteristics of the Upper Alice River catchment to determine areas potentially at risk from dryland salinity and to provide dryland salinity hazard ratings for various tree clearing options. The work is to help ensure that approval for land management activities (such as tree clearing) on leasehold land in the Desert Uplands of western central Queensland, is based on a sound understanding of the land resource. The Upper Alice River catchment is regarded as being a catchment representative of the Desert Uplands.

Funding: Queensland Department of Natural Resources and the National Landcare Program

Paddock scale guidelines for salinity management in the Balfes Creek catchment

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Objectives: To integrate point and catchment scale models to develop vegetation management strategies which will minimize salinity risk in the Balfes Creek catchment.

Evaporation from Trees and Regrowth

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Objectives: To measure transpiration in established and old growth and regrowth vegetation in the Balfes Creek catchment.

Prediction of landscape salinity hazard using a geographic information system

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Objectives: A pilot study to develop a methodology for mapping salinity hazard at 1: 250 000 scale on a statewide basis. The study covers the Gympie and Ipswich 1: 250 000 map sheets and includes three regions with significant occurrences of dryland salinity — the eastern Darling Downs, the Boonah-Lockyer region and the Kingaroy-Nanango region.

Method: Production of the map involves combining sets of natural resource data using a raster GIS overlay technique. Data sets include climate, geology, topographic indices (wetness index, flow accumulation, slope, plan and profile curvature, landscape position), soils and vegetation. Each attribute in a data set is assigned an independent salinity rating according to a defined set of decision rules. Data sets are also assigned a weighting and a total salinity hazard rating is determined for each unit of land by summing the values from each data set. A total of 1080 known saline sites are being used to validate the map.

Funding: National Landcare Program.

Nitrate leaching

Sustainability of *Stylosanthes* based pasture systems in northern Australia: managing soil acidity

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Background: The introduction of *Stylosanthes* into pasture production systems of northern Australia has resulted in a significant increase in the productivity of native pasture systems and profitability of the livestock industry as a whole. The positive impacts of legume introduction on the soil resource base are evident in the increase in the inherent fertility of the soil through the fixation of nitrogen and its subsequent transfer to the soil, and through the addition of superphosphate. There have, however, been significant negative effects on the soil resource. Among these is recent evidence that *Styolosanthes* pastures can cause a significant reduction in soil pH and associated base stripping. In the long-term, continued acidification can have numerous deleterious effects on the soil that together can result in decreased plant diversity, reduced plant productivity and off-site degradation.

This project is expected to have a significant effect on understanding of the long-term sustainability of legume based pasture systems in the semi-arid tropics. Its focus is to quantify the inherent fertility status over time of various pasture production systems through the establishment of long-term monitoring sites.

Objectives:
1. Establish permanent monitoring sites throughout northern Australia to assess long-term soil fertility and moisture trends under *Stylosanthes* and native pasture systems.
2. Develop a soil acidity risk assessment map fro the Dalrymple Shire at a level that will assist resource managers in identifying areas most vulnerable to accelerated acidification.
3. Evaluate the impact of different *Stylosanthes* management strategies implemented at Springmount, Mareeba, on the rate of acidification.
4. Conduct greenhouse and laboratory studies to ascertain the tolerance of grass and *Stylosanthes* species to acid soil infertility and assess the impact of ash produced after burning as an acid soil ameliorant.
5. Quantify the mineral nitrogen dynamics under a *Stylosanthes* dominant pasture in order to assess the contribution of nitrate leaching to acidification. Using published data, attempt to establish a total nitrogen budget for pastures with and without *Stylosanthes*.
6. Develop a comprehensive communication plant in conjunction with QDPI which will facilitate awareness among producers of the possible negative effects of *Stylosanthes* dominant pastures on the soil resource and to suggest management strategies to minimize these negative effects.

Subproject — Quantify the mineral nitrogen dynamics under a *Stylosanthes* dominant pasture in order to assess the contribution of nitrate leaching to acidification.

Rationale and objectives: Nitrate leaching is assumed to be an important contributor to the overall process of accelerated acidification under legume-based pasture systems. To date there is a paucity of information quantifying the nitrogen dynamics under *Stylosanthes* based pastures over time although the loss of nitrogen through leaching is an important consideration in the sustainability of these systems. This study aims to quantify the movement of nitrate, and other cations and anions, through a profile to estimate the net acidification rate due to nitrate leaching. In addition, the study will provide information on the amount of nitrogen contributed by the legume and the periods in the year when nitrate is most vulnerable to leaching. This may offer insight into potential management strategies which may reduce the risk of nitrogen loss from these systems.

Location: The study will be conducted at Lansdown in the Burdekin catchment, on adjacent plots which have been *Urochloa* or *Stylosanthes* dominant for several years.

Review 4

WATER, SEDIMENT AND NUTRIENT FLUXES — LOCAL AND SMALL CATCHMENT SCALES

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Contents

Reviewed here are measurements and estimates of water, nutrient and sediment fluxes at spatial scales ranging from tussock and intertussock patches, through to small catchment (less than about 100 ha). Most hydrological studies have tended to assess specific components of the water cycle, particularly infiltration and runoff, although there has been some work to provide information on water movement below the root zone. Between them, the studies reported here have investigated the hydrological effects of different grazing pressures, including exclosures; drought periods; tree removal; pasture improvement and fire. Most runoff work has involved associated measurement of sediment movement, but there have been very few measurements of nutrient fluxes associated either with water movement below the root zone or with surface runoff and sediment loss.

1. Infiltration studies at patch scale

There have been several investigations of differences in the hydraulic conductivity/infiltration rates of surface soils. These have typically measured differences in soil conductivity between vegetated and non-vegetated patches within particular communities. All studies, regardless of soil type and climate, have found rates of water movement into the soil profile to be higher under grass patches than in bare open areas, with rates in bare areas influenced by the period of time for which the soil had been exposed. Details of the studies are given below.

1.1. Tropical tallgrass community near Katherine, NT

This study was carried out in a *Eucalyptus* woodland with *Themeda australis* and *Sehima nervosum* predominant grasses, on red earth soils. At a second site the native grasses had been oversown with *Stylosanthes*. The study aim was to examine the properties and structure of the red-earth seals found in lightly and more heavily grazed areas. Heavy grazing was found to result in death of grass clumps which was followed by rapid sealing of the surface. Compared with grassed areas, the seals had a reduced depth of water penetration following water ponding, and reduced hydraulic conductivities. On the basis of lower organic carbon in the sealed areas, Mott *et al.* (1979) suggested that seal formation was related to rapid oxidation of organic carbon in the soil once plants were removed. This would allow the soil to slake rapidly under quick wetting, a property not observed for soils under grass cover.

1.2. Various vegetation communities near Alice Springs, NT

Infiltrometer studies were conducted by Gifford (1978) in several vegetation communities near central Australia. Communities studied included Mulga scrubland with perennial grasses and with shortgrasses growing on red earths, low open woodland on non-calcareous earthy sands, a floodplain community with shortgrasses and forbs on solonetzic (duplex) soils and a gilgai plant community growing on red cracking clay. Bare scalded areas within the floodplain unit were also investigated. Infiltration rates within the six plant communities ranged from very low on scalded areas (10 mm/hr) to moderately high within the woodland and gilgai community (35-45 mm/hr). Differential infiltration rates were found between groves (average 30 mm/hr) and intergroves (average 22 mm/hr) of the mulga community, supporting findings by Slatyer (1962). Sediment production was significantly higher from the floodplain grassland and scald areas than from the other communities.

1.3. Semi-arid woodlands at Torrens Creek, Qld

As part of a study of the hydrology of red earth soils supporting Eucalypt/Acacia woodlands with a *Triodia pungens*, *Heteropogon contortus* and *Aristida leptopoda* understorey, Williams and Bonell (1988) measured infiltration differences between soils near Spinifex tussocks and bare soil between the tussocks. A six to ten fold difference in infiltration rates occurred. Infiltration rate also increased with depth. The lower conductivity of bare areas was attributed to raindrop impact and surface slaking in the absence of protective vegetation and litter.

1.4. Semi-arid woodland (*Aristida-Bothriochloa* community) in the Nogoa/Fitzroy catchment, Qld

Infiltration was studied using rainfall simulators in open silver-leaf ironbark woodland (*Eucalyptus melanophloia*) with *Bothriochloa* spp., *Aristida* spp., *Heteropogon contortus* and *Themeda australis* grasses, on solodic (shallow duplex) soils (Connolly *et al.* 1997), at the Springvale catchment site of Ciesiolka (1987). The study included soils derived from mudstone and sandstone, grazed and ungrazed areas, open and dense trees, and a wide range of grass cover. Pooling these treatments, percent cover or above ground biomass (including litter) each explained 70% of the variation in runoff from 30 mm of rain (Glanville and Silburn, unpublished data). Runoff was about 65% of rainfall at cover < 5% and declined linearly with increasing cover or curvi-linearly with increasing biomass. Final infiltration rate increased with increasing cover, from about 15 mm/hr for bare soils to 60 - 80 mm/hr with > 80% cover, where the A-horizon was deeper (Connolly *et al.* 1997). However, where the A-horizon was shallow or absent final infiltration rate only increased to 20 - 30 mm/hr with cover > 80%. There was little difference in runoff and infiltration behaviour between sandstone and mudstone derived soils.

The infiltration response to cover was related to the longer term vegetation status (eg. roots and soil insects creating larger pores) rather than protection of the soil surface from raindrop impact during the applied rain (as is the case with crop stubble on cultivated soils) (Connolly *et al.* 1997). Addition of grass cuttings to bare scalded areas just prior to rain did not increase infiltration compared with bare areas (Ciesiolka and Glanville, unpublished data). Similarly when all cover was removed from vegetated areas, infiltration did not increase much compared with that on the intact vegetated areas. This time lag between removal or replacement of vegetation and change in soil hydraulic properties is poorly researched.

1.5. Mulga (*Acacia aneura*) woodlands near Charleville, Qld

[Compiled by Chris Chilcott, DNR Toowoomba from Miles (1993)]

Rainfall simulation studies were conducted by Miles (1993) on perennial grasslands (stable with no evidence of surface degradation), mulga (*Acacia aneura* with litter and grass cover) and Turkey bush (*Eremophila gilesii*) communities to determine effects of vegetation type on infiltration. Cover levels ranged from bare through to 80% canopy cover, and the soils were lateritic red earths. Grassed areas had the highest rates of infiltration initially and over time, and a high density of soil macropores. Bare soil had the lowest levels of macropores and, due to the absence of cover, the greatest rate of runoff. Mulga soils had a higher abundance of macropores yet lower infiltration rates. The presence of mulga litter increased soil fauna activity, which was reflected in higher abundance of macropores and soil organic matter. However this did not improve soil permeability as is expected, and requires further investigation. Overall, runoff was strongly related to the percentage of cover and vegetation. Grassed areas had a significantly lower runoff than turkey bush and mulga areas for all levels of cover measured.

1.6. *Heteropogon contortus* dominant pastures, central and southern regions, Qld

Patch scale infiltration measurements, using a disc permeameter at negative potentials, which represented pore sizes of 1 and 3 mm, were undertaken as part of a larger hydrological study within the QDPI Galloway Plains Grazing Trial and CSIRO Glenwood Grazing Trials. Measurements compared hydraulic conductivity in *Heteropogon contortus* and *Bothriochloa bladhii* patches with hydraulic conductivity in patches of *Aristida* spp. A comparison was also made of hydraulic conductivity at different stocking rates and, at Glenwood, for upper and mid-slope positions. At both Galloway Plains and Glenwood, 1 and 3 mm pores made a greater contribution to hydraulic conductivity in *H. contortus* patches than in *Aristida* patches. Stocking rate also affected the contribution of these pores to hydraulic conductivity at Galloway Plains but not at Glenwood. The lack of effect at Glenwood was attributed to a reduced period of heavy stocking or a more resilient soil. Upper slopes at Glenwood were found to have lower hydraulic conductivities associated with 1 and 3 mm pores, than were mid-slopes.

In October 1996, some additional "preliminary" infiltration measurements were carried out at the Galloway Plains site in a seca Stylo dominant pasture where there had been a grazing rate of 0.25 animals/ha. "Preliminary" infiltration measurements were also made for a burn treatment of an exclosure plot with *Heteropogon contortus* and *Chrysopogon fallax*. The four hydraulic potentials of -3, -2, -1 and 0 cm used with the permeameter, allowed the contribution to hydraulic conductivity of pores less then 1.0, 1.5 and 3 mm and greater than 3 mm, to be determined. In the burnt plot, infiltration was measured for patches of *Heteropogon* in both burnt and unburnt condition and for unburnt patches of *Chrysopogon*. Rainfall of 15 mm was recorded the night before infiltration rates were measured in the burnt plot and this may have influenced soil surface condition.

The results of the disk permeameter measurements are tabulated below. The seca Stylo pasture had the lowest average hydraulic conductivity at all hydraulic potentials and were lower than expected. Prior to these preliminary measurements, *Chrysopogon fallax* patches were regarded as having one of the lowest hydraulic conductivity rates of the various pasture species. The low values for the seca pasture were considered not to be an effect of stocking level as other pasture species have had infiltration rates that showed little variation between patches that were grazed at 0.25 animals/ha and ungrazed patches. It is expected that infiltration rates will be even lower in more heavily stocked seca Stylo pastures.

In the burnt plot, infiltration rates at all potentials in both burnt and unburnt *Heteropogon contortus* patches were higher than in *Chrysopogon fallax* patches. In these preliminary measurements, burning appeared to have the effect of reducing the contribution of larger pores (> about 1.5 mm) and increasing the hydraulic conductivity associated with pores less than about 1.5 mm. The saturated hydraulic conductivity of the burnt patches, however, was significantly lower than for the unburnt patches (147 mm/hr compared with 270 mm/hr).

Table 1. Average hydraulic conductivity for various pasture types and treatments, Galloway Plains grazing trial *(From D. Waters, pers.comm.)*

Hydraulic potential	**Corresponding pore diameter**	**Hydraulic conductivity (mm/hr)**			
(cm)	**(mm)**	***H. contortus* burnt**	***H. contortus* unburnt**	***C. fallax* unburnt**	**Seca Stylo**
-3.0	<1	16.3	9.3	5.4	2.5
-2.0	<1.5	24.5	19.9	15.8	11.9
-1.0	<3	66.3	72.0	44.1	27.2
0	≥3	147.6	270.2	89.0	48.4

1.7. Maranoa-Balonne catchment, Qld

The rainfall simulator was used during a series of field days at sites in the Maranoa-Balonne catchment to gauge the effect on runoff of plant cover and, in pasture land, using a 'crocodile' (John Grey, '*Balonne Broadcaster*', May 1996). A 'crocodile' is an implement that creates depressions in reasonably hard ground. On hard setting mulga box country, 60% of rain ran off from bare scalded areas. Use of the 'crocodile' reduced runoff to 33% of rain at Morven and 22% at Mitchell. Creation of shallow ponds on scalded areas also lead to leaching of salt out of the soil surface, allowing the soil to crack upon drying, further enhancing water entry.

1.8. Open forest with black speargrass (*Heteropogon contortus*) understorey near Mt Mort, Qld

Mt Mort in the Bremer River catchment, is one site included in a network of soil hydrology, runoff and erosion studies in grazing lands. It has duplex soil with a 0.4-0.5 m loamy sand overlying a sandy clay, acidic and sodic subsoil. As part of a larger hydrological study, rainfall simulator investigations were used to help understand the time lag, if any, between removal or replacement of cover and change in infiltration rate. The results are tabulated below and show that the length of time for which a soil is exposed following removal of grass cover, influences infiltration.

Table 2. Infiltration rates for various cover levels and periods of soil exposure at a site near Mt Mort *(From: Silburn 1994).*

Treatment	Period of reduced cover	Final infiltration (mm/hr)
Bare (< 10% cover)	18 months	5
Cover 20-30% 3 months before natural rainfall of 170 mm; final cover 24%	3 months	20
Grazed, 18% cover (grass clipped and removed just prior to rainfall)	0	22 after 10 mins of rain
Grazed (63% cover)	0	33

2. Water balance studies and recharge investigations

2.1. Field measurements

Williams and Coventry (1980) note that in many regions of northern Australia, infiltration into permeable soils is enhanced by the low topographic relief and the consequent lack of an integrated stream network. With steeper slopes and less permeable soils, such water may be lost as runoff and never enter the soil profile. Despite the geomorphic predisposition to enhanced infiltration in many areas of northern Australia, few studies seem to have quantified soil water balances, including deep drainage. Work on groundwater recharge is possibly more extensive than reported here due to some grazing areas in northern Australia being located in recharge areas for the Great Artesian Basin and consequently subject to investigation by agencies interested in groundwater.

2.1.1. Comparison of soil types

Some of the first measurements of soil water regime were undertaken by Williams and Coventry (1979 and 1980) on red, yellow and grey earth profiles at Torrens Creek in the Burdekin catchment. As a result of these studies they showed that saturated conditions could occur in these soils in some years and concluded potential for groundwater recharge below these soils existed, despite the semi-arid environment.

2.1.2. Comparisons of vegetation types

At 'Redlands', 45 kms west of Charters Towers in the Burdekin Catchment, experiments were undertaken to measure the comparative water balance of the native eucalypt woodland, native grasses (*Heteropogon contortus* and *Chrysopogon fallax*) and *Stylosanthes* pastures with adequate and suboptimal levels of phosphate application (Williams *et al.* 1997). Clearing and the introduction of pastures had a clear effect on the water balance. Plant water use was reduced by tree killing, with water use by pastures depending on phosphate nutrition. Reduced plant water use was associated with reduced water withdrawal from the soil and hence greater potential for deep drainage with further rains. Over the same period of plant water use, the loss in soil water content to a depth of about 4.5 m, was 223 mm under woodland, 137 mm under the 'Seca' pasture with adequate applied phosphate, 94 mm under the 'Seca with low levels of applied phosphate, and 67 mm under the native grass. These data show quite clearly that neither native grasses or the introduced perennial legume can exploit all water available in a profile if nutrients are limiting plant growth. This observation in itself has important implications for the benefit of tree clearing and pasture improvement.

The paired catchments studies at the Narayan (Prebble and Stirk, 1988) and Brigalow Research Stations (Lawrence and Sinclair 1989, and Lawrence *et al.* 1991) also investigated the effects of clearing and pasture establishment on components of the water balance. At Brigalow, clearing had a substantial affect on recharge in a very high rainfall year prior to complete pasture establishment (30 mm/yr compared with 7 mm/yr under the natural brigalow) but not in the lower rainfall years; in years with lower rainfall there was no recharge. The lack of differences in recharge rates between brigalow and pasture were attributed to the slowly permeable duplex soils, the climate and the water use characteristics of Brigalow. Brigalow is a shallow-rooted species with only a small proportion of roots extending below 0.8 m. If anything, the pasture was considered to have slightly greater water use than the brigalow. An annual water balance was determined, and evapotranspiration and runoff were found to be about 97% and 3% of the annual rainfall under brigalow. When cleared, the runoff component increased to about 4.6% and evapotranspiration decreased to 95.4%.

Similarly, Prebble and Stirk found little change in the soil water regime at the Narayan catchments between cleared and uncleared sites. Here the native vegetation was *Eucalyptus melanophloia* open woodland with a *Heteropogon contortus* understorey. The lack of difference in water regime was considered to result from most trees having similar rooting depths to the pasture plants. Following clearing, the increase in drainage below 3.0 m was regarded as negligible, on the basis of changes in water content at this depth.

2.1.3. Work in the arid zone

Barnes *et al.* (1992), in a study of nitrate contamination of groundwater near Ayers Rock, concluded that significant episodic recharge was occurring. A subsequent study using data from pre-existing bores suggested a long-term average annual recharge rate of about 20 mm/yr (Barnes *et al.* 1994). This latter study also noted that although localized recharge occurs in the arid zone as a result of infiltration through the beds of ephemeral streams, distributed recharge was likely to be the major source of groundwater renewal in the study area.

2.2. Hydrological modelling

2.2.1. Water balances following clearing and pasture improvement

The hydrological response of a land unit to tree killing and/or pasture improvement, will depend on a number of factors:

- rainfall regime and daily balance between rainfall and evapotranspiration;
- topography;
- soil hydraulic properties;
- soil nutrient status (influences the capacity of plants to use the available water);
- the soil water holding capacity; and
- rooting behaviour of the replacement species compared with the natural vegetation.

Clearly, experimental work alone cannot hope to cover the range of variability found. Simulations using mathematical models offer a way of predicting the response of different land types to clearing or other management practices affecting soil and vegetation.

Williams *et al.* (1997) used the SWIM (Soil Water Infiltration and Movement)and PERFECT (Productivity, Erosion, Runoff Functions to Evaluate Conservation Techniques) models to extend the soil water balance measurements at the 'Redlands' site near Charters Towers. Specifically, they were used to:

- quantify drainage beyond 3.6 m for the soil on which soil water measurements had been made;
- quantify drainage for different soils assuming the same climatic conditions;
- quantify the drainage for different rainfalls over a long period of time.

Soil water balance simulations with SWIM, using soil data from the 'Redlands' showed deep drainage increased by a factor of ten in the native grassland compared with woodland over the period January to June 1980 (86.1 mm compared with 8.9 mm). This result indicated that, while tree clearing can increase the water available for use by pasture plants, the water cannot be converted to dry matter while nutrient or other edaphic constraints remain. Moreover, excess water which cannot be used is likely to be lost from the system.

The comparative water balances for a red earth, sandy red earth and yellow podzolic soil, were simulated for native grasses and for trees with native grasses, using SWIM. The three soil types all exhibited increased drainage below 3.6 m under native grasses compared with under trees and native grass.

PERFECT was used to simulate drainage for a red duplex and red earth soil over a long period of rainfall records (1889-1988). PERFECT predicted that the occurrence of deep drainage would increase from 17% of years to 66% of years for the red earth, and from 4% to 42% for the neutral red duplex, when trees are removed from the landscape. These simulations confirmed the highly episodic nature of recharge in the wet/dry tropics.

2.2.2. Effect of pasture cover on soil water content

At the Brigalow research station, above average rainfall can be experienced in winter when pastures are not actively growing. Lawrence and Cowie (1992) report on the use of PERFECT in conjunction with long-term rainfall records, to simulate soil water content to 1.0 m under different levels of pasture cover. Under pasture with a 90% cover, there is a 10% probability that soil water will exceed 100 mm between April and June while water content levels in excess of 50 mm during these months can be expected 25% of the time. In contrast, water contents to 1.0 m are considerably less if pasture cover is reduced to 10%. Under these conditions, soil water content is likely to exceed 50 mm in only 10% of years and extremely unlikely to exceed 75-100 mm between April and June. The difference in soil water storage was attributed to very high evaporative losses of water from bare soils. The significance of these simulations is that soils with low cover are likely to have reduced soil water available for pasture growth once temperatures are suitable.

2.3. Current and proposed research

The literature obtained on water balance studies within the grazing areas of northern Australia was not extensive. This is probably a reflection of the lack of work undertaken as far as soil water regimes are concerned but may not reflect the state of work with respect to drainage beyond the root zone and recharge to aquifers. The Australian Geological Survey Organisation (AGSO) in particular, as well as relevant State Agencies, may be able to provide more information. Recharge investigations in the intake zone of the Great Artesian Basin are currently being planned as part of the AGSO project on the hydrogeology of the Great Artesian Basin (see Attachment 1). Two other current projects (see details in Attachment 1) will also provide further measurements on water balance components for particular areas. The '*Water use by savannas*' project in the Northern Territory is showing recharge rates of about 200 mm per annum at a site near Darwin and is expected to provide further estimates of recharge in other environments. The project being run by Andrew Noble is only just beginning but will provide data on soil water changes under *Stylosanthes* pasture for a greater range of climatic and soil conditions.

3. Runoff, sediment and nutrient loss — studies in the arid zone

Generally low but highly variable rainfall and very low slopes are usually dominant factors in determining the hydrology of the arid zone. Overland flow rather than channel flow often predominates, and, as a result, characteristics of the soil surface, such as microtopography and vegetation cover, often control water movement (Stafford Smith and Pickup 1993). Sediment movement is correspondingly controlled by these factors, and is mostly transport limited. Under natural conditions, deposition of eroded sediment typically occurs in close proximity to the area from which it was eroded, giving rise to observable 'erosion cells' within the various landscape units. An 'erosion cell' encompasses the sediment production zone, the sediment transfer zone and the sediment deposition zone or sink (Pickup, 1985). Transport of sediment from local landscapes usually depends on large and infrequent rainfall events.

Recent erosion work in the arid zone has focussed on the erosion cell concept rather than on the plot erosion studies which have been used in more humid areas. Terrain in the arid zone is characterised by a mosaic of natural erosion cells, often superimposed on each other, with areas of relative stability between them. Pickup (1985, 1988) describes the sequence of processes that can occur in such a landscape if erosional forces are increased or the erosion resistance of the landscape is decreased, for example, by grazing. The smallest erosion cells tend to be mobilized first and the area from which sediment is removed becomes a runoff or source zone. This, in turn, increases the amount of runoff generated, transport capacity is increased and sediment tends only to be deposited in the larger sinks which have sufficient capacity to reduce the velocity of overland flow. Consequently, as a result of grazing, 'erosion cells' tend to decrease in frequency, and increase in size.

Vegetation patterns can be strongly influenced by whether the land surface is erosional, depositional or undergoes alternating erosion/deposition (the transfer zone of an erosion cell). For example, Pickup (1985) notes that 'it only requires 0.2 m of deposited material to allow the development of a woodland community on what was previously eroded and probably bare ground'. The association of higher plant productivity in sediment sinks is attributed to the higher nutrient status, presence of a seed bank, relative stability compared with eroding areas, and higher soil water contents due to runon and also often coarse material which promotes infiltration. This review, however, found no literature for arid environments which quantifies the differences in these attributes between erosional and depositional areas although some data have been obtained for semi-arid areas (for example, Tongway and Ludwig 1990). The development of vegetation is a positive feedback on sink development, with further enhancement of surface stabilization, infiltration and trapping of sediments and nutrients. Conversely, loss of vegetation destabilizes the system and leads to water, sediment and nutrient leaving the local landscape.

4. Runoff, sediment and nutrient loss — studies at large plot scale (semi-arid and wet/dry tropics and subtropics)

There have been at least ten large plot scale (30 m^2 to 0.25 ha) hydrological studies in the semi-arid and wet/dry tropics and subtropics of northern Australia, with nine of these in Queensland. In addition, the literature indicates work by Pressland and Miles in the mulga, and by Novelly in the Ord Regeneration Area but information was not obtained from these studies for this review. Williams (1976) also carried out runoff and erosion experiments in the Alligator Rivers area of the Northern Territory that involved relative small areas (< 10 m^2 ?). Except for this study and the work at Torrens Creek, which was in a relatively undisturbed Eucalypt woodland on red earths (Bonell and Williams 1986, 1987), the hydrological investigations reported here have all been associated with grazing trials. The emphasis has been runoff production and changes in soil physical properties at different stocking rates, and, in some instances, for different pasture managements. While sediment loss with runoff was measured at all grazing trial sites, nutrient loss was only measured at the Cardigan and Mt Mort sites.

Grazing trials with a hydrological component to the work have been undertaken in the Northern Territory at the Douglas Daly Research Station in the Daly River catchment (Dilshad *et al.* 1994). In Queensland, sites are in the Burdekin catchment (Cardigan and QDPI sites near Charters Towers and Greenvale), the Fitzroy (QDPI Kielembete and Glentulloch grazing trials; QDNR Springvale site), the Calliope (QDPI Galloway Plains grazing trial), the Burnett (CSIRO Glenwood grazing trial) and the Bremer (QDNR Mt Mort site).

Except for the site at Mt Mort where slopes were 10-15%, sites were on gently undulating or sloping plains, with gradients less than 6%. Soils were gradational (red earths) or duplex and were developed on a variety of parent materials including granite, granodiorite, sedimentary rocks, alluvium and deeply weathered adamelite. Native vegetation was mostly eucalypt woodland with *Heteropogon contortus* a dominant grass, the exceptions being at Kielembete, Glentulloch and Springvale sites where *Aristida* and *Bothriochloa* were dominant. Most trials involved stocking the native pasture at different rates. Trials involving tree clearing and/or pasture improvement were those at the Douglas Daly Research Station, where *Eurochloa mosambicensis* had been established, and at the Cardigan site. At Cardigan, the four treatments were: trees and native pasture with plots burnt in January 1990 (the last wet season of the trial); trees killed and native pasture with plots burnt in January 1990; trees killed and a legume—grass pasture established by oversowing; and trees killed, mechanically removed and a legume—grass pasture established by sowing onto a cultivated seedbed. Each system was grazed at two stocking rates.

Tabular summaries of the objectives, environment, treatments and results associated with the hydrological and sediment components of these different trials are given in Attachment 2.

4.1. Runoff

In the study of the natural hydrology of undissected plains near Torrens Creek (Bonell and Williams 1986, 1987), only 2% of total rainfall was found to be exported from the slope, with a maximum of 4% for any event, although there was substantial variation in runoff and infiltration within the slope. Runoff generation was controlled by the spatial variability in surface hydraulic properties, particularly between bare and vegetated patches. Correlated with the low runoff from the slope as a whole, there was little net sediment export. A severe fire increased the amount of sediment movement within the 100 m slope but there was no significant change to net loss of sediment. The low runoff from the plots as a result of local runoff reinfiltrating, is consistent with the lack of channel incision in the broad valley bottoms and an integrated channel network in the landscape.

With the imposition of different grazing regimes, measurements of runoff and soil loss were highly variable at each site, and depended on cover and rainfall intensities and amounts, though losses under heavier stocking rates were nearly always higher than losses under lighter grazing or in exclosures. For example, at Galloway Plains, cumulative runoff over the period of study from the heavily grazed plots (0.5 steers/ha) was 778 mm, about 250 mm from the plot grazed with 0.25 steers/ha and 235 mm from the exclosure. Cumulative soil losses (bedload + suspended sediment?) were 1171 kg/ha for the heavily grazed pasture and 106 kg/ha for the exclosure. Similar results were obtained at the Glenwood trial.

Correlations between runoff and sediment loss and percent cover (with variable definition of "cover") were able to be developed for some studies. For example, McIvor *et al.* (1995) showed that for I_{30} rainfall intensities less than 15 mm/hr and total rainfalls less than 50 mm, runoff and sediment loss were low at groundcover levels greater than 40% and increased exponentially as covers decreased below 40%. As rainfall intensity or amount increased, greater cover was needed to reduce runoff and soil loss. At very high intensities or amounts (I_{30} > 45 mm/hr or total > 100 mm), cover had no effect on runoff although soil movement was still reduced. Similar relationships have been found for speargrass woodlands on coarse textured duplex soils in south-east Queensland (Mark Silburn, pers. comm.) and for the *Eurochloa mosambicensis* pasture at the Douglas Daly Research Station.

With respect to the effect of clearing and pasture improvement, soil loss measured at the Cardigan site was greatest for the plots with trees and native pastures, and declined in the order of trees/native pasture > cleared/sown > killed trees/native pasture > killed trees/sown pasture though not all differences were significant. Although the most significant factor associated with runoff and sediment loss is cover, at similar covers plant form can have an effect. For example, *Bothriochloa pertusa* was found to generate less runoff than pastures dominated by native tussocks at sites in the Burdekin catchment (Scanlan *et al.* 1996).

The contribution of bedload and suspended sediment to total soil loss was not always determined. The studies in the Burdekin catchment, however, indicated that at high levels of cover, bedload concentration was quite low but significant soil losses from suspended sediment could still occur. Measurements were also made in the NT study and showed that bedload soil losses were about an order of magnitude less than suspended sediment losses for individual storm events. Scanlan *et al.* (1996) make the general observation that the amount of soil lost as suspended sediment will depend on the particle size distribution of surface soil.

Other interesting findings from these trials included the observation by McIvor *et al.* (1995) that erosion at the Cardigan site appeared to be controlled by supply capacity rather than transport capacity. This would suggest that any activity that increased particle detachment and exposure at the soil surface would result in increased soil losses. Also of interest were the abundant soil pores (associated with previously vegetated areas) found to be important in reducing runoff immediately following fire at the Cardigan plots. With increasing exposure of the soil, surface macroporosity and microrelief was reduced (John Williams, pers. comm), and runoff increased.

4.2. Nutrients

Nutrients associated with runoff and sediment losses were measured only in the Cardigan and Mt Mort studies, and even the data available from this work are limited. At Cardigan, nitrogen losses, predominantly as dissolved inorganic nitrogen, were greater under heavy compared with light grazing and varied with pasture type. Annual losses of 5 kg/ha were recorded under heavy grazing of native pasture and 8 kg/ha under heavy grazing of legume pasture, with negligible losses for both pastures under light grazing. Corresponding annual losses of phosphorus under heavy grazing were 0.08 and 0.25 kg/ha, predominantly as P bound to suspended sediments. Suspended sediment was also found to have very high cation exchange capacities (Hicks, 1989 cited by Holt, this review) suggesting a high loss of nutrient cations.

At Mt Mort, annual losses of 58 kg/ha nitrogen and 24 kg/ha phosphorous were measured for a grazed pasture with 10% cover. These losses reduced to 2 and 0.5 kg/ha for nitrogen and phosphorous respectively at 80% cover, and to 0.2 ka/ha for both nutrients at 90% cover.

5. Runoff, sediment and nutrient loss — studies of small catchments

Five small catchment studies have been identified in this review. One of these, the Brigalow Experimental Catchment Study, is on-going. All are in central and southern Queensland, although a small catchment study is also about to commence in the Burdekin catchment (see '*Coping with rainfall* *variability*', in Attachment 1). As with the large plot studies, not all have measured nutrient losses. A current project '*Land management to reduce nutrient movement from catchments*' in the Murray-Darling catchment of Queensland (see Attachment 1), involves monitoring nitrogen and phosphorus loads in runoff. This project involves a nested set of catchments, several of which range in size from 1 to 10 ha.

5.1. Kangaroo Hills farm dam survey (Burdekin Catchment, Qld)

Reference: Prove et al. (1992).

In 1975, small dams on the Kangaroo Hills property were surveyed for sediment storage as part of a study estimating erosion rates for the Burdekin dam. Soils were predominantly solodics developed on shale. In 1990 the dams were resurveyed and erosion rates for their catchments calculated. Depth of sediments and bulk densities derived from cores, were used to give sediment mass. Average annual erosion rates for the shallow solodic soils ranged from 2.6-20.4 t/ha, with amount of sediment measured relating to the severity of erosion in each catchment. Annual values were:

- Catchments with sheet erosion: 2.6 t/ha;
- catchments with minor gully and sheet erosion: 4.2 t/ha;
- catchments with severe gully erosion: 18.3 t/ha.

5.2. Brigalow Experimental Catchment study (Dawson catchment, Qld)

This study is located on the Brigalow Research Station near Theodore, Queensland in the semi-arid sub-tropics. It commenced in 1965 and is on-going, although with reduced data collection in recent years. The study aims to determine the long-term effects of land clearing and subsequent development for grazing (and cropping) on soil properties, catchment hydrology and loss of soil and nutrients in runoff. Hydrology of three catchments (11-17 ha) was monitored for 15 years prior to land clearing/burning of brigalow forest on two of the catchments in 1982. The third catchment was retained as brigalow forest. The pasture catchment (13 ha) was sown to buffel grass following clearing and for the five years after establishment was grazed at a rate of 8-10 animals per group of cattle introduced.

A detailed report on the study (Lawrence and Thorburn 1989) was written in conjunction with a major review of the study. Only limited data are available on runoff and nutrient losses between 1983 and 1988, since few major runoff events occurred during that period. However, mean runoff measured from the cleared catchment was 47.4 mm which compared with a value of 23 mm estimated as the mean runoff had clearing not taken place. Prior to clearing, runoff was estimated as about 4% of rainfall and as about 7% of rainfall after pasture establishment. Peak runoff rates also increased, with the range in increase being 0.1 mm/hr to 28 mm/hr.

Between 1984-1987, average soil loss as suspended sediment per event was 19 kg/ha for brigalow and 32 kg/ha for the pasture. Average annual soil loss as suspended sediment was 0.1 t/ha from brigalow and 1.7 t/ha from pasture. Soil loss as bedload was considered a negligible component of total soil loss.

Concentrations of nitrogen (N), phosphorus (P) and potassium (K) in runoff during a significant event that occurred about 5 months after clearing/burning were considerably higher from the cleared catchments than from the brigalow forest. This probably reflected the large increases of plant available forms of N, P and K that were measured in soil (0-10 cm) following burning of the cleared brigalow forest. However, following pasture establishment, nutrient losses in runoff (for the few events that were recorded) from the pasture catchment were only slightly higher than in runoff from the forest catchment. It is worth noting that over this period, the grazing pressure was light and the buffel grass pasture was in good condition.

5.3. Narayan small catchment study (Burnett catchment, Qld)

The Narayan small catchment study (Prebble and Stirk 1988) was undertaken to investigate the change in hydrology associated with clearing an open grassy woodland with *Eucalyptus melanophloia* and

Heteropogon contortus, and sowing to improved pastures. A paired catchment approach was adopted with four small catchments 9-31 ha in area instrumented to measure rainfall, runoff, soil water and climatic variables. The Narayan site, with a mean annual rainfall of 720 mm, is in the Burnett catchment. The predominantly duplex soils have developed on weathered granitic material and the slopes are about 2 degrees. Monitoring began in 1972 and treatments were imposed in 1975. This involved killing the trees in two catchments and seeding with Sirato (*Macroptilium atropurpureum*) and green panic (*Panicum maximum*). Monitoring stopped in 1978.

Following treatment, ratios of the annual runoff for catchment pairs showed no major change and it was concluded that, provided a good grass cover were maintained, the clearing and pasture establishment would not greatly affect runoff.

5.4. Springvale catchment study (Nogoa catchment, Qld)

5.4.1. Field measurements

The 9.6 ha catchment (Springvale) is located on the property 'Springvale', 75 km west of Emerald, Queensland, Australia, in the Nogoa river catchment and is described in detail in Ciesiolka (1987), Connolly *et al.* (1997) and Connolly *et al.* (in press). The climate is semi-arid tropical. Average annual rainfall is 690 mm but highly variable, with a coefficient of variation of 38%. Average annual evaporation is 2100 mm. Larger rainfall events are the result of either depressional rainfall or thunderstorms, though thunderstorms are more common (Ciesiolka, 1987). Thunderstorms are characterised by high intensities (peak intensities in excess of 100 mm/h) and short durations (0.25-2.5 hours), while depressional rainfall is characterised by intensities typically less than 20 mm/h and durations of up to 96 hours.

Geologically, the catchment consists of a series of alternating beds of sandstone, siltstone and mudstone that have been folded and eroded to form a cuesta and valley landscape. Topography varies sharply across the catchment, from low sloping areas (1% slope) to steeply incised channels (up to 14% slope). Surface soils typically have a sandy loam or loamy sand texture, poor structure and high bulk density (around 1.5 Mg/m^3); depths vary from 0 to 0.15 m. Valley floor alluvial soils are poorly sorted sands and loams, are moderately hardsetting, and may have an A-horizon 0.5 m deep. B-horizons derived from sandstone are hard yellow-orange clay loams to sandy clays while those derived from mudstone are hard grey-green clays. All soils belong to the solodised solonetz-solodic Great Soils Group (Stace *et al.*, 1968).

Vegetation and cover are highly variable across the catchment. The predominant vegetation is an open silver-leaf ironbark woodland (*Eucalyptus melanophloia*) with the grasses *Bothriochloa* spp., *Aristida* spp., *Heteropogon contortus, Themeda australis*. Bare areas with smooth hard-setting surfaces (scalds) are found throughout the landscape. Little natural revegetation occurs on these bare areas, with algal crusts developing when not disturbed by animals.

Ciesiolka (1987) studied the effects of cattle grazing and pasture management on runoff and sediment yields from the catchment. Measurements were made for two years (commencing in 1979) over which time the catchment was heavily grazed. The measurements were continued for the next three years with the cattle excluded. Vegetative cover, however, did not increase for almost two years after exclosure, due to low rainfall. Significant regrowth only occurred toward the end of the experimental period in 1984 when rainfall was higher. Despite this variability in rainfall and pasture growth, and the small data set (79 days of runoff), significant differences in runoff were found between the grazed treatment and the final year of exclosure, as listed below:

- initial losses (amount of rainfall before runoff occurred) increased with pasture regrowth;
- duration of rainfall excess (amount of rainfall contributing to 'quick flow') decreased with regrowth, giving reduced peak discharges, in line with greater initial losses;
- significant changes in hydrograph shape occurred with pasture regrowth; attributed to increased retardation of channel flows with the increase in biomass on channel floors; and

- runoff for the final year of the exclosure treatment was about 15 % of rainfall, compared with an average of 28 % for the previous 4 years. However, Ciesiolka (1987) noted that, while annual runoff was reduced by the increased cover, reduced runoff was partly related to lower rainfall intensities associated with a predominance of depressional rain in that year — 76 % of rainfall in 1984 occurred as depressional rainfall compared with 58 % in the previous four years.

Ciesiolka (1987) concluded that there was considerable potential for reducing runoff with improved grazing management and revegetation. His conclusions, however, were based on data collected over a short period and with limited revegetation of the catchment. He questioned whether a sufficient range of covers had been sampled, and whether exclusion had been for a sufficient length of time for litter and soil fauna to build up and substantially change soil infiltration. Silburn *et al.* (1992) in later work, found that maintaining pasture cover above 40% significantly reduced runoff and soil loss compared with the cover levels of less than 20% found in the catchment prior to exclosure.

5.4.2. Catchment modelling

Measurements of rainfall and runoff from the catchment in an ungrazed state, were continued following the work of Ciesiolka, so that 13 years of data are now available. No comparable periods of data are available, however, for the land in other condition, particularly the bare, grazed state found in much of the surrounding area. The ANSWERS (Areal Non-point Source Watershed Environment Response Simulation) model (Beasley and Huggins 1991) was used to supplement and extend the measured data, thereby producing a synthetic "paired catchment" experiment that provided data on runoff from the catchment under bare (grazed) and heavy cover (ungrazed) condition. The model was also used to evaluate the effects on runoff of rainfall type, valley floor wet-zones, and various revegetation strategies. These simulated runoff data could then be used to analyse the effects of various management practices on runoff from the Springvale catchment.

ANSWERS is a distributed parameter model that represents a catchment using a grid of square elements. It explicitly represents topographic features and spatial distribution of rainfall, soils, vegetation cover and channel networks. The model was parameterised and tested using techniques described in Silburn and Connolly (1995) and Connolly *et al.* (1997). Rainfall simulation studies were used to determine the infiltration properties of each soil type and the changes in hydraulic conductivity with increased cover. Antecedent soil water for each event and for each soil-cover class were simulated using the GRASP (GRASs Production) model (McKeon *et al.* 1990). Parameters describing vegetation cover were derived from field observations and surface roughness parameters were estimated from published sources. Topographic survey data were also input into the model. Simulations of hydrographs from rainfall events of various magnitudes were tested against measured data recorded over the 1979-1993 experimental period, and was found to give accurate predictions (Connolly *et al.* 1997).

Connolly *et al.* (in press) used both the measured rainfall and runoff data, and the simulated runoff data, to evaluate ways of reducing runoff from the once overgrazed, bare Springvale catchment. Revegetating a large proportion of the catchment through de-stocking and natural pasture regeneration was the most effective means of reducing runoff. Increasing average cover levels from 20% to 60% resulted in a 75% reduction in measured annual runoff. The average rainfall threshold required for runoff to occur increased from 11.1 mm for the bare catchment to 21.6 mm when the catchment had 60% cover, regardless of storm size. Storm size did, however, influence the effectiveness of cover in reducing peak runoff rates, with cover reducing peak runoff rate for event sizes up to a 3 year average recurrence interval only.

The catchment's shallow soils with low water holding capacity and relatively impermeable B-horizons were a substantial impediment to some revegetation strategies successfully reducing runoff. Intensively revegetating small areas within the catchment, for example, was often ineffective in reducing runoff, as restriction of infiltration by the B-horizon and the small storage potential of the shallow A-horizons resulted in insufficient additional rainfall entering the soil to have a marked effect on reducing runoff. Also varying roughness and antecedent soil water conditions in channel alluvium did not influence runoff at the catchment outlet as the channels were a relatively small contributor to the catchment's hydrologic characteristics. Revegetating scalds, however, did reduce runoff from low intensity rainfall events.

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ATTACHMENT 1: WATER, SEDIMENT AND NUTRIENT FLUXES — CURRENT & PROPOSED RESEARCH

Water balances in the natural system

Water use by savannas - estimation of sustainable groundwater pumping rates

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Background: Two facts suggest *a priori* that groundwater is important in the structure and functioning of native vegetation. First, the wet-dry tropics are characterised by an annual, predictable, 5-6 month drought when rainfall is essentially zero. Second, the leaf area index of the tree canopy of savannas does not show a very wide reduction despite the absence of rainfall. Approximately 25% of all tree species are evergreen, and a further 50% are brevi-deciduous or semi-deciduous. These trees maintain a high transpiration rate throughout the dry season and therefore have access to deep water.

Objectives:
1. The NT Department of Lands, Planning and Environment intends to develop additional groundwater bore fields. This project aims to determine the extent to which native vegetation is dependent on groundwater so that it is possible to obtain a quantitative evaluation of how much groundwater can be extracted in the long-term without having a negative impact on the vegetation. Dependence of native vegetation on groundwater resources is being assessed by attempting to determine a catchment scale water balance within a tropical savanna woodland. Once a water balance has been determined, the effect of different management strategies (fire regime, tree density, stocking rate) on the water balance will be identified.
2. A second objective of the work is establish whether trees compete with grasses for water and whether grass production is increased by removing trees. This work is being done in conjunction with the Department of Primary Industries (NT).

Methods: Measurements being made include:
1. leaf area per unit ground area (LAI) for different vegetation types at different times of the year;
2. the relationship between LAI and diameter at breast height of trees on savanna sites;
3. rate of water use per tree, estimated using Greenspan sap flux measurements, as a function of species and season;
4. rate of water use of whole canopies using eddy covariance techniques, as a function of time of day and season; and
5. rate of movement of groundwater depth and rate of recharge of groundwater, using peizometers, neutron moisture meters and isotope studies.

Results to date:
1. The tree canopy LAI is approximately 0.9-1.1 for savannas near Darwin where rainfall ≈ 1600 mm pa) and varies minimally (about 10%) seasonally. LAI of the grass and shrub layer varies from a high value of less than 1 (wet season) to a low of 0.1 (dry season).
2. Depth of water use varies between 0.5-2 m in the wet season and 9-12 m in the dry season.
3. Wet season evapotranspiration from savannas accounts for about 55-65% of the annual rainfall of about 1600 mm. Surface run-off and shallow through flow to rivers is about 400 mm, groundwater recharge is about 200 mm, and soil storage is about 200 mm. In the dry season, about 300 mm of water from the soil store is used in evapotranspiration.

Future work: Future work includes:

1. refining estimates of canopy water use;
2. refining estimates of changes in daily and seasonal soil water content in the upper 10 m of the profile; and
3. extending the analyses to other land types in the NT where rainfall, vegetation and disturbance patterns differ.

Hydrogeology of the Great Artesian Basin

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Objectives: To provide high-level technical and scientific advice relating to groundwater issues in the Great Artesian Basin (GAB) to contribute to the sustainable development of the basin's natural resources.

Subprojects:
GAB wireline log and database map - Digitising of nearly 4000 AGSO acquired wire-line logs has been completed.

GAB groundwater model - a groundwater model based on MODFLOW is being developed; definition of aqifer boundaries and structure contours for the ten model layers have been completed.

GAB monitoring network - design of the basin-wide observation bore monitoring network is continuing in consultation with the states.

GAB hydrogeological map - Preparation of a 1: 2 500 000 scale GAB hydrogeological maps is proceeding concurrently with the modelling.

GAB recharge pilot study - now being established with state agencies. The proposal is for a project involving catchments in northwest NSW and southeast Queensland that overlie the Great Artesian Basin. Among other things, detailed recharge studies will be conducted which quantify recharge flux from all sources, particularly river leakage compared with diffuse rainfall recharge.

Suppression of meso-scale heterogeneity by the tree layer in a tropical woodland

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Background: The functional characteristics of savannas with respect to the interactions between the herbaceous and woody components, have not been well defined. Interactions between trees and grass may occur over different scales, depending on site conditions. Effects of trees on grasses have been observed at both an individual tree level and at a paddock scale level. The distribution of resources (water, nutrients and seeds) within a paddock will determine patterns of pasture growth and thus grazing behaviour of cattle. If resources are uneven, patches of higher grass biomass may occur.

In the tropical tallgrass savannas or open eucalypt woodlands of north Queensland, it has traditionally been the grass layer which has been the focus of management, although trees and grasses coexist. Management of the tree layer has often been directed at increasing pasture productivity, by removing or thinning trees to reduce competition to grasses.

Objectives: to examine the effects of individual trees and of tree clearing on the distribution of soil resources and on grass water potential at a site south of Charters Towers, in north Queensland. The vegetation consists of an open woodland with *Eucalyptus drepanophylla* and *E. erythrophloia*, and an herbaceous layer dominated by perennial grasses of which the most important species are *Heteropogon contortus, Chrysopogon fallax, Bothriochloa ewartiana* and *Sehima nervosum*.

Methods:

1. Individual tree effects — time domain reflectrometry (TDR) was used to measure soil moisture along transects between mature trees. 15 and 30 cm TDR rods were placed every 2 m along 5 transects extending 10 m from 4 individual trees. Predawn and midday leaf water potentials of 6 *Chrysopogon fallax* grass tussocks beneath and outside two of the same mature tree canopies were also measured.

2. Paddock treatment effects — three paddock tree clearing treatments were investigated at each site: "regrowth" - cleared for ten years with regrowth; "cleared" - cleared for ten years without regrowth; "intact" - an intact tree layer.
   - (i) overall effects — soil moisture in the top 30 cm of soil was measured in each paddock using TDR. Moisture to 2 m was measured using a neutron moisture meter in four access tubes in each paddock. Predawn and midday water potentials of grasses in each paddock were measured while they remained active; 14/3/95 to 8/6/95, and 1/2/96 to 29/2/96.
   - resource distribution effects — at the beginning of the 1995/96 wet season, in each paddock (regrowth, cleared and intact) grass patches of relatively high and low apparent biomass and vigour were chosen. Weekly measurements were made on soil moisture and grass water potential within each patch for five weeks. Soil moisture measurements were taken with three pairs of 15 and 30 cm TDR rods, and one NMM access tube to 155 cm. Midday and predawn water potentials were taken on the same three *Chrysopogon fallax* and *Bothriochloa ewartiana* plants in each patch at each sampling time. At the end of this sampling regime phosphorous, carbon and nitrogen in the top 10 cm were measured in each patch. Bulk density was also measured at the end of the sampling period.

3. As a possible determinant of moisture distribution, a theodolite and surveyors rod was used to measure topography at 25 cm intervals across the patch and approximately 4 m either side in each direction (N, S, E and W). As a measure of deviation from a straight line (and hence an indication of any hollows which may trap water) a correlation was made between transect distance and topography.

Soil water and nutrient change following clearing and pasture improvement

Sustainability of Stylosanthes *based pasture systems in northern Australia: managing soil acidity*

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PMB,
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Background and objectives for this project are given in Attachment 2 for the review of salinity and nitrate contamination of groundwater. Given here are details for the subproject assessing soil fertility and water changes.

Sub-project objectives: Establish permanent monitoring sites throughout northern Australia to assess long-term soil fertility trends and water changes under *Stylosanthes* dominant and native pasture systems.

Methods:

- Soil fertility monitoring sites (32) will be on soils representative of the major soil types on which *Stylosanthes* is currently being grown within the 500 to 1200 mm rainfall zone.
- Sites will have a range of treatments including: native pasture; *Stylosanthes* dominant pasture; and cleared and uncleared areas with and without *Stylosanthes*.
- At four of the soil fertility monitoring sites, a comparison will be made of soil water content between native pastures and *Stylosanthes* dominant pastures. At these sites, rainfall and soil water content at 0.50 and 1.2 m depth will be monitored on a daily basis.

Surface water, sediment and nutrient fluxes

Brigalow Experimental Catchment studies

Bruce Cowie,
Brigalow Research Station,
Department of Natural Resources,

Some data is still being collected for catchments at this site, on nutrient loss in runoff. A current project being developed by DNR proposes to incorporate this monitoring in a nested catchment study of water quality in the Fitzroy Catchment (see project description below).

Coping with rainfall variability: grazing management strategies for seasonally variable tropical savannas

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Overall project objectives:

1. Assess and demonstrate the ability of different grazing strategies to copy with rainfall variability in terms of their effects on animal production, economics, pasture condition, soil loss and biodiversity.
2. Develop, in conjunction with graziers, practical and sustainable grazing management strategies to copy with present and future rainfall variability.
3. Promote adoption of these strategies through demonstration and direct links to PMP, LCD and local Landcare/grazier groups.
4. Synthesise available data into simulation models to allow extrapolation to a range of different environmental and economic conditions.

Relevant subproject (proposed): soil and nutrient loss
Objective: To determine the effects of different grazing management strategies on soil loss and nutrient discharge into catchments.

Methods: Sub-catchments of 10-50 ha will be established, in each of the 100 ha experimental paddocks, to measure runoff and suspended sediments, bedload, and major nutrients (N, P & K). Smaller run-off plots will be nested within each mini-catchment so as to establish more precise relations between runoff and factors such as cover and soil surface condition.

Location: Wambiana Station, approximately 100 km S of Chartres Towers, in the Burdekin Catchment, in the semi-arid tropical savannas of northern Queensland.

How long will soils last with current grazing practices

Mr Mark Silburn,
APSRU,
Department of Natural Resources, Queensland,
PO Box 318,
TOOWOOMBA, QLD 4350

Objectives:
1. to calculate how long soils will continue to produce economically viable pasture growth, given the erosion and nutrient (nitrogen?) decline occurring with current and alternative grazing practices; and
2. to use this information to provide a rational and quantitative basis for determining grazing pressures and practices which will not degrade the soil through nutrient and soil loss.

Methods: Modelling will be used in conjunction with field experimental results, grazier knowledge and historical rainfall records, to calculate pasture production, and soil erosion and nutrient (nitrogen?) losses. Loss of nitrogen and soil (affects soil water storage capacity) results in lowered pasture productivity, an indicator of unsustainable management. Assessments will be undertaken on properties in *Aristida-Bothriochloa* eucalypt woodlands in the Balonne/Maranoa and Nogoa/Fitzroy catchments. These areas have a recognized risk of degradation as a result of soil erosion and previous or on-going field studies with pasture production, erosion and nutrient loss data.

The case studies involved will be conducted jointly with grazier and/or NLP groups and their advisers in each region, as well as with staff from within existing extension programs such as Droughtplan, PMP and Safe Carrying Capacity.

Anticipated outcomes: as well as outcomes stated in the objectives, these include, among others definition of sensitivity of various land types to losses of soil and nutrients (nitrogen?).

Duration: July 1996 to June 1999

Funding: NLP, QDPI (APSRU, Extension programs), DNR Resource Management Institute.

Land management to reduce nutrient movement from catchments

Mr Geoff Titmarsh,
Department of Natural Resources,
TOOWOOMBA, QLD 4350

Objectives:
1. Define nutrient contribution and composition from different land uses and soil types within catchments using point water balance models within a GIS and monitoring;
2. provide generic models and decision support tools to encourage informed and effective land management practices and catchment planning;
3. demonstrate application of these tools to a catchment having a diversity of land uses.

Nutrient monitoring:
- N, P and sediment loads in runoff water will be monitored at 14 locations;
- downward movement of chemicals in the soil will be estimated from deep soil sampling and analysis;
- monitoring will sample a wide range of soils and land uses in nested catchments

Water quality in the Fitzroy Catchment (proposal for NHT, MRC funding)

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Department of Natural Resources,
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Objective: to reduce the effects of agricultural production on water quality in the Fitzroy catchment.

Methods: the concept is to use a cascading catchment approach within each main land use type — grazing, dryland cropping and irrigation. This will involve:

1. on-farm research to measure plot-scale transport and the effects of management;
2. development of management practices at farm scale and measurement of water, sediment, nutrients and pesticides at the farm boundary;
3. stream measurements from farm to ocean to understand transport through the system.

Implementation of proposal for grazing land:

1. continuation of runoff and soil loss measurements from grazing trials at Galloway Plains and Keilambete, and from the Brigalow experimental catchments, plus monitoring of nutrients and chemicals;
2. establishment of catchment monitoring sites below each experimental catchment to link in with the ambient water quality, river health and gauging stations network.

ATTACHMENT 2 — TABULAR SUMMARIES OF HYDROLOGY & EROSION STUDIES

Small plot study in the Northern Territory

Williams (1976) carried out what seem to have been small plot studies (<10 m^2?) on 1-3 degree slopes on granite and sedimentary (sandstone) rocks in the Alligator Rivers area of the Northern Territory. In summary, the results of this work were:

- on the gentle granite slopes with sandy topsoils, soil loss per unit of rainfall momentum could be 20-40 times greater at the beginning of the wet season than by the middle of the wet season — this was attributed to the differences in surface cover;
- erosion from overland flow was greater on the steeper lower slopes of the low granite hills, with surface runoff augmented downslope by lateral seepage;
- on the sandstone hills, erosion from surface runoff was three times greater on the gentle, stone-free colluvial-alluvial foot slopes than on the steep rocky hill slopes — the lower rate on the steeper slopes was due to the protective stone cover; and
- disturbance to the natural vegetation, particularly if cover is destroyed during the wet season, could increase rates of erosion by 100-1000 times.

Williams also noted that deep soils were absent from slopes greater than about 5%, — even on these slopes, unprotected soils were vulnerable to erosion, emphasising the severe erosional regime in this environment.

Summaries of large plot studies

Land Management Strategies for the Semi Arid Tropics (LAMSAT) —Douglas Daly Research Farm, NT

Objectives:	To determine the relationships between ground cover, surface runoff, bedload and suspended matter for an improved pasture species *Eurochloa mosambicensis.*
Catchment:	Daly River
Climate:	Mean annual rainfall is 1200 mm
Topography:	< 2%
Soils:	Kandosols (gradational soils)
Vegetation type:	Improved pasture with *Eurochloa mosambicensis*
Plot size:	100 m^2 plots within larger areas of about 4 to 8 ha
Treatment:	Various stocking rates and artificial treatments (herbicide spraying, clipping and mowing) to obtain a range of ground cover conditions.
No of years	Data were obtained over the 1992/93 and 1993/94 wet seasons.
Results:	• Above 50% attached cover (ie, cover not including litter), runoff losses

were greatly reduced for all rainfall amounts.
- Below a ground cover of about 50%, bedload and suspended sediment losses start to increase at an accelerated rate.

References: Dilshad *et al.* 1994

Torrens Creek Hydrological Study — natural environment

Objectives:	To determine the nature of overland flow, its generation and place in the hydrology of the environment.
Catchment:	Burdekin
Climate:	Mean annual rainfall is 552 mm
Topography:	Undissected plains, with slopes generally < 3.5% and lacking integrated drainage; slope of landscape segment with experimental work was 1.5%.
Soils:	Low fertility deep red earths (gradational) with loamy textures and clay contents grading from 13-26% in the top 0.60 m.
Vegetation type and surface conditions:	Low open woodlands with *Eucalyptus* or *Acacia* spp. and a discontinuous ground cover with *Triodia pungens*, *Heteropogon contortus* and *Aristida leptopoda.* Low termite mounds and bare areas, either crusted or covered with a fine sand deposit, are scattered throughout the area. Soil faunal activity, for example that of ants, is important in producing macropores.
Plot size:	Total landscape segment was 100 m, monitored by a cascading sequence of 5 troughs, 10 m in length; trough length was that considered necessary to cover the inherent pattern in the landscape.
Treatment:	Natural conditions
No of years	Two years (January 1982 - March, 1984)

Results:

- Only small amounts of rain (<3.6 mm) at intensities equal to or greater than 10 mm/hr are needed to satisfy surface detention and initiate overland flow;
- the temporal variability in saturated hydraulic conductivity of bare surface soil appear to determine the runoff process for any rainfall event;
- substantial redistribution of overland flow occurred over the 100 m transect so that only 2% of total rain is exported from the slope, with a maximum for any event of 4%;
- a severe fire in June 1982 increased the amount of sediment movement but there was no significant change in net loss or gain from the 100 m plot.
- the low runoff from the landscape as a whole as a result of local runoff reinfiltrating, explains the lack of channel incision in the broad valley bottoms and an integrated channel network.

References: Bonell and Williams (1986, 1987)

Cardigan Experimental Plots
Part of the Ecological Studies in the Semi-arid Tropics (ECOSSAT) Program

Objectives:	To investigate the effect of pasture management on runoff and soil movement from pastures.
Catchment:	Burdekin
Climate:	Average rainfall approx. 650 mm
Topography:	Undulating; slope 3%
Soils:	Neutral red duplex
Vegetation type:	Tropical tallgrass; Eucalypt woodland with herbaceous layer dominated by *Heteropogon contortus, Chrysopogan fallax* and *Bothriochloa ewartiana.*
Plot size:	Plot sizes varied to give different stocking rates; sizes were 0.5, 1.25 and 2.5 ha.
Treatment:	1. trees and native pasture; plots burnt in January 1990 2. trees killed and native pasture; plots burnt in January 1990 3. trees killed and legume—grass pasture established by oversowing; 4. trees killed, mechanically removed and legume—grass pasture established by sowing onto a cultivated seedbed. Each pasture system was grazed at two stocking rates.
No of years	Measurements were made from 1987-1990.
Results:	• Ground cover had a marked effect on runoff and soil movement, with increase in cover decreasing runoff and soil loss; • the influence of cover depended on rainfall amount and intensity — for small storms (total rainfall < 50 mm and intensity < 15 mm/h), runoff and sediment loss decreased rapidly as cover increased and 40 % cover reduced runoff to a low level; amount of cover needed to keep runoff and soil loss low increased as storm size increased, with cover having little effect in large storms; • data suggest that erosion is controlled by supply capacity rather than transport capacity; • soil loss was greatest for the plots with trees and native pastures and declined in the order of trees/native pasture > cleared/sown > killed trees/native pasture > killed trees/sown pasture though not all differences were significant; • suspended sediment contributed about half the total sediment; • for small storms immediately following burning, runoff and soil loss were smaller than for other plots with comparable cover; this was attributed to the still loose and friable surface of the soil — cover is thought not only to protect the surface directly but to be associated with soil faunal activity; in later larger storms, runoff and sediment loss were similar to that from unburnt plots with similar cover levels.
References:	McIvor *et al.* (1995)

QDPI sites near Charters Towers and Greenvale

Objectives:	To quantify run-off and soil movement in grazed woodlands and to determine the importance of cover, soil water status, rainfall intensity, rainfall event size and pasture type in determining rates of run-off and bedload and suspended sediment loss.
Catchment:	Burdekin
Climate:	Mean annual rainfall 600-675 mm
Topography:	Upper and mid-slope positions; slopes 1.5-5%
Soils:	6 sites with neutral red duplex soils derived from granodiorite 4 sites with neutral yellow duplex soils derived from sedimentary rocks
Vegetation type:	Eucalypt woodland with native or naturalized grass understoreys of greatly different composition. Dominant grass species included *Bothriochloa pertusa*, *Heteropogon contortus* or mixed species dominance.
Plot size:	4 ha.
Treatment:	Two treatments at each site — a 4 ha block fenced to exclude domestic stock and an adjacent 4 ha block open to stock.
No of years	5 year recording period; 1986-1991
Results:	• At similar covers, sites dominated by *Bothriochloa pertusa* generated less runoff than those dominated by native tussock grasses; • the effect of cover also depends on soil wetness, storm intensity and total rainfall — wet soils and high rainfall intensity can result in a high proportion of runoff even with high levels of cover; • high bedload and suspended sediment losses and runoff percentages were associated with low cover (<30%); soil movement from areas with >40-50% cover was very low; • although not statistically analysed, annual runoff in exclosures was always less than runoff in grazed areas with the same pasture type, although not always by much.
References:	Scanlan *et al.* (1991); Scanlan *et al.* (1996).

QDPI Kielembete and Glentulloch Grazing Trials
(Pasture stability in Aristida/Bothriochloa woodlands —MRC project DAQ.090)

Objectives:

Catchment: Fitzroy

Climate:

Topography:

Soils:

Vegetation type:

Study area size:

Treatment:

No. of years:

Results: *Glentullock 1996/1997 average runoff/soil loss summary for cleared plots*

	Grazing pressure		
	High 50% cover	**Medium 56% cover**	**Exclosure 85% cover**
Runoff (mm); (% of rain)	75 (12)	63 (10)	52 (8)
Suspended load (kg/ha); (% of total)	801 (38)	649 (36)	208 (25)
Bed load (kg/ha)	1316	1145	612
Total load (kg/ha)	2117	1794	820
kg soil lost/mm rainfall	3.3	2.8	1.3
kg soil lost/mm runoff	28.2	28.4	15.7

Kielambete 1996/1997 average runoff/soil loss summary for cleared plots

	Grazing pressure		
	High 69% cover	**Medium 64% cover**	**Exclosure 95% cover**
Runoff (mm); (% of rain)	234 (30)	217 (28)	63 (8)
Suspended load (kg/ha); (% of total)	2602 (41)	2481 (60)	41 (21)
Bed load (kg/ha)	6847	1714	117
Total load (kg/ha)	9449	4196	158
kg soil lost/mm rainfall	12.2	5.4	0.2
kg soil lost/mm runoff	40.4	19.3	2.5

Reference David Waters (pers.comm.)

QDPI Galloway Plains Grazing Trial
(Stability of speargrass pastures — central region; MRC Project DAQ.080)

Objectives:	To study soil hydrology changes associated with alteration of pasture due to different stocking rates. This was done by: 1. measuring runoff and sediment loss from both size plots for rainfall events; 2. measuring soil hydraulic conductivity with a disc permeameter at negative potentials which represented 1 and 3 mm pore sizes; 3. measuring peak runoff rate and total runoff from small plots following application of water at an intensity of 86 mm/hr, using a rotating disc rainfall simulator, until a steady state of runoff occurred.
Catchment:	Calliope
Climate:	Mean annual summer rainfall is about 882 mm
Topography:	Slope 6%
Soils:	Duplex (solonized solonetz) soils developed on granite.
Vegetation type:	Tropical tallgrass; *Heteropogon contortus* dominant
Plot size:	Small plots 60-80 m^2, encompassing local patch variation, and a larger landscape plot 0.4 ha.
Treatment:	Stocking rates were 0, 0.25 and 0.5 steers/ha
No. of years:	1988-1995(?)
Results:	*Pore size characteristics* • in patches of *Heteropogon contortus* and *Bothriochloa bladhii*, 1 to 3 mm pores made a greater contribution to hydraulic conductivity than in *Aristida* spp. and annual grass patches; • stocking rate also had an effect on the contribution of 1 to 3 mm pores, with the hydraulic conductivity attributable to these pores in the exclosure being 164 mm/hr, 89 mm/hr in the plot stocked at 0.25 steers/ha and 26 mm/hr in the plot with 0.5 steers/ha; *Cumulative surface runoff and sediment movement following rainfall* • cumulative runoff from the heavily grazed large plots (778 mm) was much greater than from the exclosure (235 mm) or the plot with 0.25 steers/ha (approx. 250 mm); runoff and peak runoff rate for individual storm events also varied with stocking rates; • cumulative soil loss followed the same trends as cumulative runoff, except that there was a greater difference in soil loss between the heavily grazed plot (1171 kg/ha) and the exclosure (106 ka/ha); • runoff in small plots sometimes did not result in runoff in large plots, indicating the importance of patches and their distribution.
Issues:	A critical question is whether the loss of macroporosity associated with the higher stocking rates and change in pasture composition can be reversed with change in grazing management, and if so, how long such a change would take.
References:	QDPI (1996); Sallaway and Waters (1994)

CSIRO Glenwood grazing trial
(Stability of speargrass pastures —southern region; MRC Project CS195)

Objectives:	To study soil hydrology changes associated with alteration of pasture due to different stocking rates. This was done by: 1. measuring runoff and sediment loss from both size plots for rainfall events; 2. measuring soil hydraulic conductivity with a disc permeameter at negative potentials which represented 1 and 3 mm pore sizes; 3. measuring peak runoff rate and total runoff from small plots following application of water at an intensity of 86 mm/hr, using a rotating disc rainfall simulator, until a steady state of runoff occurred; 4. piezometer were installed in the A horizon, clay B horizon and granitic parent material in upper, mid and lower slope positions.
Catchment:	Burnett
Climate:	Mean annual rainfall: 708 mm; over the 79 month experimental period of the project, the site was in drought for 60 months.
Topography:	Undulating rises formed from the erosion of the deeply weathered adamellite parent material; slopes: 5%
Soils:	Mainly yellow podzolics with sandy topsoils
Vegetation type:	Eucalyptus woodland with *Heteropogon contortus* dominant; historical records indicate *Themeda triandra* is likely to have been a major species.
Plot size:	Landscape plots were 0.24-0.36 ha; smaller plots were 70-90 m^2; small plots were located so as to cover a patch of *H. contortus* and a patch of *Aristida* which was the smallest hydrological unit recognized in the field.
Treatment:	Exclosure, low and high stocking rates on landscape segments which included upper and midslopes
No. of years:	1989-1995
Results:	*Pore size characteristics* • *Aristida* patches had fewer pores between 1 and 3 mm as determined by differences in hydraulic conductivity; • there was a difference in the hydraulic conductivity associated with both 1-3 mm pores and pores < 1 mm between upper and mid slopes, with upper slopes having lower conductivities; • there was no clear stocking rate effect on the contribution of 1-3 mm pores and pores < 1 mm; this was attributed to possibly a more resilient soil or a reduced period of heavy stocking compared with the Galloway Plains site where similar measurements were undertaken. *Runoff from simulated rainfall* • *Heteropogon* patches had a lower peak runoff rates (3%)and total runoff (2%) than *Aristida* patches (14% and 8%); • mid-slopes similarly had lower peak runoff rates (4%) and total runoff (2%) than upper slopes (8%, 12%). *Cumulative surface runoff and sediment movement following rainfall* • Annual cumulative runoff and sediment loss was higher from upper slopes than mid-slopes, averaged over the different stocking rates; • cumulative runoff and soil loss from small plots in each slope position increased with an increase in stocking rate — in upper slope positions,

cumulative soil loss reached 3092 kg/ha under high stocking rates compared with only 79 kg/ha soil loss in the exclosure
- runoff from small plots did not always result in runoff from large plots;
- high sediment loss was associated with isolated high intensity rain events during drought conditions when cover was low.

References: McIntyre (1996); Sallaway and Waters 1994

Mt Mort Cattle-producer Demonstration Site

Catchment: Bremer

Climate: Mean annual rainfall is 852 mm

Topography: Slope: 10-15%

Soils: Soloths (duplex - Dr3.41) with a loamy sand topsoil overlying a sandy clay subsoil

Vegetation type: Open forest with *Heteropogon contortus* pasture community

Plot size: 30 m^2

Treatment: Bare, grazed (paddock conditions) and exclosure

Objectives: To measure runoff, erosion and phosphorus losses under medium tree density.

No. of years: 1992 — on-going

Results: 92/93 - 95/96 (4 years)

	Average annual values (Av rainfall = 427 mm)		
	Exclosure	Grazed	Bare
Average cover (%)	90	79	5
Total runoff (mm)	9	18	79
Runoff/rainfall (%)	2	4	19
Total soil loss (t/ha)	0.2	0.6	34
Nitrogen (kg/ha)	0.2	2.0	43
Phosphorous	0.2	0.5	18

- Suspended load contains little clay and a large proportion of silt and sand sized particles which appear to be organic rather than mineral.
- 40% N, 20% of P and 20% of sediment is in the suspended load.
- The four years for which results are given had only 50% of the long term average annual rainfall = drought.

Issues: Runoff on bare soils was much lower for these sandy topsoils than for a duplex soils with fine textured surface soil, but soil loss was greater

References: Silburn 1994

QDNR Springvale Runoff/Soil Loss Plots - Nogoa (Fitzroy) catchment, Qld

Objectives:	1. To determine the response of hillslope runoff and soil movement to cover for two solodic soils (sandstone and mudstone derived), including high and low tree density and +/- grazing, and to incorperate these responses into simulation models. 2. To quantify the spatial distribution of runoff and soil movement within the Springvale catchment and at the catchment outlet, and to validate use of distributed parameter hydrologic models.
Catchment:	Nogoa River, tributary of the Fitzroy River, central Qld
Climate:	Mean annual rainfall 650-730 mm (CV = 40%), semi-arid/subtropical to tropical
Topography:	In most of the catchment, the runoff arrives at a gully or concentrated flow channel within 50-100 m from the catchment boundary, ie. this is the typical maximum hillslope length. Plot runoff measurements are generally located on lower or mid-slope positions. Some plots are artificially bounded to include only one soil and uniform vegetation, while others include an entire hillsope sequence, artifically bounded along approximate natural boundaries or are unbounded, upto or approaching the top of the hillslope. Slopes are 4 - 8 %, with one of 17 %.
Soils:	Duplex soils and lithosols derived from a) mudstone and b) sandstone
Vegetation type:	Vegetation consists of grasses (*Bothriochloa* spp., *Aristida* spp., *Heteropogon contortus, Themada australis*) under open silver-leaf ironbark woodland (*Eucalyptus melanophloia*), with much less grass biomass and poorer grasses under dense groves of silver-leaf ironbark.
Plot size:	Plots representing one soil/vegetation are 14 - 80 m^2; bounded hillslope plots are irregular shapes of upto 640 m^2. Whole catchment area is 9.6 ha.
Treatment:	Two plots are located on bare areas with smooth hard-setting surfaces (scalds); four plots have a high tree density; eight plots are in open woodland; one plot is on a highly eroded area that includes small gully headcuts; and four plots are in a grazed area.
No. of years:	8 years; 1987 - 1995 (some on-going measurements)
Results:	• Runoff and soil loss were both highly related to the proportion of on/near-ground cover, with only minor differences between the cover (eg grass or tree litter) or soil types studied. • Runoff was a large component of the water balance in degraded pastures (cover < 15%), with up to 50% of annual rainfall lost as runoff. Rain is still lost as runoff from low cover areas during droughts. • Annual runoff at the catchment outlet declined from 30% of rainfall when the catchment was heavily grazed to 4% of rainfall after destocking and revegetation. • Annual soil losses from degraded pasture were 15-25 t/ha, equivalent to about 2 mm depth of soil lost per year. As these soils are shallow (400-600 mm) and have most nutrients concentrated in the upper layers (Ciesiolka 1987) this soil loss is excessive. • Maintenance of pasture cover above 40% reduced runoff and soil loss significantly. • Soil loss studies need to consider both bedload and suspended sediment, as

they can be approximately equal components of total soil loss.

- Where active rills and head-cuts occur, soil loss is greater than otherwise expected for the cover present, due to contributions from gully erosion.
- Dense tree cover greatly reduced grass growth and favoured poorer, shorter grasses. In the absence of grazing, cover on the ground remained > 50% due to leaf litter from the trees. This tree litter may not persists under heavy grazing. This is a critical point in assessing effects of trees on erosion and requires further research. Tree canopy cover was 20 - 40% in dense groves of ironbarks, but is not considered to reduce erosion due to the large fall height of water drops.
- measured total plant available water capacities (PAWC) of soils were:- 100-115 mm mudstone derived soils (500 mm deep), 70-80 mm sandstone derived lithosol (400 mm deep), 120 mm sandstone derived duplex (600 mm deep), 38 mm mudstone eroded to C horizon (400 mm deep).
- Good predictions of measured soil moisture and runoff were obtained using the runoff model from PERFECT (Littleboy *et al.* 1992) in the grass production model GRASP (McKeon *et al.* 1990). A single set of runoff parameters was derived which allowed runoff to be predicted from all plots, with models predictions of differences in cover accounting for differences in runoff between plots.
- Runoff data from the hillslope plots within the catchment was used to show that the spatially distributed model ANSWERS predicted runoff from areas of difference soil and cover within the catchment, as well as giving good predictions of runoff hydrographs at the catchment outlet.

References: Ciesiolka (1987), Silburn *et al.* (1992), Yee Yet (1994), Yee Yet *et al.* (1994), Connolly *et al.* (1997), Connolly *et al.* (in press).

Summaries of small catchment studies

Brigalow Experimental Catchment Study (near Theodore)

Catchment:	Dawson/Fitzroy
Climate:	Semi-arid to subtropical; Annual rainfall range: 420-1100 mm; mean 650 mm Evapotranspiration > rainfall in all months Rainfall during the five years of monitoring after clearing was consistently lower than the mean of 400 mm.
Topography:	Slopes: 0-4%; mean 2.5%
Soils:	Dark cracking and non-cracking clays; duplex soils
Vegetation type:	Brigalow forest and woodland; woodland with *Casurarina cristata* and *Eucalyptus cambageana* also dominant.
Catchment size:	Cleared: 12.7 ha; control: 16.8 ha.
Treatment:	Monitoring commenced in 1965; the smaller catchment was cleared in 1982 and sown to buffel grass pasture in 1983; grazing commenced in the following year.
Objectives:	The general objective was to understand catchment response to land use change and management in a semi-arid region, particularly where the soils are shallow and relatively impermeable. The specific objectives were to quantify the effects of clearing brigalow in Central Queensland for grazing, on: • catchment hydrology (runoff and hydrograph shape); • catchment erosion • soil and watertable salinity; • soil fertility • productivity
Results:	• Mean runoff measured from the cleared catchment was 47.4 mm; this compared with a value of 23 mm estimated as the mean runoff had clearing not taken place. • Clearing increased catchment runoff from 3% of rainfall to around 6% where pasture had a good cover (? >60%) of buffel grass. • Variation in runoff was associated more with rainfall amount than with rainfall intensity. • Clearing had a substantial affect on recharge in a very high rainfall year prior to complete pasture establishment (30 mm/yr compared with 7 mm/yr under native vegetation) but not in the lower rainfall years; in years with lower rainfall there was no recharge. • The lack of differences in recharge rates between brigalow and pasture were attributed to the slowly permeable duplex soils, the climate and the water use characteristics of Brigalow. Brigalow is a shallow-rooted species, with only a small proportion of roots extending below 0.8 m.
References:	Lawrence *et al.* (1991), Lawrence and Sinclair (1989), Thorburn *et al.* (1991)

Narayen Small Catchment Study

Catchment:	Burnett
Climate:	Mean annual rainfall: 720 mm
Topography:	Slopes: 2°
Soils:	Predominantly duplex soils that have formed on weathered granitic material; surface soils coarse sandy to gravelly overlying sandy clay to heavy clay subsoils.
Vegetation type:	*Eucalyptus melanophloia* open woodland with *Heteropogon contortus*
Catchment size:	Four catchments, 9 - 31 ha
Treatment:	In 1975, trees in two catchments were killed and seeded with Siratro (*Macroptilium atropurpureum*) and green panic (*Panicum maximum*)
Objectives:	To investigate the effect on hydrology in a subhumid area, of a change in land management
Methods:	Paired catchment approach. Monitoring began in 1972 and treatments were imposed in 1975.
Results:	• there was little change in the soil water regime between cleared and uncleared sites, attributable to most trees having similar rooting zones to pasture plants; • following clearing, the increase in drainage below 3.0 m was considered to be negligible on the basis of changes in water content at this depth (*note*: change in water content on its own is not an accurate means of assessing drainage); • runoff data is difficult to interpret due to monitoring after clearing coinciding with very dry years.
References:	Prebble and Stirk 1988

Review 5

WATER, SEDIMENT AND NUTRIENT FLUXES — LARGE CATCHMENT AND RIVER BASIN SCALES

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Contents

Determining the effects of different grazing and pasture management strategies on water, sediment and nutrient movement at plot and small catchment scales is a relatively straightforward procedure. At these scales it is possible to establish areas with contrasting grazing and management treatments and compare the results. At large catchment to basin scales (thousands of square kilometres), determining the change in fluxes that can be attributed to grazing is much more problematic. While in the more humid climates at least, runoff and dissolved nutrients will be carried relatively rapidly from source areas to the coast, the same is not true for sediments and their sorbed nutrients, other than possibly very fine particles. Many factors impinge on sediment fluxes at large catchment scales and disentangling the effects of grazing in the absence of being able to establish comparative studies that hold some factors constant and vary those of interest, is difficult.

1. Extrapolating from plot and small catchment studies

While plot and small catchment studies show conclusively that stocking rates and pasture management practices can have quite pronounced effects on sediment and nutrient loss, this increased loss does not automatically translate into increased sediment and nutrient fluxes at the mouth of a river or even the outlet of a large subcatchment. Sediment and associated sorbed nutrients eroded from a slope can be deposited downslope, or downstream on floodplains or in the river system, and remain there for appreciable lengths of time, before being remobilized at a later date. Finlayson and Silburn (1996) point out, for example, that only 9% of the sediment eroded from a hillslope in SE Queensland was 'suspended sediment' and hence likely to have travelled any large distance during the storm. Most of the bedload sediment would have travelled little further than the base of the erosion plot.

Sediment storage in northern Australian river systems seems not to have received a great deal of attention but, as an example of storages that can occur, Finlayson (1992) notes that clays in suspension are the only sediments now passing downstream from the Brown River past Lake Nuga Nuga (Fitzroy catchment, central Queensland). Further, the geomorphology of the site suggests that no coarse river sediment from the Brown River has been transported beyond the lake for perhaps thousands of years, though this has never been formally investigated.

It seems to be fairly well established that in many landscapes, most N and P move attached to particles, particularly very fine particles, rather than in solution. Consequently, fluxes of these nutrients depend on the transport and deposition of the sediments with which they are associated. Not all sediments, however, contain equal concentrations of N and P, with the nutrient concentration having been found to be related to particle size (organic matter>clay>silt>sand).

Attempts to determine the effect of grazing on river basin sediment and nutrient yields by measuring the yields from plots or small catchments and summing these for the whole catchment, would seem to have validity only for fine sediments, which are likely to remain in suspension, and their attached nutrients. A further difficulty with such approaches, however, is the variation in loss that can occur throughout a basin in response to differences in land type, including climate. Losses measured for a particular land use in one part of the catchment cannot be assumed to be the same in others.

Whatever the shortcomings, several studies have adopted a 'scaling up' approach to estimate the effects of grazing on catchment sediment and nutrient fluxes. Those by Moss *et al.* (1993) and Neil and Yu (1996) are discussed below.

1.1. Estimates of catchment sediment exports by Moss *et al.* (1993)

Moss *et al.* (1993) made a preliminary estimate of sediment and nutrient exports from Queensland coastal catchments using a desk-top model approach. Their report has not been obtained for this review and information given here is derived from Moss *et al.* (1996) and Wasson (1996). To derive their preliminary estimate of total sediment reaching the Great Barrier Reef Lagoon, Moss *et al.* developed two simple statistical models. The first was based on flow-weighted sediment concentrations and annual average stream discharge. The second model took into account land use, catchment erosion rates and a sediment delivery ratio that was held constant for all catchments. Calculation of sediment loads was based on published sediment loss rates obtained from plot and small catchment studies for each land use and then summed across the whole catchment. The authors noted that the data available for calculating such losses were very limited and recommended further studies to obtain relevant data.

Current sediment loads from all Queensland coastal catchments were estimated as being 3-4 times greater than pre-European loads (see Table 2 in Review 6). The study also concluded that about 84% of sediment from Queensland coastal catchments is from grazing land, but this estimate does not distinguish between what would have been natural inputs and the increase that can be attributed to grazing.

1.2. Estimates of catchment sediment exports by Neil and Yu (1996)

Neil and Yu (1996) also estimated sediment input from all streams discharging into the Great Barrier Reef lagoon using a modelling approach. The model was derived from sediment concentration and daily streamflow data for the Barron, Tully, Herbert and Burdekin Rivers; Babinda Creek; and the headwaters of the Flinders River. These data were used to construct sediment rating curves, from which mean annual sediment yields were calculated using daily streamflow data. Mean annual sediment yields, catchment area and mean annual rainfall were then used to determine unit sediment yields (sediment yield per unit area per unit runoff per unit time). Unit sediment yields for undisturbed catchments were estimated from the calculated unit sediment yields by adjusting these downward using the factors of Moss *et al.* (1993) for change in sediment yield associated with land use change. A change to cropping or grazing was estimated to increase sediment yield by a factor of 10 and 4 respectively, except for grazing in areas with rainfall greater than 2 000 mm/yr where the increase was estimated to be by a factor of 2.

Using this model, Neil and Yu estimated a total increase in sediment yield from the entire east coast of Queensland, of about 3.8 times that prior to European settlement, with the proportional contribution from individual catchments remaining very similar. The estimated increase in input from the Burdekin and Fitzroy catchments was about 4 times that of the natural yield, with these catchments together contributing about 68% of total sediment export. Neil and Yu also estimated the proportion of current nutrient export attributable to natural processes, grazing and cropping as 26%, 66% and 8% respectively although they noted considerable spatial variation in the relative contributions of grazing and cropping. Grazing contributes a higher relative proportion of sediment in the wet-dry tropics and cropping a higher proportion in the humid tropics.

The estimates of sediment yields in this study, do not represent a 'scaling up' from small catchment and plot data to the same extent as model 2 of Moss *et al.* (1993) appears to do. There is, however, extrapolation of relationships of unit sediment yield and runoff from catchments in which the relationships were derived, to other catchments, not all of which have the same climatic regimes, land types and so on.

1.3. Estimates of nutrient fluxes

Wasson (1996) compiled various published estimates of total phosphorus and nitrogen yields to the Great Barrier Reef. These estimates, however, are all of total amounts of nutrient currently exported and no indication is given either of the sources (slopes and plains, gullies, channels and floodplains or of the particular geographic location within a catchment) of these nutrients or of how these nutrient levels are thought to compare with nutrient inputs under natural conditions. Wasson noted that Moss *et al.* (1993) derived estimates of nutrient losses using measured sediment losses from plot experiments combined with soil nutrient concentrations, but cautioned against using these estimates as a guide to the significance of the different land uses as sources of nutrients. This was partly because the formulation used could not be tested and partly because the values appeared to be high compared with other estimates.

2. Measuring fluxes at a catchment outlet

An alternative to summing runoff, sediment and nutrient fluxes across a catchment, is to monitor fluxes at the catchment mouth and to correlate change in flux with a major change in catchment land use, such as the introduction of grazing. An immediate problem here is that monitoring records often post-date changes of interest or a sufficiently long monitoring record is not available to distinguish between changes due to variation in climate and those attributable to grazing. Wasson (1996) noted that, while it may be expected that introduction of current land uses would be expected to have changed the proportion of rainfall that runs off of the land and hence river flows, there have been no relevant analyses of data for catchments entering the Great Barrier Reef lagoon. The same lack of analysis is likely to apply to all northern Australian coastal catchments.

Identified state monitoring programs which could provide relevant water, sediment and nutrient flux data are listed in Attachment 1, though it is recognised that this is an incomplete list. In addition, perusal of the proceedings from the recent *Downstream Effects of Land Use* conference (Hunter *et al.* 1996) suggest there are various research programs that are also collecting relevant data. Moss *et al.* (1996) in an assessment of the effect of land use on rivers, estuaries and bays in southern Queensland, recommended a review of all runoff, sediment and nutrient data-gathering exercises in the south of the state. This recommendation needs to be extended to the whole state and, as far as the grazing industry is concerned, to relevant areas in northern Australia. Data already available, data collection methods and distribution of monitoring sites has not been investigated in this project. Chris Barnes commented on the need to assemble a data base of river monitoring records from different authorities, at least for some of the larger Queensland catchments. This was regarded as a matter of urgency as data were in danger of being lost as departmental program objectives changed. He also noted that flow and turbidity records in the Fitzroy catchment extend back to about 1926 and that some useful insights might be gained by examining this record, particularly if this were done in conjunction with other sediment-sourcing studies.

Most studies that are currently monitoring river water quality and sediment and nutrient fluxes in relation to land use, are providing data on the contribution of different land uses to total fluxes but little information on the change in fluxes brought about by different land uses. An approximation can be made by comparison of fluxes from particular land uses with fluxes from natural areas but differences in rainfall and other landscape characteristics usually remain a problem.

An alternative to correlating monitoring records with grazing history directly, is to use a surrogate for grazing, such as plant cover. For example, Andrew Ash (pers. comm.) has a proposal to correlate plant cover over the catchment with rainfall and Burdekin River flow records. Since heavy grazing is known to influence cover, including during droughts, a correlation between flows and cover would strongly suggest a grazing influence on flows. Preliminary data analyses of rainfall and Burdekin River flow records suggests a major change in the relationship in flows per unit annual rainfall over the last thirty years. During this time there has been a major increase in the number of cattle retained during dry years and it is suspected that this may be a cause of the relatively higher increase in turbidity per unit rainfall.

3. Alternative records of sediment and nutrient flux change

Sediments eroded from hills and slopes are transported varying distances before being deposited, with the distance of transport depending on sediment size and transport capacity of the stream or river flow. Floodplains, lakes and river estuaries are often environments of reduced water flow velocities and hence sediment deposition. Saline water at river mouths and in estuaries also promotes the flocculation of fine suspended particles. Over time, large amounts of sediment can accumulate and, provided material is incorporated which can be dated, these provide a record of the change in rate of sediment deposition over time. Dating does not necessarily need to be absolute but could be by the incorporation of a marker specific to a particular land use. Analyses of the material deposited are also needed to ensure that it is of terrestrial origin. If grazing (or other land use) within a catchment has had a marked effect on the amount of sediment being eroded and transported by a river, then the expectation is that this change can be identified by identifying a changed rate of terrestrial sediment accumulation, that is correlated in time with the change in land use.

It is worth noting, that even if a change in sedimentation rate in downstream deposits is observed, it can not necessarily be assumed to be associated with increased sheet erosion. Wasson (1996) points to the work of Wallbrink and Murray (1993) and Wallbrink *et al.* (1996) that has used radionuclides to show that about 90% of the suspended sediment transported in the lower Murrumbidgee catchment in New South Wales comes from channel and gully erosion, with little material supplied by the main channel. Any increases in sediment transport and deposition in northern Australian rivers associated with grazing practices may well be primarily due to increased gullying or reduced stability of channel banks.

Another record of changes in flux of material from the land to the sea is found in corals. Coral cores provide a means for investigating century long records of coral growth in relation to climate and water quality changes.

3.1. Sediment deposits on floodplains, in estuaries and on the continental margin

Away from the Queensland coast in the vicinity of the reef, there seems to have been relatively little investigation of coastal floodplain or delta sediment stores, at least from the point of view of their record of change in sediment deposition associated with land use change in the contributing catchment. Coastal floodplains and estuaries, however, seem to have been the subject of several studies investigating coastal landform evolution and changes in the Holocene, for example, Chappell and Woodroffe (1984), Woodroffe *et al.* (1984), Lees (1984) and Semeniuk (1982), to name a few.

Development of uranium mining in the Alligator Rivers Region of the Northern Territory and the need for disposal of tailing wastes which would not contaminate the environment, lead to the detailed study of the Magela Creek Plain and investigation of erosional, depositional and fluvial processes in the region (Wasson 1992 and work cited in this). This report has not been examined in detail but presumably contains much that is relevant to understanding the current environment and processes operating but little that can be used directly in this current overview of the effects of grazing.

Current work in the Herbert River catchment in Queensland involves a study of coastal floodplain deposits (see Attachment 4) but data are not yet available. A project which aims to use sediment cores to reconstruct changes in carbon and nitrogen inputs to, and the trophic status of, the system over time, is also to be undertaken in the Fitzroy catchment as part of the National Eutrophication Management Program (see component review on eutrophication and algal blooms). This project has been initiated as it has not yet been properly demonstrated that changes in water quality have occurred as a result of human activity. So far, a location for obtaining suitable cores has not been obtained. Criteria for suitability include a location not being subject to physical disturbance, sufficient rates of sediment deposition for deposition over relatively small time intervals to be easily measurable and a period of deposition of sufficient length to cover the time span of interest.

3.2. Coral core records

Variability in the growth of coral can be determined from assessments of cores taken from them. Since coral colonies have life spans greater than 200 years, they can be used to evaluate the natural variability in coral growth that occurred prior to European settlement. They can also be used to assess whether anthropogenic activities are likely to have caused a decline in the water quality of the Great Barrier Reef lagoon. Research programs at the Australian Institute of Marine Science are currently involved with examining growth rates of coral colonies with a 237 period of growth and also with assessing cores for evidence of episodic floods (see Review 6).

4. Sediment sources

Plot scale investigations of sediment loss measure the amount of sediment removed from a given area by sheet and rill erosion. As already noted, not all of this sediment will be transported immediately to, and through, the stream channel network. Some will be deposited before reaching the channel network, and sediment reaching the network may be deposited either within the channel or on floodplains. Such deposited sediment remains stored until it is remobilized by a subsequent erosion event. Consequently, the movement of at least some sediment (particularly the coarser size classes) through a catchment is episodic. The corollary of this is, that sediment exported from a catchment will not be derived uniformly from throughout the catchment. Also, not all sediment will be derived from sheet and rill erosion from slopes and plains. Some may be from gullies, stream and river channels, and floodplains.

4.1. The capacity of different landscapes to contribute sediment at a river mouth

4.1.1. Geomorphic Provinces

Williams and Bonell (1988) suggested, with respect to measurements of runoff and soil movement on slope segments, that "*many of the apparently intractable problems of field spatial variability, characteristically associated with soil infiltration properties, are due to an inappropriate scale of measurement.*" In essence, they went on to suggest that such problems could be overcome by determining and analysing the hydrologic unit that encompassed the pattern of variability.

Precisely the same comment could be made for trying to understand processes at large catchment scales. That is, much of the variability in a catchment with respect to transport and deposition could be understood by careful analysis of the surface hydrology of the landscape entities comprising that catchment. Essentially such an approach has been adopted by Aldrick in land resource assessments in the Ord and Roper River catchments and the Southern Gulf Region of the Northern Territory (Aldrick *et al.* 1978, Aldrick and Wilson 1990, 1992). In each of these land surveys, Aldrick has identified geomorphic provinces, where a geomorphic province is "*an area of land having attributes of landform and/or soils and/or vegetation that differ consistently from those of other terrain, because of the direct influence of a geomorphological landscape-forming process or processes operating there but not operating elsewhere at the same rate*" (Aldrick 1985).

Over long time-periods, geomorphic features, rather than vegetation or soils, exert a dominant control on sediment supply and the transport capacity of water at different places within the catchment. Provinces have been identified on the basis of these controlling geomorphic features and the implications described for natural erosion and the transport of sediment towards the coast. Soils and vegetation, however, may provide very important shorter-term secondary controls within the overall process regime defined by the geomorphology. For example, Province G2 in the Southern Gulf Region, represents a geomorphically unstable area as the protective laterite, clay or sandstone cap rock has been incised, exposing the underlying soft materials, and rates of erosion and sediment transport are potentially high. High potential erosion and transport rates result from the upper landscape position (height above base-level) and high relief. Current stability is imparted by the vegetation cover which, if removed, would result in a rapid shift to an unstable phase.

The basis of a geomorphic province is usually either an influence of base-level or the occurrence of a specific substrate, such as pre-weathered materials or weakly consolidated deposits. In the case of base-level, two situations occur. In one, there is a local base-level of erosion within a catchment (for example, due to the presence of a hard erosion resistant rock) such that there is a difference above and below the barrier in relative rates of sediment production/accumulation and sediment removal through the system. In the other situation, there has been a 'recent' change in base-level (for example, due to river capture or breaching of a local base-level) so that drainage rejuvenation is occurring, and a new wave of natural erosion is working back up a particular catchment, as is occurring in the Ord River area (John Aldrick, pers. comm.). Full descriptions of the different provinces recognized in the Southern Gulf Region, are given in Attachment 2 as examples of geomorphic provinces, to help illustrate the principles behind their recognition.

Little use appears to have been made of the concept of geomorphic provinces and resultant landscape stratification despite its obvious value as a framework for understanding the inherent differences in sediment production and transport between different landscapes within a catchment. It would seem to offer potential for providing initial hypotheses and as a basis for locating research and monitoring sites. Since, more generally, geomorphic provinces identify areas with different rates and types of landscape processes, they can also be used in a broad assessment of the susceptibility of land to degradation. This aspect is considered later in this report in the section commenting on use of land resource information.

4.1.2. Local relationships between slopes and channels

Recently, several authors (e.g. Finlayson and Silburn 1996, Wasson 1996) have pointed out that the position of a slope in relation to a stream channel affects the extent to which erosion on the slope can result in sediment input to the channel. In headwater catchments, there is usually a direct connection but as stream order increases, slopes often become separated from channels by floodplains. Consequently, a large proportion of sediment eroded from the slope tends to be deposited on the plain and does not reach the channel. An aspect of the National Rehabilitation of Riparian Lands Program is to identify relationships between stream order/river geometry and surrounding terrain morphology, and their control on water and sediment movement to channels. This assessment is concerned with processes at a relatively local scale, and hence, ideally, needs to take place within the larger framework of geomorphic provinces described above.

4.2. Sediment tracing — the Ord catchment

Several sediment tracing studies have been undertaken in southern Australia to determine the source of sediment in river and channel systems (see Section 5 below). The only sediment tracing study for northern Australia identified during this review, was that by Wasson *et al.* (1994) for Lake Argyle in Western Australia. This project, which aimed to determine the sources of sediment reaching Lake Argyle, was undertaken as part of the assessment of the Ord River Regeneration Project by the Western Australian Department of Agriculture. Key findings of this project (Wasson *et al.* 1994) were:

- a best estimate for sedimentation rate in Lake Argyle of $23.5 \pm 4.7 \times 10^6$ t/yr (based on reservoir survey), with 80% of the sediment silt and clay sized; the catchment of Lake Argyle is 46 000 km^2;
- annual specific sediment yield (t/km^2), derived from estimates of sediment yield available for subcatchments, increased with catchment area — this was attributed to the most erodible rocks and soils being in the downstream part of the catchment;
- about 60% of the sediment in Lake Argyle comes from the Hardman Syncline and about 34% is derived from the area between the Negri River and the lake, as indicated by Nd isotope tracers; of the tributaries, the Bow, Negri, Osmond and Panton Rivers make the largest relative contributions; and soils on the western side and basaltic soils on the eastern side are not major sources of sediment;
- only 10% of Lake sediment was derived from surface erosion, the remainder coming from channel erosion of subsurface soils; the major river channels (particularly the Ord) and gully network are therefore the major contributors of sediment, with possibly some deep sheet erosion;
- grazing of areas revegetated in the Ord River Revegetation Program combined with poor wet seasons has resulted in bare areas in some catchments that are able to generate sufficient runoff to initiate rills and continue to erode gullies, thereby reducing the effectiveness of revegetation.

Historical records suggest that severe erosion and gully development post-date European settlement. Given the identified contribution of subsoil to Lake Argyle sediments, it would seem that this is an area where grazing can be shown to have increased sedimentation in a downstream waterbody.

5. Variation in sediment deposition and transport attributable to grazing

Various sediment tracing and sediment budget studies (Olley *et al.* 1993; Wallbrink *et al.* 1996 Wasson *et al.* 1994) are indicating that a high proportion of the sediment reaching reservoirs and river mouths is derived from subsoil, and hence from stream channel and gully erosion, rather than from sheet erosion of topsoils. These results from sediment tracing fit with the observation of higher sediment yields from gullied catchments rather than ungullied catchments (eg, Wasson 1997). While sediment tracing work is not extensive, intuitively the results seem sensible and likely to apply to catchments with extensive gully and channel networks given the direct connection between erosion and transport. Consequently, investigations of the effect of grazing on gully establishment and channel stability are highly pertinent to evaluating the effects of grazing on the downstream flux of sediments and nutrients.

Accession to the channel network of sediments eroded by overland flow, however, can still be an important source of sediment. This may be particularly true for local systems and their ecology. It is therefore also necessary to consider the effects that grazing in the riparian zone may have on these accessions.

5.1. Changes in channel stability

There appears to have been relatively little investigation of northern Australian fluvial systems and changes within them following European settlement, although Finlayson and Brizga (1993) note that the morphology and Quaternary evolution of anastomosing streams in the Channel Country have received some attention, and Pickup *et al.* (1988) have looked at the importance of major flood events in determining morphology of the Finke River.

Of more interest to this review is the study of Finlayson and Brizga (1993) that describes changes in the Nogoa River in the area known as Lake Salvator (central Queensland) from the first European contact to the present. During this period, the form of the river has changed from a number of anastomosing channels distributed over the surface of what Finlayson and Brizga describe as a low-angled alluvial fan, to a single incised channel. Incision has reached a depth of around 5.0 m and the incised sediments show no evidence of previous periods of channel incision. A mass of charcoal from 3.5 m below the present surface and dated at 3350 $\pm$ 70 years BP, indicates a long period of sediment deposition. A suggested mechanism for channel incision is loss of vegetation cover and disturbance to the surface as a result of cattle congregating in the area. Vegetation loss would have reduced the threshold for scour erosion, enabling the large floods in the 1950s to incise a single main channel. Such a mechanism has been suggested by Prosser and Slade (1994) to explain the development of gullies on the Southern Tablelands of NSW in previously swampy valleys with a 'chain of ponds'.

There are also records of the effect of grazing on gully development, based on observation. For example Williams (1976) noted that gullies in parts of the Alligator Rivers area of the Northern Territory were often developed along former cattle and buffalo tracks.

5.2. Role of the riparian zone

Being at the interface of a channel with its catchment, riparian vegetation is considered to play an important role in both stabilizing the edges of the channel, and filtering sediment and nutrients from water running off the land into the waterway. Despite recognition of this likely role of vegetation, there are very few data quantifying the magnitude of the effect that vegetation can have and how this might vary for different land types (ie for areas with different climatic regime, geology, geomorphology, soil, vegetation) and stream order. Marked variation is to be expected given the control these factors exert on the rate and balance of hydrological processes.

Given the possible importance of riparian vegetation in controlling the accession of sediment and nutrients to streams, and the lack of quantitative data defining this importance, the LWRRDC established the National Rehabilitation and Management of Riparian Lands Program. The CRC for Catchment Hydrology runs Program A which is investigating the potential of vegetation for filtering sediments and nutrients from overland flow and for improving channel stability. Program B, managed by the Centre for Catchment and In-stream research at Griffith University, is studying the ecological functions of the riparian zone.

Specific objectives in Program A include:

- developing a conceptual framework for understanding and managing physical and chemical processes in riparian systems;
- quantifying the hydrologic regime of riparian zones across a range of channel orders and channel types;
- quantifying the capacity of riparian vegetation to reduce sediment and absorbed nutrient accession to channels;
- quantifying the effect of riparian vegetation on channel erosion and bank stability, particularly its role in preventing bank scour and mass failure of banks;
- constructing a mathematical model of the riparian system to allow the effectiveness of riparian vegetation in different landscapes to be tested; and
- communicating results from the research, particularly in the form of management guidelines.

Major project sites for Program A are the Johnstone River in north Queensland, the Kalgan River in south-west Western Australia, the LaTrobe River in Victoria, Jugiong Creek in New South Wales and Ripple Creek in Tasmania. Although a catchment from northern Australian is included in the experimental sites, most work in this catchment relates to the role of riparian vegetation in the lower catchment where intensive agriculture predominates and there is little work that is directly associated with grazing lands (see descriptions of current research in the Johnstone catchment in Attachment 4).

Extrapolation of research from one area to another has been regarded as a potential problem since the initiation of the Program. Consequently the research schedule has been designed to provide as much information of a generic nature as is possible and the incorporation of modelling (both conceptual and mathematical) is also to assist in extending the results to a wide variety of environments. Despite this, lack of data from northern Australia systems may reduce the extent to which information can be transferred to this region. Major differences in climatic regime, strongly seasonal or highly episodic flows, extensive shallow sandy channels in landscapes of very low relief, and so on, provide conditions outside the range being studied. The generic information from the Rehabilitation of Riparian Lands Program will, however, provide hypotheses which should be tested in this environment.

6. Current and proposed river basin water quality and catchment management projects

While there are several river gauging and water quality monitoring programs in Queensland, the Northern Territory and Western Australia that are relevant to any studies of the downstream effects of grazing (see Attachment 1), this section lists identified projects that aim to integrate investigations from a number of sources to provide information for complete river catchments or large sections of them.

6.1. Fitzroy River catchment, Qld

A study conducted between 1994 and 1996 investigated water quality (physico-chemical and biological) at eleven sites in the Fitzroy River system. Grazing accounts for around 90% of the land use in the catchment, which is one of the largest in Queensland. A full report on the project has yet to be released. Initial results indicated that at most sites, the diversity and abundance of invertebrates and native fish species suggested the stream conditions were relatively healthy. However, concentrations of suspended solids and nutrients (N and P) were generally higher than environmental guideline values, particularly at downstream sites. Blue-green algal blooms were also recorded at several locations. Funding support for this project was provided by the National Landcare Program.

Prior to this study, there was little base data for the catchment on water quality. The data obtained suggested that water quality could be improved by reducing the inputs due to grazing, dryland cropping and irrigation. As a result, the Central Region of the Queensland Department of Natural Resources currently has proposals submitted for a research program investigating aspects of water quality in the Fitzroy Catchment (see Attachment 3). In addition, research projects will be undertaken in this catchment as part of the National Eutrophication Management Program (see component review on eutrophication and algal blooms).

6.2. Herbert River catchment, Qld

The CSIRO has been involved in research in the Herbert River Catchment as part of the CSIRO Coastal Zone Multi-Divisional Programme that commenced in 1992?? The Australian Institute of Marine Science (AIMS) and several other research groups have also had a number of off-shore projects in the vicinity of the mouth of the Herbert catchment. The 1996 Great Barrier Reef Conference (James Cook University, November 1996) indicated the converging interests of these research groups and in February this year, Bob Wasson convened a meeting with relevant research scientists to review on-going work and identify a framework for a larger, more integrated programme of research. Another impetus for more integrated research is the possibility of this catchment being a participating catchment in the PAGES project "*Land Use and Climate Impacts on Fluvial Systems during the Period of Agriculture*". PAGES (Past Global Changes) is a core project of the International Geosphere Biosphere Program (IGBP).

As a result of this meeting, those involved formed an informal research group (The Herberts). While the specific aims of this group are still being resolved, generally the objectives relate to developing an holistic understanding of past and current land and marine environments, the effects of natural climatic shifts, and the effect of land condition on the marine environment. The emphasis on conditions prior to European settlement is to provide a context for current changes — pre-settlement conditions not only allow the changes in processes due to, say, the introduction of grazing to be more clearly identified, but also can provide a record against which the severity and uniqueness of current conditions can be assessed. Such a comparison may prove invaluable in future decisions relating to the use of our environment.

That science has a role in informing and enlarging the awareness of the whole community is a basic philosophy of the group and hence interpreting the data obtained from the various projects for different groups is an overall priority. A number of possibilities for extending the information to others have emerged. These include, in addition to the current avenues for interaction with management, producer and Landcare groups, science meeting presentations and a book on the Herbert River Region.

As a result of the workshop, the group has put together an inventory of the current and future research interests of scientists working in the Herbert River and adjacent marine environment (see Attachment 4). While not exhaustive, this provides a useful overview of current and proposed research in the Herbert region. It is apparent that the emphasis so far, with respect to the effect of anthropogenic activity, has been on land use in the lower Herbert catchment, particularly sugarcane.

6.3. North Johnstone River catchment, Qld

The North Johnstone River Catchment in north Queensland has been the focus of a water quality monitoring and modelling program run by the Department of Natural Resources as well as a focus catchment for the LWRRDC National Rehabilitation and Management of Riparian Lands Program. As with the Herbert Catchment, these programs have been concerned primarily with the more intensive land uses occurring lower in the catchment although Program A of the Rehabilitation and Management of Riparian Lands Program has a component project that will investigate the effects of cattle grazing on the accession of sediments and nutrients to the river.

Details of the projects within these programs are provided in this report (see Attachment 5) as they provide information relevant to methods being used to investigate and model water, sediment and nutrient fluxes from different land uses and subcatchments and to determine management practices which reduce the effects of practices offsite.

7. Summary

While it has been shown that grazing and grazing management can affect runoff, sediment and nutrient fluxes at plot and small catchment scales depending on management practices, the extent to which fluxes at the catchment mouth and their distribution in time have been altered is far from clear. A confounding issue is the degree to which sediments and nutrients lost from an area are redeposited before reaching the catchment mouth and the time of residence in such deposits. Another problem is the variation in climate. Neil (1996) for example, notes that the potential for sediment yield has increased over the last 50 years in the Tully catchment as a result of land use changes but that this has been offset by a reduction in rainfall erosivity over the same period. The effect of grazing on water, sediment and nutrient dynamics within the whole catchment requires a better understanding, where sediment and nutrient are taken to refer to the range of sediment particle sizes and nutrient species involved. A variety of techniques will be needed to provide this understanding. The emphasis of this work is to understand how catchments are functioning — which areas and processes are critical — so that appropriate management can be developed. At the same time, that any sediment or nutrient input to the river system represents a loss to the land resource, should not be forgotten. Degradation and loss of productivity on the land is just as much a reason for improved management as are the downstream effects.

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ATTACHMENT 1 — STATE WATER QUALITY MONITORING PROGRAMS

Queensland

State-wide Ambient Water Quality Monitoring Program

A network of sites is being set up throughout the state for regular monitoring (generally 4 times per year) of water quality and stream flows. Water quality parameters measured include major ions, nutrients (total N and P plus dissolved inorganic N and P) and (at selected sites) other parameters such as pesticides and heavy metals. Upstream land use is one of several factors that has been considered in selecting the sites to be monitored. Results of the monitoring will indicate long-term trends in water quality with time.

Contact: Dr Voytek Poplawski, Resource Sciences Centre, Department of Natural Resources, Brisbane.

Monitoring by Great Barrier Reef Marine Park Authority

Details not obtained

Monitoring River Health

This study forms part of a national program funded by LWRRDC to assess the ecological health of streams by relating the composition of the macroinvertebrate community structure to water quality and habitat characteristics. An initial three year study to develop and refine methodologies is now being followed by an assessment phase in which 300 Queensland sites will be evaluated in 1997. Sites have been selected throughout the state to reflect effects of potential impacting activities such as land use (including grazing).

Contact: Dr Satish Choy, Resource Sciences Centre, Department of Natural Resources, Brisbane.

State of the Rivers Program

This study aims to describe the ecological and physical condition of watercourses in Queensland catchments using a standardised methodology that combines desk-top appraisal with field survey techniques. Riparian and in-stream features are assessed, including issues such as: condition of land immediately bordering streams; riparian vegetation and bank stability; stream bed stability; aquatic vegetation; and aquatic habitat. Catchments already surveyed that include grazing as a major land use include the Thompson River, Barcoo River and Cooper Creek, Dawson River, Herbert River and Mary River. Surveys of other catchments are continuing.

Contact: Glen Moller, Resource Sciences Centre, Department of Natural Resources, Brisbane.

Community monitoring

Several programs are operating in Queensland to facilitate community involvement in monitoring the condition of catchment land and water resources. Landholders, community groups and schools are participating in monitoring programs such as Grass Check; Soil Check; Waterwatch; Saltwatch and Pasture Watch. The programs provide a framework for involving community members in catchment management issues and raising levels of awareness on natural resource issues. They also harness the enthusiasm and commitment of participants to collect monitoring data from many more locations than could be attempted by more traditional agency-based studies. One such example is the Lake Eyre catchment water quality monitoring project, where property owners and others are involved in a coordinated stream sampling program covering a vast area of mainly grazing lands in the far west of the state.

Contact: Lynne Turner, Resource Sciences Centre, Department of Natural Resources, Brisbane.

Northern Territory

Details not obtained

Western Australia

Details not obtained

ATTACHMENT 2 — GEOMORPHIC PROVINCE DESCRIPTIONS FOR THE SOUTHERN GULF REGION, NT

The following descriptions are from Aldrick and Wilson (1990).

Province G1(a)

This geomorphic province consists of intact areas of mature laterite on the old, stable erosion surface referred to by Christian *et al.* (1954) as the Tertiary Lateritic Plain. Due to the very low relief, the maturity of the drainage, and the inherent permeability of the laterite, very little erosion and sediment production occur. The modern, rejuvenated drainage pattern has not yet encroached upon these plains. Geologically, these areas correlate with the Mesozoic Group rocks.

Province G1(b)

This province contains the broad, extensive clay plains of the Barkly Tableland. These are in a similar category to the areas of G1(a), but here the soils have a very low permeability, and despite the drier climate, runoff and erosion rates are greater.

Province G2

This contains the escarpments, low hills, footslopes and gently sloping plains that occur around the inland edges of the area, and occasionally within it as well. Here, the laterite, clay or sandstone caprock has been incised, exposing relatively soft underlying materials. Rates of erosion and sediment transport are high, and because of the upper catchment position and relatively high relief there is no restriction on sediment transport. Geologically, this province occurs downstream from the Mesozoic Group rocks, especially in areas where rocks of the Roper Group are exposed.

Province G3

This province contains high, rocky sandstone plateaux and ridges. These are included mainly within the Palaeozoic Group of Lower Cambrian rocks and the Tawallah Group. Some older rocks are included. Here, rates of erosion are low due to the resistant nature of the rock. Rates of sediment removal are high due to the relief and the competence of the streams, although little sediment is available for transport. Because rates of sediment removal are greater than rates of sediment production in the catchments, rocky, skeletal areas result.

Province G4

Drainage in this province is strongly controlled by structure. A series of linear, mainly sandstone ridges lie across the direction of drainage. These consist of erosion-resistant rocks which have inhibited the normal down-cutting of streams.

In the past, rates of sediment production in the catchments have exceeded the capacity of the streams to remove it, and detention of sediment has resulted in some fluvial and lacustrine accumulations. Rates of erosion immediately upstream from these deposits have been slowed, and broad shallow valleys have resulted. Because of water impoundment, springs are a prominent feature, eg Butterfly Springs. In the upper catchment areas, erosion continues unabated, but most rocks in those areas are resistant sandstones. This geomorphic province correlates with the Tawallah and McArthur Groups of rocks in the central part of the area. Drainage here is superimposed and has incised down to, exposed, and been modified by the sandstone ridge systems.

Province G5

This province occurs on the coastwards side of the prominent ridges of the G4 province. Here, there is no restriction to coastwards sediment transport. Low relief, gentle erosional slopes and competent, low gradient streams are characteristic. Depositional plains occur in some areas, as sediment is temporarily impounded. Most areas occur on parts of the Roper and McArthur Groups of rocks north-east of the Masterton Horst, but also on some very old Lower Proterozoic rocks and on some sub-coastal Cainozoic deposits.

Province G6

This geomorphic province occurs near the coast, and coastal influences are prominent. The influence may be directly depositional, or due to proximity to base level. The immediate coastal strip with its beaches, berms and dunes is naturally quite dynamic. Further inland, almost flat coastal terraces (old sea floor materials) have been exposed. Rates of landscape denudation here are very slow due to the low relief, high soil permeability, and juvenile disintegrated drainage patterns. Apart from through-flow from inland areas, rates of sediment production are very low, and there is no impediment other than ultimate base level to sediment transport. This province occurs on the more recent of the Cainozoic deposits.

ATTACHMENT 3 — PROPOSED WATER QUALITY RESEARCH FOR THE FITZROY RIVER, QLD

Water quality in the Fitzroy Catchment

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Objective: to reduce the effects of agricultural production on water quality in the Fitzroy catchment.

Methods: the concept is to use a cascading catchment approach within each main land use type — grazing, dryland cropping and irrigation. This will involve:

1. on-farm research to measure plot-scale transport and the effects of management;
2. development of management practices at farm scale and measurement of water, sediment, nutrients and pesticides at the farm boundary;
3. stream measurements from farm to ocean to understand transport through the system.

Implementation:

1. grazing land: details are provided in Attachment 1, Review 4
2. dryland cropping:
   - the current project "Water quality impacts from dryland cropping in the Fitzroy Catchment" (funded by CRC for Sustainable Cotton Production) measures runoff, and sediment, nutrient and pesticide transport from a range of treatments and rotations involving dryland cotton;
   - a project currently being reviewed by GRDC and LWRRDC proposes to measure runoff, sediment and agri-chemicals from two paddocks with different managements on six farms;
   - an NHT proposal "Water quality impacts from dryland cropping in the Fitzroy Catchment" proposes to measure off-farm transport below each site (farm boundary and first order streams).
3. irrigation:
   - The project "Irrigation areas study" (funded by LWRRDC) measured runoff, and sediment and chemical transport through the drainage system of the Emerald Irrigation Area;
   - the cotton research and development corporation has funded a project "Best management practices to minimize pollutant transport from cotton production systems" that will develop on-farm management practices to reduce pesticide and nutrient transport. Water quality data will be collected within this project at paddock and farm scale.

All farm and first order stream monitoring will be linked with the ambient water quality monitoring network. Other relevant monitoring programs are the River Health Initiative and Gauging Stations Network. Since the Fitzroy is one of four focus catchments for the National Eutrophication Management Program, a program of research will also be carried out in parts of the catchment to help understand and control blue-green algal blooms and other eutrophication problems (see Attachment 1 in the review *Eutrophication and algal blooms in freshwater systems of Northern Australia* for details).

ATTACHMENT 4 — CURRENT COASTAL ZONE RESEARCH IN THE HERBERT RIVER CATCHMENT AND ADJACENT MARINE ENVIRONMENT

An inventory of integrated R&D being undertaken by CSIRO Tropical Agriculture, CSIRO Land and Water, CSIRO Marine Research, Australian Institute of Marine Science and The Australian National University.

Climate record

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Background: Climate varies on all space and time scales – it has varied in the past and is currently changing as a result of the enhanced greenhouse effect. The climate of north Queensland is highly seasonal and very variable from year to year. A major source of this inter-annual variability is the El Niño-Southern Oscillation. Understanding the nature and possible causes of past climate variability is necessary to assess the sensitivity of existing ecosystems (natural and man-made) to climate and possible future climate. To do this we need long, high-quality records of climate. Massive corals of the GBR contain annual banding patterns, similar to tree rings. These have the potential to extend the measured climatic and environmental record for the region back in time to before major agricultural activities. Achieving this objective requires ongoing development of understanding of the biological processes whereby corals record their environment.

Objective: To determine the nature and possible causes of climate variability in Queensland and adjacent ocean areas for the past century (using records from measured data) and the past several centuries (using proxy climatic records obtained from massive corals).

Goals:
- To develop reliable indices of climate variability as determined from measured data.
- To develop reliable proxy climate indices from massive corals of the Great Barrier Reef
- To interpret these records of climate variability in terms of regional and global climate change

Output to date:
- Indices of seasonal temperature and rainfall for Queensland for the past century. These show that there are no significant trends towards wetter or drier conditions in Queensland but average and night-time temperatures have significantly increased and the daily temperature range has significantly decreased (as has occurred in other parts of the world).
- Index of massive coral growth variations on the GBR for the past 237 years that is also a proxy for sea surface temperature variations. This shows that average coral growth on the GBR is very variable and that recent trends towards reduced growth may only reflect a return to long-term "average" conditions.

Proposed future work:
- Develop and interpret indices of climate variation for the past century in the Herbert River Catchment region from measurement records.
- Use coral records to assess the nature and extent of terrestrial effects on waters of the GBR.

Recent relevant publications or reports:

Lough, J.M. (1997). Regional indices of climate variation: temperature and rainfall in Queensland, Australia. *Int. J. Climatology*, 17: 55-66.

Lough, J.M. and Barnes, D.J. (in press). Several centuries of variation in skeletal extension, density and calcification in massive *Porites* colonies from the Great Barrier Reef: a proxy for seawater temperature and a background of variability against which to identify unnatural change. *J. Exp. Mar. Biol. Ecol.*

Isotopic studies of organic carbon (^{13}C and ^{14}C) to help understand the terrestrial carbon cycle in relation to global climate change

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Background: The terrestrial carbon cycle is poorly understood in comparison with the atmosphere and oceans, and the large range of variation in the carbon-isotope composition of carbon in terrestrial environments makes the terrestrial carbon pool particularly amenable to isotopic investigations. A quantitative understanding of the natural carbon-cycle and human perturbations to the carbon cycle (both past and present) is a pre-requisite to understanding climate change, and isotope techniques offer the best approaches to providing quantitative information relevant to global change research.

Objectives: To develop a quantitative understanding of the processes controlling the carbon-isotope composition of carbon in the terrestrial carbon pool, and how processes operating within the terrestrial carbon pool influence to global carbon cycle.

Goals:
- to develop million year records of fire incidence for the Australian continent
- to develop an understanding of processes controlling variations in the isotopic composition of carbon in the soil organic carbon pool.

Output to date:
- development of a chemical technique to quantify, using sedimentary records, the abundance of elemental carbon from biomass burning.
- development of an empirical understanding of factors controlling variability in the isotopic composition of the soil organic carbon pool

Proposed future work relevant to the Herbert catchment:
- development of a chemical technique designed to separate labile from refractory carbon and use of the technique to determine the 'active' and 'passive' proportion of carbon in a soil or water sample.
- application of knowledge of carbon-isotope variations in the soil organic carbon pool, to problems associated with past vegetation and land-use change in the Herbert River catchment

Recent relevant publications or reports:

Bird, M.I., Chivas, A.R. and Head, J. (1996) A latitudinal gradient in carbon turnover times in forest soils. *Nature*, **381**, 143-146

Bird, M.I. Summons, R.E., Gagan, M., Roksandic, Z., Dowling, L., Head, J., Fifield, L.K., Creswell, R.G. and Johnson, D. (1995) Terrestrial vegetation change inferred from n-alkane d^{13}C analysis.in the marine environment. *Geochim. Cosmochim. Acta*, **59**, 2853-2858

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Effects of rural land use on water quality

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Objective: To quantify the effects of different rural land uses on water quality in the lower Herbert River.

Goals:
- Estimate nutrient and sediment export from the lower Herbert catchment.
- Quantify the relative importance of cane land in whole-catchment nutrient and sediment export.
- Evaluate the relative importance of groundwater in nutrient export from sugar cane land in two contrasting catchments.
- Identify and quantify different sources of sediment and nutrient export from sugarcane land (paddocks, drains, headlands)
- Develop strategies to minimise nutrient and sediment export, including design integrated drainage networks and develop drainage management guidelines to minimise nutrient and sediment export from caneland.

Output to date:

Water quality and effects of different land uses:

- Nutrient concentrations in creeks associated with the dominant Herbert land uses were generally below the ANZECC (1992) target levels for freshwater of 500 mg N and 50 mg P L^{-1}. Exceptions occurred during wet season peak flow events when river discharge was closely correlated with rainfall, as expected.
- Nutrient loss in the Herbert River catchment is predominantly event-based, and is insignificant outside the wet season months. For example, heavy rain associated with tropical cyclone Sadie (approximately 600 mm in 2 d) resulted in a peak Herbert River discharge at Ingham of 254,440 ML d^{-1}, peak concentrations of soluble N and P_i of 649 mg N and 38 mg P L^{-1}, and an estimated peak export of these soluble nutrients moving downstream from Ingham of approximately 120 t N and 9 t P d^{-1}. The peak load of suspended solids (SS) during this event was 904 mg SS L^{-1}. This contrasts with typical dry season flows of less than 500 ML d^{-1} and concentrations of soluble N and P_i of the order of 50 mg N and 8 mg P L^{-1}.
- On the basis of concentration data, nutrient losses from intensively managed cane lands tended to exceed those from other land uses. However, these losses might occur irrespective of type of intensive agricultural production because of the strongly seasonal climate, high rainfall intensities, and levels of fertiliser use in intensive agriculture.
- Two fertiliser trials indicated considerable scope for minimising nutrient export by refining agricultural practice on-farm.

Losses from cane lands:

- Paddock scale flumes installed in a sugarcane ratoon and plant crop on a clayey alluvial soil, yielded runoff in five out of eight major rainfall events in the wet season 1995/96, the most important one with a peak rate of 100 mm in four hours. This event lead to temporary flooding, with a maximum water height of 560 mm recorded in the flumes. On an event basis, the runoff coefficient was observed to vary from 2 - 18% on the ratoon plot, in comparison to 2 - 30% on the plant crop plot. These appear to be comparatively low values and reflect the dry wet season encountered 1995/96 (753 mm total rainfall).
- With respect to sediment concentration and total amounts of sediments leaving the plots, at this stage no conclusive results can be presented. In general, sediment concentration seemed to remain well below 1 g/L, corroborating results from previous years. No clear trends between the two treatments were observed, with values ranging between 0.3 to 0.4 g/L for the ratoon and 0.02 to 0.6 g/L for the plant crop treatment. Assuming mean runoff coefficients of 10 - 16 % and mean sediment concentrations of 0.35 g/L, soil losses (suspended solids only, no bed load) would be in the order of 260 - 420 kg/ha for the wet season 1995/96. These are comparatively low values and raise the

question of whether erosion from headlands, drains and stream banks might be as or more important contributors of nutrients and sediments.

Proposed future work:

- Water quality monitoring is continuing with particular focus on automated water sampling, and real time measurement of river height and turbidity, at five key sites in the lower Herbert (Chris Barnes). A PhD student (funded by SRDC) is working on linkages between P behaviour in suspended sediments and P reaction in the soils from which these sediments may be derived. The practicality of commencing work on precision agriculture is being assessed. The idea is that this would maximise the efficient use of farm inputs, especially fertilisers, and minimise the export of agrochemicals off farm.
- The flume studies have been continued in the current wet season and are planned to continue during the next years to broaden the existing database. The site has also been upgraded with additional equipment to obtain relevant soil physical data on soil water status to allow for site calibration of models. This will enable long-term scenarios to be simulated, in evaluating long-term effects of sugarcane production on runoff and nutrient export. It is also hoped to set up additional flumes on contrasting soils in other locations of the Lower Herbert.
- At the same time, a new 5 yr. joint BSES/CSIRO Land & Water/HCPPB/CSR/HRIC research proposal has been approved by SRDC to study effects of drainage management on runoff and sediment production, and to develop integrated surface drainage systems in the Ripple Creek sub-catchment. This project will greatly improve understanding of sources of sediment within the selected sub-catchment. It will provide soil physical baseline data that will enable a catchment scale assessment of hotspots of runoff and sediment generation to be carried out by coupling grid based water balance simulations to existing soil maps and terrain attributes within a GIS environment. Strong linkages exist to the work being carried out by Chris Barnes, and it will also feed into the development of the Herbert DSS (Andrew Johnson/Dan Walker).

Recent relevant publications or reports:

Bramley, R.G.V. and Johnson, A.K.L. 1996. Land use impacts on nutrient loading in the Herbert River. In: Hunter, H.M., Eyles, A.G. and Rayment, G.E. (Eds). Proceedings of a Conference on the Downstream Effects of Land Use, University of Central Queensland, Rockhampton, 26-28 April, 1995. Department of Primary Industries, Queensland, Brisbane.

Bramley, R.G.V., Johnson, A.K.L. and Wood, A.W. 1996. Nutrient loss in the Herbert River catchment and strategies for its reduction. In: Uren, N. (Ed). Soil Science - Raising the Profile. Proceedings of the Australian and New Zealand National Soils Conference, Melbourne, July, 1996. Vol. 2. Oral Papers, 23-24.

Mitchell, A.W., Bramley, R.G.V. & Johnson, A.K.L. 1997. Export of nutrients and suspended sediment during a cyclone-mediated flood event in the Herbert River catchment. *Marine and Freshwater Research* 48 In press.

Roth, C.H. and R. Bramley, 1996: Overview of main results, 1995/96 wet season - Palmas site. Unpublished report. 3 pp.

Nutrient and sediment delivery from the Herbert River

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Background: In assessing nutrient and sediment delivery from the catchment, prime questions relate to: the production rate of sediment and nutrients from various combinations of land use/soil type/climate; the contribution from each combination to the local stream network, and to the GBR lagoon; and whether it is possible to discern an anthropomorphic effect on measured concentrations and loads. Answering these questions requires the development of a methodology to relate input and output measurements at different scales, and initially at least, the analysis will be carried out from determining residence time distributions for the various materials, and what affect, if any, different management strategies might have on production rates and these distributions. On a more theoretical note, the project will attempt to identify catchment scale parameters related to production, storage and material velocities which allow an efficient description of catchment response. In some ways, this approach is similar to the Unit Hydrograph approach of engineering hydrology, except that we are concerned with a parameterisation of the residence time distribution in terms of observable catchment properties.

Objectives:

- To quantify the fluxes of major nutrients (N and P) from the Herbert River Catchment to the Great Barrier Reef (GBR) lagoon; and to identify significant interactions between, and the relative importance of, the major factors (climate, soil type, land use etc.) influencing these fluxes.
- To identify current and potential management practices which may affect the temporal and spatial distribution of these fluxes, and their magnitudes.
- To provide this knowledge in a form suitable for encapsulation in a Decision Support System (DSS), for use by stakeholders in the Herbert River region.
- To develop modelling techniques which utilise measurable landscape and system properties (eg stream network topology), rather than point parameters (eg hydraulic conductivity) to describe system behaviour at a range of scales.
- To distinguish between purely local influences, and those of a more generic nature, in order to maximise the potential for transferring the developed analytical processes to other catchments.

Outputs to date:

- A sampling network has been set up to monitor water quality and quantity, including turbidity and stage height. There are four main sampling sites and the Herbert catchment is subdivided into four main regions using this strategy: the upper Herbert; the lower Herbert above the Stone River confluence; the Stone River Catchment; and the lower Herbert below the Stone River confluence. Each area has appreciably different climate, soils, and land usage, and the aim of the monitoring is to look for significantly different responses from different areas (in terms of sediment and nutrient production), and where such differences are identified, to attempt to relate them to the above factors.
- Equipment at monitoring sites (samplers, turbidity meters, pressure transducers and data loggers) has been duplicated, in an attempt to increase the reliability of data collection in this relatively hostile environment.
- A monitoring site on cane land has been established using small flumes on adjacent plots of fallow and productive land (see. This site is intended to characterise sediment and nutrient production from this particular land use. Approximately 20 additional stream sites are also being sampled for stream chemistry and sediment concentration, in order to characterise the range of variation in concentrations and loads across the catchment, and to indicate areas which need further investigation. (See project on effects of rural land use)

Proposed relevant future work: A major problem in the present design is due to the expected dependence of material transport in the Herbert on extreme (and hence rare) events. It is intended to develop an additional program of field sediment sampling to characterise the historical and spatial distribution of sediments, using a variety of tracers and analytical techniques (ICPMS, radio-emitter spectroscopy etc.) to complement and supplement the stream sampling program, and to add to the work being done by AIMS in the near-shore region of the GBR lagoon.

Project duration: June, 1995 - June, 1998

Sediment history of the Herbert River floodplain

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Background: The CSIRO Coastal Zone Program, Herbert River Project, aims to determine the role of land use in affecting the amount of sediment and nutrients transported to the coast from this catchment. A material budget is required as one means of determining the effect of land use, and monitoring of fluxes in the Herbert is well underway. But every few years, the Herbert floods overbank and a lot of material is transported to the floodplain. To determine this component of the material budget, analysis of deposited sediment is necessary.

By such analysis, it is also possible to determine the impact of European settlement on rates of material deposition. If there is no detectable evidence of settlement then land use change since settlement will have had little effect on this component of the material budget.

Objectives:
- To determine the total quantity of sediment and particulate P deposited on the Herbert River floodplain.
- To determine if the post-European settlement rate of P and sediment deposition has increased, and if land use change within the post-settlement period is detectable in the sedimentary record.

Goals:
- To finish in 1997, analysis of sedimentary records sampled over the last 2 years.
- To produce a summary of the results from these analyses.
- To sample the freshwater swamps this coming summer.
- To begin integration of stratigraphic results with those from off-shore obtained by Greg Brunskill.

Proposed relevant future work:
- Sample at least two more lateral accretion scroll plain sequences on the Herbert, and two more vertical accretion levee deposits.
- Extend the sampling and analysis of the freshwater swamps.
- Create a material budget for the Herbert fan-delta, including modern material fluxes, deposits in the alluvial area, and in the mangrove and other coastal areas.
- Determine the sensitivity of the Herbert River and fan-delta to climate change by examining the pre-European Holocene alluvial record in conjunction with independent reconstructions of post climate.

Marine biogeochemistry and sedimentation history

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Australian Institute of Marine Science
PMB 3
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Objectives: To determine the history of sediment accumulation on the continental shelf in the vicinity of the Herbert River mouth, delta, estuary, GBR Lagoon, and slope, using radiochemical and contaminant tracers of recent sediment inputs

Goals:
- Sediment, carbon, nitrogen, and phosphorus mass balances for the terrestrial and marine inputs to the shelf.
- Contaminant (Cd, Hg, As, U, Tl, pesticides) mass balances for the Herbert River catchment, estuary, and shelf, in relation to the known 50-100 year history of land-use change.
- Calibration of methods and tools (e.g., natural and man-made isotopic tracers, geochemical determinations) for sedimentary history work in this region.
- Geochemical research on coral core history from fringing reefs of this region.
- Interaction with other projects to create synthetic models of catchment and continental shelf interactions.

Output to date:
- Many conference proceedings and presentations, no journal publications yet.
- 500 grab sample reference collection for this portion of the GBR Shelf
- 30 Kasten cores of mainly riverine sediments in Hinchinbrook Channel mangrove mudbanks, Missionary Bay, Rockingham Bay, and the shelf out to 1000 m water depth.
- Geochemical contour maps of chemical elements across the shelf
- Rough models relating catchment land-use change to sediment core chemical changes.
- Beginning stages of mass balance models for organic and carbonate carbon in the Herbert Estuary and shelf region.

Biological resources of beds of the tropical continental shelf

Dr C. Roland Pitcher
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CLEVELAND, QLD 4163

Background: The Project's core area of research for about a decade has been in Torres Strait with research on tropical lobster, Islander traditional fisheries, and seagrasses. Recently, with increased exploitation and declining catches, the importance of benthic communities as nursery areas and habitats for tropical species has been recognised and the project has become involved in mapping critical habitats, analysis and management of spatial habitat data, habitat dynamics, assessment of impacts such as the effects of prawn trawling and dredging, and developing technology to facilitate habitat mapping. Currently, research is being undertaken in ten main sub-project areas: tropical rock lobster, Torres Strait habitats, TS geographic information system, TS traditional fisheries, effects of fishing, aquaculture spatial information system, ecology of megabenthos, acoustics habitat discrimination and remote vehicle technology.

General objectives:
- To identify and understand the factors that determine the distribution, abundance, population dynamics and annual productivity of tropical continental shelf seabed resources; in particular tropical rock lobster, habitats critical for tropical fisheries and the impact of those fisheries on benthic communities.
- To develop information systems that make research data more accessible to managers and to provide scientific advice for rational and effective management of the exploitation and conservation of tropical shelf-bed resources.
- To develop and implement new technologies for mapping, assessing and conducting research on tropical shelf-bed resources.

Proposed future work relevant to the Herbert region:

Title: Effects and interactions of Herbert River runoff and prawn trawling on GBR lagoonal seabed "softbottom" habitats in the ~1°x1° area adjacent to the Herbert River mouth.

Objectives:
- conduct benthic sampling representatively throughout the study area
- classify seabed habitat based on physical & biological attributes
- accurately map the distribution and attributes of terrigenous sediments, including if practical, tracers specific to the Herbert River.
- accurately map the distribution and intensity of prawn trawling on the seabed
- compare benthic faunal communities within and outside areas influenced by the Herbert and in areas of different prawn trawl effort

Expected Outcomes: Quantitative understanding of the effects of Herbert River runoff on, and interactions with, prawn-trawling in the GBR lagoon "softbottom" seabed habitats and consequences for biodiversity

Recent relevant publications or reports:
Pitcher, C.R., Skewes, T.D., Dennis, D.M., Prescott, J.H. (1992) Distribution of seagrasses, substratum types and epibenthic macrobiota in Torres Strait, with notes on pearl oyster abundance. Aust. J. Mar. Freshw. Res. 43: 409-419

Decision support development

Dr Andrew Johnson[1] and Dr Daniel Walker[2]

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ST LUCIA, QLD 4067

[2] CSIRO Tropical Agriculture
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Background: The core of the CSIRO Tropical Agriculture involvement in the Herbert River catchment is in the development of Decision Support Systems for improved natural resource management. This involves the development of tools to assist decision makers to evaluate the effect of changes in land use and management practices on nutrient loads in the coastal zone. Our research is targeted at policy development and analysis and intended to contribute to the development of more effective integrated approaches to natural resource management that account for social, economic, institutional and technical factors. Our key stakeholders are state government agencies, local government, the sugar industry and the broader community.

Our approach to developing and delivering decision support involves rigorous needs analysis, the establishment of active partnerships in software development and delivery, investment in means of fostering appropriate environments for technology transfer and a commitment to evaluating the impact of process and product. Data collection, analysis and synthesis at a catchment scale is also a key component of our activities and provides a foundation for the decision support work.

Objectives:
- Develop analytical tools and methods for improved environmental and socio-economic assessment of natural resource policy, planning, and management in tropical coastal catchments;
- Contribute significantly to the development of improved natural resource policy, planning and management to ensure the ecologically sustainable development of northern Australia.

Goals:
- To develop effective tools and strategies to support decision-making at policy, planning and enterprise levels on the use and management of natural resources in northern Australia

Output to date:
- Systematic and rigorous analysis and documentation of stakeholder needs in the Herbert River catchment.
- Evaluation of current natural resource policy, planning and management for the sugar industry.
- Development and implementation of an innovative, toolkit-based approach to decision support for improved sustainable natural resource planning and management in the Herbert River catchment, that integrates existing information and technology (eg GIS, models) as well as the products of new research outputs;
- Synthesis and integration, within a systems framework, of biophysical and social research to underpin improved development and analysis of policy, planning and management at the catchment scale;
- Development of innovative approaches to delivering R&D to stakeholders in the Herbert River catchment, based on the development of active partnership with clients and stakeholders focused on operational implementation of research products;
- A rigorous approach to evaluating both the R&D process and R&D products developed for the Herbert catchment, with a view to applying the results of the R&D to other parts of the Australian coastal zone.

Proposed future relevant research: By collaborating with others working in the Herbert Catchment, we aim to improve the functional capabilities of NRM_Tools. Proposed extensions to the current toolkit include tools to support:
- problem formulation and task analysis;
- application and interpretation of legislation;

- management of interactions between groups;
- and the use of argumentation in decision making and presentation in natural resource management.

Recent relevant publications or reports:

Johnson, A.K.L. (1996). Quantifying current and historical inputs of fertiliser N and P to rural lands in the Herbert River Catchment. *Proceedings National Conference on Downstream Effects of Land Use.* Rockhampton, Queensland. pp 273-276.

Walker, D.H., and Johnson, A.K.L. (1996) Delivering flexible decision support for environmental management - a case study in integrated catchment management. *Australian Journal of Environmental Management*, 3, 174-188.

Walker, D.H., and Johnson, A.K.L. (1996) NRM Tools: a flexible decision support environment for integrated catchment management. *Environmental Software*, 1, 19-24.

ATTACHMENT 5 — CURRENT AND PROPOSED RESEARCH FOR THE NORTH JOHNSTONE RIVER CATCHMENT, QLD

The Johnstone River is a 1,600 km^2 catchment draining from above the coastal escarpment to the Great Barrier Reef lagoon in far north Queensland. About 50% of the catchment has been cleared, with the main land uses being sugar cane, banana and horticultural crop production; dairying; and beef cattle grazing. The work reported here has involved little investigation relating to the beef industry but the research has been included as it is a major catchment study that involves relevant concepts and techniques. Information on the research programs below has generally been extracted directly from reports and summaries provided by program staff.

National Rehabilitation and Management of Riparian Lands Program

Program A — Aspects of physical and chemical processes

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Background to Johnstone River study

The combination of tropical storms and intensive cropping of a dissected landscape has the potential to produce extreme rates of sediment and nutrient delivery from agricultural land to streams. Stock access to streams is also a contentious issue on land used for intensive dairying. The only alleviating factors for agricultural runoff are the well structured soils and changes to crop management over the last decade. Vigorous vegetation growth and the stable soils make channel erosion a less significant issue than it is in southern Australia.

Much of the natural riparian vegetation has been cleared or is degraded, although revegetation schemes are addressing this problem. Clearing of riparian vegetation has led to problems of para grass invasion and the sedimentation of channels.

Work in the catchment will focus on using riparian management to buffer streams from intensive cropping, and on understanding the effects of cattle access to streams. A lower level of work will be undertaken on the potential of riparian vegetation to reduce channel erosion and on the effect of para grass and riparian vegetation on the conveyance of floodwaters. (From Prosser 1996)

Sediment budgets

Aims: Large amounts of fine grained sediment have been supplied to tributaries of the Johnstone River, reducing channel capacity and having a substantial effect on in-stream ecosystems. The aim is to construct sediment budgets at various levels, from a single event in a small subcatchment to a budget of 40 years across the whole catchment, to:

1. identify dominant sources and stores of sediment; and
2. compare sediment inputs with the export of sediment from the catchment mouth.

Methods: Various methods are being used to construct the budgets including historical records, research literature, field surveys of channel stores and radionuclide tracing of sediments.

Radionuclide tracing: the principal aims are to:

- determine the relative importance of surface erosion compared with bank erosion as a source for sediment within streams of the Johnstone River catchment; and
- to determine the average net surface soil erosion and redistribution of soils in two representative catchments, over the last 35 years

Two main areas of investigation have initially been proposed.

1. Surface soils are relatively strongly labelled with radionuclides from the atmosphere. In an ungullied catchment, it should be possible to observe a pure topsoil signature in the sediment of 1st order streams. This signal may then be altered by dilution from gullies and channels as stream order increases. To test this hypothesis a number of samples were taken from slopes, first, second, third and fourth order streams from basaltic catchments with a mixture of banana; sugar cane and grazing land uses.

2. The soil content of ^{137}Cs is used to determine the amount of soil loss and redistribution. However, there is evidence that the rate of soil loss in the Johnstone River catchment has been as high as 1 cm/yr. If this is true, then it is possible that the ^{137}Cs label has been removed from the soils, making it difficult to quantify the erosion rate. Consequently a number of samples have been taken from slopes and alluvial fans, which represent both sources and sinks of sediment, to measure their ^{137}Cs content.

Results to date:

1. Small 1 km^2 catchment: a sediment budget following an extreme tropical storm resulted in soil erosion from the banana plantation in the catchment, of almost 25t/ha. Almost all this sediment was delivered to the stream with little storage in the riparian zone. Sheet erosion was almost 20 times greater than gully erosion which was mainly from gullies cut into the newly formed plantation. About 15% of the sediment was trapped in the first and second order streams and the remainder was delivered to the North Johnstone River.
2. An estimated budget for the whole catchment for the same storm event, indicated that about 30% of the eroded sediment was deposited in tributaries and the main river channel, about 14% was deposited on floodplains around Innisfail and about 36% was exported from the mouth; about 20% of the sediment was unaccounted for, demonstrating the difficulty of precisely determining sediment stores and sinks across a large area.
3. A catchment budget for the period 1942-83 estimated that 82% of eroded sediment was from croplands and 18% from bank erosion;36% of eroded sediment was trapped in the main channel near Innisfail and is regarded as having caused narrowing of the river with an increase in the severity of flooding.
4. Preliminary results from the radionuclide analyses suggest that a maximum time averaged rate of cropland erosion less than that from previous plot ersosion studies. This confirms the problems of extrapolating from plot to hillslope scales and to time periods an order of magnitude greater than the monitoring period.

Sediment and nutrient filtering

Aims: Plot experiments will be carried out to compare the abilities of riparian rain forest and grassed buffer strips for storing runoff, sediment and nutrient derived from intense cropping. A second aim is to investigate how effective these stores are in highly convergent land where the fluxes of water, sediment and nutrient are greatest.

Methods: All plot experiments are being conducted in association with banana cropping although the results will be able to be applied to any intensive crop.

The comparison of grass and forest riparian buffer strips is being conducted on a planar 200 m long slope of banana trees which descends gently to a 15 m wide riparian zone bordering a 1st order stream. Grassed and forested riparian zones are adjacent within the ripian zone. Runoff is being measured in flumes at the base of the slope and after passing through each of the riparian zones. The flow is subsampled for analysis of suspended load, bedload, and total phosphorus and nitrogen. Sediment and nutrient trapping will be computed from the difference between fluxes at the two plots and the results confirmed by detailed measurements of the sediment deposits on the plots. Piezometers were installed to monitor any interaction between overland flow and shallow sub-surface flow and to assess the importance of sub-surface flow as a pathway for pollutants.

Two hillslope hollows have been instrumented on a second property. One hollow has dense grass cover which is potentially an excellent filter strip. At the other, cultivation continues across the hollow with only the steep foot of the hollow grassed. Comparison will be made of sediment and nutrient export to the stream network from each hollow, using flumes and samplers as described above. The grass filter strips are being investigated as a potential addition to forested buffers, not as an alternative to streamside forest.

Cattle exclusion from riparian zones

Aims: To determine the effect of cattle access to streams on sediment and nutrient fluxes to the waterway.

Methods: Experiments are likely to involve paired first order catchments with in-stream monitoring, and plot-based monitoring and sampling of runoff. Likely treatments are complete cattle exclusion, exclusion of cattle from sensitive areas and limited access to stream-based watering points; and no restrictions on cattle access.

Program B — Ecological issues

Dr S.E. Bunn,
Centre for In-stream and Catchment Research,
Griffith University,
NATHAN, QLD

Para grass, Bamboo Ck Innisfail

DNR research program

Nutrient balances and transport from agricultural lands

Dr Brian Prove,
Department of Natural Resources,
Centre for Wet Tropics Agriculture,
PO Box 20,
SOUTH JOHNSTONE, QLD 4859

Aims:
1. use nutrient balances to determine fertilizer application efficiencies;
2. measure the quantities of nutrients and sediments being removed from agricultural land and the mechanisms and pathways for their removal;
3. apply existing water-sediment-nutrient simulation models to determine significant rainfall, soil and agricultural management practices leading to substantial potential losses;
4. determine management strategies which improve fertilizer application efficiency and minimize export of nutrients and sediments;
5. extend findings to industry groups.

Water quality monitoring and modelling

Dr Heather Hunter,
Department of Natural Resources,
80 Meiers Road,
INDOOROOPILLY, QLD 4068

Objectives:

1. To quantify the loads of sediment and nutrients (N & P) discharged by the Johnstone River system into the GBR.
2. To assess water quality in the catchment.
3. To assess the relative importance of different land use practices on downstream water quality and exported loads.

The detailed studies are being undertaken as part of the pilot study of Integrated Catchment Management in the Johnstone River catchment.

Methods:

1. Sixteen initial and a later three, monitoring sites were selected to reflect a dominant land use upstream. Five of these sites are located at flow gauging stations; at the remaining sites flow is recorded at time of sampling.
2. Between 1991-1995 sampling at gauged sites was weekly during base-flow and much intense during higher flows (up to 36 samples/day). Other sites had a minimum sampling frequency of one month.
3. A modelling program was initiated to provide a long-term estimate of loads under different climatic conditions. The model being used is HSPF (Hydrological Simulation Program - Fortran).

References

Prosser, I.P. (1996). Milestone Report No. 2, Rehabilitation and management of riparian lands, Program A: Aspects of physical and chemical processes. Report to LWRRDC for Project Reference No. CWA15. Unpublished report.

Review 6

SEDIMENT AND NUTRIENT EXPORT INTO, AND EFFECTS ON, THE GREAT BARRIER REEF LAGOON — A SHORT REVIEW

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Contents

1. Introduction

There is considerable concern that human activities in the coastal catchments of the Great Barrier Reef Lagoon (GBR), will cause irreparable damage to the Great Barrier Reef ecosystem. Recently it has been suggested, when discussing the effect of activity along the coast of the GBR lagoon, that land use and management within the whole catchment should be considered rather than that associated with individual industries and activities. That is, the effects of grazing, intensive agriculture, mining, urban development, tourism, fishing and recreational use need to be considered together. This integrated view is adopted here, although given the purpose of the review, the effects of grazing are specifically referred to where possible, particularly as the grazing industry occupies a major area of the north Queensland coastal catchments.

A difficulty in determining the effects of the grazing industry, however, is that the terrestrial environment has naturally always contributed sediment, nutrient and other materials to the Great Barrier Reef Lagoon. Separating anthropogenic contributions from natural processes can be particularly difficult and there has been considerable research effort to try and adequately define and quantify the input from terrestrial activities and those from natural phenomena. Research effort has also been devoted to determining ecosystem processes in near-shore and reef environments and whether increases in terrestrial nutrient inputs are changing the species diversity of these systems. Differing interpretations of the results from these studies has sometimes led to a division of opinion.

The purpose of this review is to collate the most recent and pertinent literature on sediment and nutrient transport from catchments adjacent to the Great-Barrier Reef Lagoon marine environment, and the effects of these sediments and nutrients on the marine environment.

2. Sediment and freshwater inputs into the GBR lagoon

A feature of the freshwater discharge from north Queensland catchments is the very high variability in seasonal, inter-annual and episodic event-related flow which is associated with the monsoonal climate. Over decadal time scales, regional rainfall and discharge are modulated by fluctuations in the strength and duration of the summer monsoons, which in turn are coupled to the El Nino Southern Oscillation climate variability (Lough 1994; Lough 1995). The largest flows occur during episodic events associated with monsoonal rain depressions and tropical cyclones. These may result in periods of extremely heavy rainfall and dramatic changes in river discharge on an hourly or daily time-scale (Mitchell and Furnas 1996).

In-stream gauging indicates that more than half the average rainfall runs-off the northern "wet catchments" (Murray to Daintree) (Pulsford 1993), but runoff from southern "dry catchments" is more variable. Mitchell and Furnas (1996) note that during the wet season, the Burdekin and Fitzroy Rivers represent 71-77 % of the total gauged discharge from catchments draining into the Great Barrier Reef lagoon. This contribution can drop to 11.7 and 12.4 % during dry periods and years for the Burdekin and Fitzroy catchments respectively. In contrast, because of the lower inter-annual variability of rainfall, the fresh water discharge into the GBR lagoon from the far northern catchments is relatively constant at an estimated 42 % of the annual gauged discharge. Mean annual discharge together with minimum and maximum annual discharge are shown in Table 1 for some major river systems draining into the GBR lagoon.

Sediment is transported from catchments into the waters of the GBR, with the amount of material transported varying between wet and dry seasons, in response to the variability in flow. Flood events have been identified as the greatest contributor to annual sediment and nutrient discharge from rivers into the GBR lagoon (Furnas *et al.* 1995; Mitchell and Furnas 1996). Most of the sediment deposited in the Great Barrier Reef lagoon is in a narrow wedge adjacent to the coastline. Only during extreme events associated with monsoon rain depressions is sediment or nutrient enriched freshwater carried into the reef proper.

River	Period	Mean Annual Discharge (ML x 10^6)	Minimum Annual Discharge (ML x 10^6)	Maximum Annual Discharge (ML x 10^6)
Normanby	1968-92	0.911	0.054	2.615
Daintree	1968-92	1.011	0.351	2.252
Barron	1958-92	0.807	0.144	2.617
Mulgrave	1966-92	0.567	0.187	1.045
Russell	1966-92	0.851	0.488	1.344
Nth Johnstone	1967-92	1.840	0.651	3.761
Sth. Johnstone	1958-92	0.813	0.291	1.384
Tully	1972-92	3.039	1.660	4.704
Herbert	1958-92	3.370	0.407	10.418
Burdekin	1958-92	9.272	0.540	50.927
Fitzroy	1964-92	5.574	0.172	22.126
Burnett	1958-92	1.050	0.117	6.237

Table 1. Flow data to 1992 for gauged major rivers draining into the GBR lagoon. (After Lough 1992 and Furnas *et al.* 1995)

Early observations of flood plumes were made around Low Isles (Orr, 1933) and were correlated with flooding in the adjacent Daintree River. Freshwater from the Burdekin river after the floods of 1979-80 and 1980-81 was tracked 40 km offshore (Wolanski and Jones, 1981). After the Fitzroy River flood, Brodie and Mitchell (1992) observed low salinity plume water for three weeks. Van Woesik (1991) observed significant coral mortality on the fringing reefs around the Keppel Islands, and reefs more than 200 km north of the river mouth were also affected although damage was not as extensive. This mortality was associated with the low salinity water.

As with seasonal flood events, the effect of cyclonic flooding on freshwater, sediment and nutrient discharge can also be significant. Short-lived river plumes from numerous North Queensland rivers have been observed during and after cyclonic floods. Although cyclones can have similar catchment rainfall and discharge (eg Winifred, Sadie, Violet) their distinctly different paths leads to different plumes and lagoon disturbance patterns (Brodie 1996).

Cyclone Winifred (Category 3) caused resuspension of GBR lagoon sediments due to large waves (Gagan *et al.*, 1990) and it was difficult to discern the muddy river plume from resuspended sediment. Both, the plume and resuspension are thought to have caused a phytoplankton bloom (primarily diatoms), one to three days after the cyclone (Furnas, 1989). In another case Cyclone Sadie did not cause visible resuspension of sediments in the lagoon and plumes from the Johnstone River were merged with plumes from the Black and Daintree Rivers, in the south and north respectively. Although extending to Noreaster Reef in the Outer Shelf (Brodie 1996) the plume was short lived and there was little observance of it in the water column (Devlin *et al.*, 1995). Distinguishable from these two cyclones was the effect of Cyclone

Violet where a riverine plume was clearly distinguishable with very little resuspension confined to inshore waters. Rainford (1925) and Hedley (1925) reported widespread coral losses in the Whitsunday region after the major floods of January 1918 associated with the Mackay cyclone.

The Burdekin-Haughton, North-East Cape York and Fitzroy catchments have been identified as contributing the most sediment to the marine environment with annual amounts totalling 2,711,000, 2,387,000 and 1,774,000 tonnes, respectively (Moss *et al.* 1992). This estimate depended on a statistical model based entirely on flow weighted in-stream sediment concentrations of 125 kg/ML for northern catchments and 250 kg/ML for southern catchments. Wasson (1996) recently reviewed the estimates of annual freshwater and suspended sediment input into the Great Barrier Reef lagoon from the Queensland coastal catchments based on various statistical models and summarised the data (Table 2). Although there is significant variability between estimates derived from the different statistical models, they nearly all indicate the Burdekin and Fitzroy catchments as being the major contributors of sediment. Since grazing land occupies nearly all these catchments, grazing lands of the Burdekin and Fitzroy catchments are regarded as the major contributors of sediment to the Great Barrier Reef.

Catchment	**Area (km^2)**	**Average sediment yield (t/yr x 10^6)**				
		1	**2**	**3**	**4**	**5**
1 Gold coast	5995	-	0.402	0.087	0.307	3.5
2 Brisbane	13560	-	0.313	0.208	0.728	3.5
3 Sunshine Coast	6565	-	0.571	0.097	0.264	2.7
4 Mary	9595	1.21	0.573	0.138	0.435	3.2
5 Burnett-Kolan	39470	1.76	0.724	0.641	2.381	3.7
6 Curtis Coast	9225	0.55	0.374	0.133	0.476	3.6
7 Fitzroy	142645	2.20	1.774	2.570	10.466	4.1
8 Shoalwater Bay - Sarina	11270	0.22	0.924	0.166	0.568	3.4
9 Pioneer - O'Connell	3925	1.54	0.657	0.064	0.240	3.8
10 Proserpine	2485	0.11	0.349	0.039	0.132	3.4
11 Don	3985	0.55	0.175	0.057	0.225	3.9
12 Burdekin - Haughton	133510	3.52	2.711	2.116	8.520	4.0
13 Ross - Black	2890	0.55	0.265	0.043	0.133	3.1
14 Tully - Murray	2825	1.87	0.660	0.069	0.124	1.8
15 Herbert	10130	1.43	0.624	0.155	0.536	3.5
16 Johnstone	2330	1.54	0.582	0.056	0.159	2.8
17 Mulgrave - Russell	2020	1.43	0.521	0.050	0.137	2.7
18 Barron	2175	0.33	0.137	0.035	0.094	2.7
19 Mossman - Daintree	2615	1.32	0.528	0.060	0.096	1.6
20 Northeast Cape York	43300	7.26	2.387	0.649	2.008	3.1
TOTAL	450515	27.39	15.25	7.35	28.03	

1. Bellperio (1983)
2. Moss et al. (1993) model 1
3. Neil and Yu (1996) - natural
4. Neil and Yu (1996) - current
5. Increase of current over natural yield, after Neil and u (1996)

Table 2. Estimated sediment yields to the Great Barrier Reef Lagoon (From Wasson 1996)

3. Catchment use and sources of material in river discharge.

The Australian Water Resources Council divides Australia into 13 drainage divisions for the purpose of monitoring and reporting. The north-east coast division extends from the NSW-Queensland border to near the tip of Cape York, occupying an area of 415 000 km^2 and with a mean estimated outflow of 83 900 × 10^3 ML. The division is further divided into 46 catchments of which the largest is the Fitzroy catchment . Thirty three of these catchments drain directly into the Great Barrier Reef lagoon and long term discharge data for 12 of these catchments has been extrapolated to give an estimated annual terrestrial freshwater input of 42 km^3 (Mitchell and Furnas 1996).

In the Daintree drainage basin in the north, a high proportion of the land is classified as World Heritage and most of the South Western basin is classified as National Park (Pulsford 1993). Wet tropical rainforest dominates most of the steeper slopes but the upper Daintree, Stewart Creek and Douglas Creek have been cleared for cattle grazing. With clearing, grasses such as *Setaria*, green couch, guinea grass and blady grass dominate the landscape. The coastal lowlands are dominated by sugar cane farms but this represents only 1.8% of the total drainage basin area.

The use of coastal lowlands for sugar cane also occurs in the Mossman drainage basin and contributes about two thirds of the total sugar cane produced in the Douglas Shire. In contrast, the adjoining drainage basin of the Barron is more utilised for other crops such as maize, peanuts, tobacco and sugar cane. On last estimates, the cattle industry represented about 47.7% of this drainage basin. The adjoining drainage basins of Mulgrave-Russel, Johnstone, Tully, Murray and Black support a significant sugar cane industry as does the Haughton basin.

Further south, the area used for grazing increases. It is about 71.1 % in the Herbert, reaches a maximum of 94.8% in the Burdekin and remains well above 65% for all drainage basins along the Queensland coast as far as the Burnett basin. Table 3 gives the percentage of each drainage basin used for grazing.

Pulsford (1993) recently collated data on the amount of fertiliser applied to land in each Queensland catchment draining into the Great Barrier Reef lagoon. Data for application of nitrogen and phosphorus over five year intervals are presented in Figure 1 for a number of catchments. It is also important to note that other materials contained in fertilisers, such as cadmium, have also been applied in these basins.

4. Land use change and export of material to the Great Barrier Reef marine environment

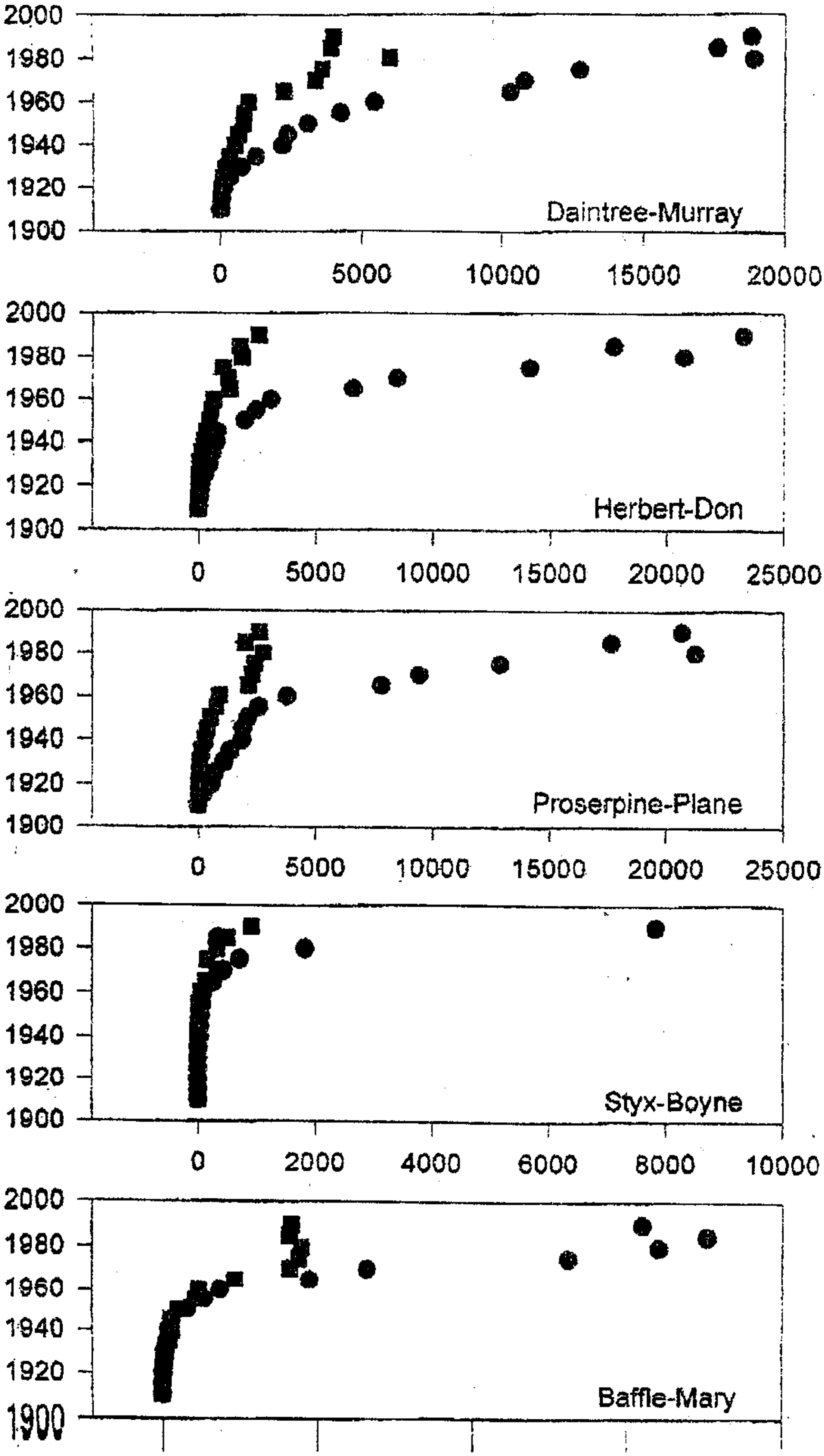
Land use changes are thought to have greatly affected the type of material entering the Great Barrier Reef lagoon. The influence of clearing and changes in vegetation can be noticed in the marine environment (Togersen and Chivas 1984, Bird *et al.* 1995). For example, (Bird *et al.* 1995) show an increase in terrestrial carbon in marine sediments since clearing of the forested Johnstone River drainage basin for sugarcane and pasture began in the 19^{th} century.

The effect of detrital out welling around Hinchinbrook Island and Rockingham Bay was studied by Alongi and he concluded that the highest organic carbon and total nitrogen concentrations were found at sites that received the highest amount of mangrove litter. This study also showed that there was no relationship between total phosphorous concentrations and amount of mangrove litter received at each site. The relationship between inorganic nutrient [NH_4^+, NO_2^+ NO_3^-, PO_4^{3-}, $Si(OH)_4$] and out welling of mangrove litter was less clear but it appeared that the fluxes and concentrations of these species were related to sediment type and proximity to land. Cauwet (1988), and Machado and Knoppers (1988) reported similar concentrations of sedimentary organic carbon in other tropical regions.

The daily nitrogen and phosphorous requirements of phytoplankton are estimated to be between 7 and 0.4 $mmol.m^{-2}$ (Alongi 1990) and given that the benthic contribution to nutrient regeneration is small, other inputs such as river run-off and nutrient release by sediment re-suspension are necessary for the rates of primary production observed in this region.

Table 3. Characteristics of catchments draining into the Great Barrier Reef Lagoon. Data compiled from Moss *et al.* (1992), Pulsford (1993) and Wasson (1996).

Drainage Basin	**Area (km^2)**	**Mean Annual Rainfall (mm)**	**Mean Annual Run-Off ($\times10^3$ML)**	**Land Use (% catchment area)**			
				Grazing	**Sugar**	**Pristine**	**Other**
Daintree	2125	2576	3560	26.7	1.8	31.7	39.8
Mossman	490	2459	687	44.6	10.0	11.0	34.4
Barron	2175	1447	1153	47.7	2.1	2.0	48.2
Mulgrave-Russel	2020	3233	4193	38.9	13.1	25.1	22.9
Johnstone	2330	3405	4698	41.6	14.8	12.8	30.8
Tully	1685	2970	3683	20.7	9.6	2.1	67.6
Murray	1140	2485	1628	29.6	6.1	27.3	37.0
Herbert	10131	1331	4991	71.1	6.6	9.7	12.6
Black	1075	1510	509	67.4	0.7	9.3	22.6
Ross	1815	1071	372				
Haughton	3650	923	756	74.0	10.4	10.8	4.8
Burdekin	129860	640	10100	94.8	0.2	1.3	3.7
Don	3885	1022	689	91.3	1.1	2.6	5.0
Proserpine	2485	1562	1431	74.6	7.5	4.0	13.9
OConnell	2435	1705	1668	70.5	11.1	4.4	14.0
Pioneer	1490	1418	994	48.5	17.9	6.1	27.5
Plane	2670	1499	1370	67.4	21.0	2.9	8.7
Styx	3055	1157	825				
Shoalwater	3705	1102	832				
Waterpark	1840	1317	700				
Fitzroy	142645	702	7127	87.5	0	2.3	10.2
Calliope	2255	889	340				
Boyne	2540	1031	401				
Baffle	3860	1173	750	75.9	0.4	4.4	19.3
Kolan	2980	1162	464	79.0	4.5	0	16.5
Burnett	33150	765	1743	79.9	0.8	0.4	18.9
Burrum	3340	1104	718	53.4	8.8	6.3	31.5
Mary	9595	1158	2309	64.5	1.2	0.6	33.7


2000
1980
1960
1940
1920
1900
Daintree-Murray
0
5000
10000
15000
20000
Herbert-Don
0
5000
10000
15000
20000
25000
Proserpine-Plane
0
5000
10000
15000
20000
25000
Styx-Boyne
0
2000
4000
6000
8000
10000
Baffle-Mary

Sedimentation rates have been calculated for some areas of the Great Barrier Reef lagoon, particularly the Hinchinbrook Channel region, and continuing work in the Burdekin region shows some variability in sedimentation rates. Sediment cores from mangrove, mudbank, and coastal riverine materials show typical accumulation rates of 2-5 $kg.m^{-2}.yr^{-1}$ (Brunskill, 1995). Although annual accumulation rates can not be calculated from this type of analysis, it provides an average over the period of agricultural history of the catchment adjacent to the marine environment.

Recently, Walker and Brunskill (1996) showed that anthropogenic mercury accumulated in the sediment of Cape Bowling Green Bay and is thought to have been derived from the amalgamation process of gold mining in the Charters Towers/Ravenswood area between 1870 and 1890. Fertilisers, fungicides and herbicides that are applied to farms along the coast adjacent to the GBR lagoon may also have accumulated with coastal sediment. Although there has been limited research on the accumulation of herbicides and pesticides transported to the marine environment, studies are currently underway on sediment cores to ascertain whether such chemicals have been transported to the GBR lagoon.

Trace elements that are associated with fertilisers (eg Cd, U, As), have been river transported to coastal sediment. Not only is the toxicity of such trace metals on marine biota significant, these trace elements may be used as tracers of anthropogenic sediment input into the GBR lagoon and serve as surrogate indicators for sources of nutrient input. Cadmium, uranium and arsenic have been found to be in excess of background levels by a factor of 2 to 3 (Tesiram 1995), but unlike the mercury signal observed by Walker, the concentration profile from an historic perspective is somewhat more complicated. However care must be exercised in using metal tracers, as enrichment of these trace elements may have had a diagenetic origin, and therefore may not be a true reflection of anthropogenic input (Ridgeway and Price, 1987, and Zwolsman *et al.*, 1993). The use of N and P as indicators of anthropogenic sediment input are inadequate signals because they are taken up by algae.

5. The known risks: eutrophic case studies

Coastal eutrophication is recognised as a world wide and growing problem in areas affected by intensive agriculture and urbanisation (Steven 1996). On the global scale, it is now estimated that the input of nutrients to the ocean from human sources via rivers is equal to or greater than the natural flux (Windom 1992). The impact of increased loads of nitrogen and phosphorus on phytoplankton and benthic communities are the primary concern. Recent experiments have also reinforced the significance of other micro-nutrients such as iron, in the regulation of phytoplankton populations (Behrenfeld *et al.* 1996, Cooper *et al.* 1996, Turner *et al.* 1996).

Regions comparable to the GBR (344 000 km^2) are temperate: the North Sea (575 000 km^2) and the adjoining Baltic (373 000 km^2). Nitrogen and phosphorus loadings to these seas has increased this century by ~4 and 8 fold respectively. These increase have resulted in increased benthic biomass and anoxia (Baltic; Josefson 1990; Koop *et al.* 1990), and an increase in phytoplankton biomass and change in community structure (North Sea; Cadee 1986; Zevenboom *et al.* 1991). Deleterious effects reported include increased phytoplankton and benthic biomass, loss of species, collapse of fisheries, benthic anoxia, and noxious algal blooms. The most obvious lesson learned from many of these studies is that little indication of change in nutrient status was detected before chronic ecosystem collapse was observed.

On coral reefs there is some evidence that nutrients can directly impinge on coral growth and reproduction (Kinsey and Davies 1979 Tomascik 1990; Tomascik and Sander 1985). On a broader scale Wilkinson and Buddenmeier (1994) estimate 70% of the worlds coral reefs are already showing effects of anthropogenic stress, with 10% seriously degraded, 30% in critical state of being lost within the next 10 to 20 years, and a further 30% threatened to disappear within 20-40 years.

Various studies from around the globe have documented the rapid degradation of coral reefs through anthropogenic disturbances, often exacerbated by natural catastrophic events such as storms. Small islands nations with confined coastal embayments or lagoons are the most susceptible. Examples include Barbados (Tomascik 1990), Jamaica, Belize (refs in Steven *et al.* 1997), Kaneohe Bay, Hawaii (Smith *et al.* 1981), and the Reunion Islands (refs in Steven *et al.* 1997). However the direct effects of nutrients on coral reefs is extremely complex. Most of the literature describing the negative impact of sewage discharge is limited to studies of lagoons or embayment environments with relatively long residence times that enable build-up of nutrients and sediments to detrimental levels. Several authors have questioned the detrimental effect of nutrients, citing deep ocean sewage outfalls as examples of nutrient additions enhancing marine ecosystems (Dollar 1994; Grigg 1994; Grigg 1995). Of these, the most comprehensive examined the interaction between habitat complexity, sewage discharge and fishing pressure on Hawaiian Reefs (Grigg 1994). It was concluded that no detrimental effect could be attributed to the presence of deep ocean sewage outfalls. In fact coral cover and reef fish abundance were higher around the outfalls, probably because man made structures increased habitat complexity.

6. Evidence for eutrophication in the Great Barrier Reef lagoon

Coral reefs in particular have been identified as being sensitive to eutrophication as they typically thrive in nutrient depauperate waters (Steven and Larkum 1993). In Australia, widespread public concern for the GBR has been fuelled by considerable scientific debate as to whether the GBR is under threat from wide spread eutrophication. Some have argued that the effects of enhanced levels of nutrients are already apparent (Bell 1992), while others have concluded that there is no evidence for any effect (Walker 1991). It has been suggested that the divergence of opinion reflects inadequate information on the present levels of nutrients in the GBR, whether these levels are changing, and the extent to which these levels reflect human activity (Kinsey 1991).

The observations of Kinsey (1991) are fundamental to consider in any discussion regarding the effect of land use change and European settlement on water and sediment quality in the GBR lagoon. As Lough and Barnes observe (1995): "Detailed observations and measurements of living coral reefs began only 20 or so years ago". It is increasingly recognised that fine scale variability in water quality parameters (eg nutrients, chlorophyll etc) on scales of hours to years makes assessment of anthropogenic perturbations difficult to resolve. Coral cores provide a means for investigating more than century long records of annual growth to identify objectively the natural background variability in coral growth. Furthermore coral cores provide one means by which to assess whether deterioration in the water quality of the GBR lagoon has occurred through anthropogenic activities. Recent work undertaken on a 237 year record from 10 large colonies of *Porites* indicates that calcification rates have not declined in the 20th century.. There is no indication of recent , unusual declines in the average annual calcification that might be attributed to human activities, rather, the 20th century witnessed the second highest 50-year period (1927-76) and the third highest 10-year period (1964-73) (Lough and Barnes 1995). The effect is primarily attributed to temperature and the authors point out that calcification and possibly reef performance are highly variable at time scales much longer than decades. It is possible that better resolution of temporal changes in coral growth may be achieve if skeletal deposition is examined in faster growing species than historically used massive corals (Paul Hough pers comm).

The observations of Lough and Barnes (1995) highlights the difficulties involved with the assessments of anthropogenic impacts on water quality in the GBR lagoon. In concurrent work, Isedale and co-workers have examined massive coral cores for evidence of episodic flood events and changes in climate patterns.

Apart from anecdotal evidence that "things aren't what they used to be", what irrefutable scientific evidence is there of the deleterious effect of sediment and nutrient runoff affecting the GBR lagoon? In a series of publications Bell and others (Bell and Elmetri 1995; Bell 1992; Gabric and Bell 1993) have advocated the GBR lagoon is on the verge of widespread eutrophication. This conclusion was based on studies at Low Isles, which compared present conditions with the reports of the 1928 British Royal Expedition. Significant increases in phytoplankton concentration, changes phytoplankton class structure, and loss of hard coral on reef flats were claimed to be indicative of anthropogenic inputs causing eutrophication. The most likely cause was suggested to be increased runoff caused by increases in agricultural activity. (Bell and Elmetri 1995). In contrast other researchers have concluded that there is not yet evidence of regional eutrophication. Furnas and co-workers (Furnas *et al* 1994; Furnas and Brodie 1996) have compiled a formidable data set of hydrography of the GBR lagoon spanning the last 15 years. They conclude that there is no evidence of regional eutrophication. Similarly, analysis of a 20 year dataset of chlorophyll-a concentrations in the GBR lagoon concluded that there was no indication of long term increase in phytoplankton biomass (see Zann 1995). Recently (1992) the Great Barrier Reef Marine Park Authority initiated the GBR water quality monitoring program. The broad objectives of the program were to document the nutrient status of regional waters of the GBR lagoon using chlorophyll-a as a proxy nutrient bio-indicator. This comprehensive program has high lighted the problems involved with establishing the nutrient status of the GBR lagoon due to various scales of temporal and spatial variation (see Steven *et al.* 1997).

Phase shifts in community structure are characteristic of anthropogenic perturbations. A perceived increase in the abundance of benthic macroalgae on inshore coral reefs has been suggested as symptomatic of wide spread decline of those reefs (Bell and Elmetri 1995). McCook and Price (1996) have recently evaluated the evidence for long term changes in the abundance of macroalgae on inshore reefs. There is no irrefutable scientific evidence for a widespread increase in macroalgal abundance on inshore fringing reefs, and in some cases (eg Pandora reef, Magnetic Island), macro algae have been displaced by coral (cf. Eutrophication). The authors highlight that macro algal populations are a complicated function of numerous factors including, nutrients, grazing, sedimentation, competition and fresh water runoff. Also shown is the high degree of spatial and temporal variability. This ensures that the requisite data base to enable comparison of "pre-impact" and present conditions are not available, as the "pre-impactî data is insufficient (and may not even be "pre-impact"), and comparison with present conditions does not account for the intervening dynamics.

7. Nutrient and phytoplankton dynamics in the GBR

In well illuminated oligotrophic waters, nutrients are the principle mechanism controlling phytoplankton abundance, speciation and productivity (eg Furnas and Mitchell 1993, Revelante and Gilmartin 1982, Revelante *et al.* 1982, Sammarco and Crenshaw 1984). Nutrient inputs into GBR waters are from four principle sources: (1) atmospheric inputs by both wet and dry deposition, (2) terrestrial runoff, (3) *in situ* nitrogen fixation, particularly by the pelagic cyanobacterium *Trichodesmium spp.* and (4) intrusion of nutrient enriched Coral Sea waters (Furnas *et al.* 1994).

The first of these sources, atmospheric input and terrestrial runoff, are dependent on the spatial and temporal pattern of rainfall, which occurs predominantly in summer, and shows a high degree of interannual variation. During the wet season, particulate and dissolved nutrients are carried by river flow into the waters of the GBR (Furnas *et al.* 1994). Inputs from runoff are typically restricted to within 10-15 km of the coast, however, under some hydrometeorological conditions, and during massive floods, nutrient rich river plumes may extend to the outer reef. The input of nutrients during these sporadic events leads directly to phytoplankton blooms (Revelante and Gilmartin 1982, Sammarco and Crenshaw 1984), and in addition results in a reservoir of nutrients in shallow coastal sediments (Walker 1981). The wind and tide generated resuspension of this sediment is important in the regeneration of water column nutrients. These two processes, terrestrial runoff and regeneration from sediments, results in a general cross-shelf change in phytoplankton populations, with higher chlorophyll concentrations inshore, and a phytoplankton community dominated by diatoms (Revelante *et al.* 1982, Sammarco and Crenshaw 1984). Further offshore the phytoplankton community is dominated by dinoflagellates, which appear to outcompete diatoms under low nutrient conditions (Furnas and Mitchell 1984, Revelante and Gilmartin 1982).

While terrestrial runoff introduces new nutrients into coastal waters of the GBR, intrusion of nutrient enriched waters from the Coral Sea replenishes nutrients from the seaward margin (Furnas and Mitchell 1984). This process occurs predominantly in summer, and coincides with the seasonal upwelling along the entire east coast of Australia. The intrusions occur when the thermocline rises above the shelf break, and are readily distinguished as a nutrient rich, cool and saline water mass. The contribution of intrusive activity to nutrient input is dependent on the hydrometeorological conditions at the time of intrusion. Intruded water may be pulled back of offshore by Ekman-forced return flows, or the intrusion may be entrained by the residual southerly current flow through the reef matrix in summer, and transported into the GBR. The intrusions are normally fractured by eddy formation associated with the reefs, and broadscale correlation between intrusive activity and phytoplankton blooms is atypical. The effects of intrusive activity are instead observed as a seasonal change in phytoplankton abundance and composition, although direct response to intrusive activity may be observed in discrete patches or layers which form within a week of intrusive activity. The intrusion of nutrient enriched water typically results in an increase in microplankton (>10 μm) diatom populations. The <10 μm population which dominates the phytoplankton biomass and community composition year round, displays only modest seasonal variation.

8. Summary

1. Grazing represents the primary land use in the majority of catchments along the GBR coastline. In the largest of the catchments, the 'dry catchments', such as the Burdekin, Fitzroy and Herbert, grazing occupies about 90% of the catchment area. Soil characteristics are substantially different between catchments and will affect the transport of nutrients with eroded material.

2. Sediment is transported from the catchments into the waters of the GBR, though very little is detected more than 15 km offshore. Most of the sediment deposited in the GBR is in a narrow wedge adjacent to the coastline. Only during extreme events associated with tropical cyclones or monsoonal rain depressions is sediment or nutrient enriched freshwater carried into the reef proper. The rate of transfer of sediments from the land to the sea is rapid, chemical markers associated with changes in land use confirm this.

3. There exists an across the shelf gradient in nutrient concentrations, and a change in phytoplankton assemblage which is concomitant with the primary source of nutrients being from river runoff. Blooms of phytoplankton have been documented as a result of flood plumes. Natural fixation of nitrogen by *Trichodesmium* is a major uncertainty in the nitrogen budget of the GBR.

4. Best estimates of changes in sediment input to the GBR suggest up to a 4-fold increase associated with European settlement. The change in sediment input through aboriginal activities does not appear to have been documented but is probably insignificant. There remain major caveats on the estimates of N and P transported into the waters of the GBR. Current estimates are based on desktop models, and deposition of sediments on floodplains and within the channel network and retention of freshwater in dams, may seriously affect sediment and nutrient transport rates. This is particularly the case for the Burdekin, where flood mitigation may substantially reduce the input to the GBR.

5. There is no incontrovertible evidence of eutrophication in the GBR. There is anecdotal evidence for eutrophication in enclosed bays and nearshore fringing reefs. It is significant that in other bodies of water of similar size to the GBR, in which eutrophication has been documented, there was little evidence for eutrophication prior to major ecosystem collapse. It is unlikely that current monitoring programs will detect anthropogenic eutrophication, as the scale of natural variation is greater than that detectable by long-term trend analysis.

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Review 7

SOIL ORGANISMS, NUTRIENT CYCLING AND WATER MOVEMENT IN NORTHERN AUSTRALIA

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Contents

1. Introduction

There is an increasing awareness in Australia of the need for land managers to adopt a more ecologically sustainable approach towards agricultural production. Managing the effects of production on the 'health' of our soil and water resources is essential to facilitate progress in this direction. In this brief paper I present an overview of our present understanding of how soil organisms influence nutrient cycles and water movement in tropical grazing systems. The effects of grazing, fire and drought on soil organisms are also reviewed. Most of the information presented has been derived from experiments carried out at relatively few sites in northern Australia. The locations of the study sites are listed in Attachment 1. Current studies and studies about to commence are listed in Attachment 2.

2. Nutrient fluxes

There are very few published studies of nutrient budgets or nutrient cycling processes available for Australia's tropical savanna systems. Holt and Coventry (1990) pointed out that because of the inherently low fertility status of most Australian savanna soils, rapid recycling of the nutrients present in organic matter was a critical process in ecosystem functioning. Soil microorganisms, termites and fire were shown to be important regulators of nutrient cycling rates in northern Australian savannas.

2.1. Addition of nutrients

Nutrient additions to ecosystems can occur through a variety of mechanisms including rock weathering, atmospheric accession and in the case of nitrogen, biological fixation. With the exception of nutrient accession via rainfall however, these processes are particularly difficult to quantify.

Studies carried out at a range of sites across northern Australia show that rainwater contains low but significant levels of nutrients. The concentration of nutrient cations (e.g. Ca, Mg, K, Na) was usually less than 5 kg/ha, increasing in some near coastal areas (Wetselaar and Hutton, 1963; Hingston and Gailitis, 1976; Probert, 1976; Langkamp *et al.*, 1982; Noller *et al.*, 1985). Nitrogen and S concentrations in rainwater were less than 2 kg/ha, with P less than 1 kg/ha.

In more intensive agricultural systems, the N fixing ability of legumes may provide a major source of N to soils. Native annual legumes comprise a relatively minor component of the herbage of northern Australia's grazing lands and as such provide only very small additions of N to the soil nutrient store. Although there are no published data from northern Australia on rates of N fixation by native annual legumes, Ash (pers. com.) has suggested that it would be less than 2 kg/ha. Although limited to the higher rainfall zones of the semi-arid tropics, the introduced legume *Stylosanthes* provides a considerably greater N input to soils than the native legumes. Soil N levels at a site near Katherine increased significantly after seven years of *Stylosanthes* (Wetselaar and Norman, 1960) and *Stylosanthes hamata* pastures contributed approximately 33 kg N/ha to a red earth soil at a site near Charters Towers (Probert and Williams, 1986).

Termites are a major component of the soil fauna in savanna landscapes and make a significant contribution to organic carbon mineralization rates (Holt, 1987) and to nutrient recycling (Coventry *et al.*, 1988). The mounds of two common termite species that occur in tropical northeastern Australia, *Amitermes laurensis* and *A. vitiosus*, have mean inorganic nitrogen concentrations 50 to 130 times higher than the surrounding surface soil. This nitrogen is readily leached from the mounds to the soil during rain events (Congdon *et al.* 1993). The high concentration of inorganic nitrogen in termite mounds is thought to be derived from symbiotic nitrogen fixation in the hind gut of termites. Nitrogen fixation by termites is analogous to the nitrogen fixing properties of leguminous plants, and is therefore a potentially large source of nitrogen to the soils of some savanna landscapes. Aspects of nitrogen cycling by termites in northern Australian savannas are currently being studied by a collaborative project (CSIRO Land and Water, University of Adelaide and Fraunhofer Institute for Atmospheric Research). There is a need for wider studies on quantitative aspects of nitrogen fixation by termites.

The information available from Australia's tropical savannas suggests that, where there are no anthropogenic inputs of nutrients (e.g. feed supplements and fertilizers), the overall rate of nutrient addition is very low. The possible exception to this generalization is in those tropical landscapes where termite activity is high, resulting in significant additions of termite fixed nitrogen to soil nutrient reserves..

2.2. Loss of nutrients

Although the loss of nutrients from terrestrial ecosystems occurs as a consequence of the natural processes of erosion and leaching, the rate of loss is usually increased as a result of agriculture. The mechanisms of nutrient loss from grazing systems include: plant biomass removal e.g. grazing and tree clearing, fire, erosion and leaching Nutrient loss as a direct result of plant biomass removal (e.g. clearing) may be substantial, particularly in savanna landscapes where a large proportion of total nutrients are contained in the plant biomass. Although extensive clearing of Australia's northern savannas has occurred in recent years, the effect on nutrient reserves has not been determined.

Erosion accounts for the biggest loss of nutrients from most ecosystems, however, there are few estimates of soil loss due to erosion from Australian tropical savanna landscapes, and even fewer estimates of nutrient loss associated with the soil loss. McIvor *et al.* (1995), working in a woodland near Charters Towers, found that sediment movement was related to cover, with soil losses reduced to low levels where ground cover was at 40% or greater. Also in the Charters Towers region, studies by Scanlan *et al.* (1996) showed that bedload plus suspended sediment loads ranged up to 1000 kg/ha and were inversely linked with ground cover. In a study of gully and sheet erosion conducted in grazing lands west of Ingham in the Burdekin catchment, Prove and Ciesiolka (pers. com.) measured soil losses of 6 - 34 t/ha/yr.

Despite the potential loss of large amounts of nutrients through soil erosion, very little effort has been directed at quantifying this loss from northern Australian savanna catchments. Some preliminary data on losses of dissolved inorganic nitrogen and phosphorous has been published by Prove and Hicks (1990) and Hicks (1992). These studies showed that annual nitrogen losses were approximately 5 kg/ha in heavily grazed native pasture and that nitrogen and phosphorous enrichment ratios in suspended sediment (nutrient concentration in suspended sediment: nutrient concentration in top soil) from the experimental plots were between 13 and 15. Very high cation exchange capacity was found in suspended material in runoff from experimental plots, indicating that large amounts of nutrient cations are also lost in this way (Hicks, 1989). With the exception of a study by the DPI which is expected to begin in the near future (P. O'Reagain, Charters Towers) there are no plot or catchment scale studies on aspects of soil and nutrient loss currently being undertaken in northern Australia.

Much of the soil's reserves of nutrients are contained in the organic matter fraction which, because of its location in the upper soil profile, is often lost through erosion. Recent studies in northeastern Australia have shown that poor grazing management has resulted in the loss of up to 23% of the soil organic matter (Holt, 1997). The significantly lower pasture productivity of these poor condition soils compared with nearby well managed soils (Ash *et al.*, 1995) is no doubt linked to the soil fertility decline associated with the measured losses of soil organic matter.

Much of the savanna of tropical Australia is regularly burnt, both to reduce the bulk of nutritionally poor herbage, and to stimulate the growth of grass shoots with higher protein levels. The passage of fire through savanna causes the rapid mineralization of nutrients contained in organic matter, thereby effectively increasing the nutrient cycling rate. Most of the nutrients released are deposited as ash on the soil surface, although some may be dispersed as very fine particles in the atmosphere. In addition to the loss of some particulate matter, losses of nitrogen and sulphur occur by volatilization during most fires. Volatilization of phosphorous only occurs in hot fires when temperatures exceed 600°C. Very few studies in northern Australia have quantified nutrient losses to the atmosphere as a direct result of fire. Norman and Wetselaar (1960) found that over 90% of the nitrogen in a native pasture at Katherine, N.T. (4.5 kg/ha), was lost to the atmosphere as a result of burning. Although losses of this magnitude appear small, they may assume greater significance when expressed as a proportion of plant-available nutrients.

Nutrients are also exported from grazing systems in the form of cattle biomass. For example, using the percentage Ca and P of an adult steer carcase (Agricultural Research Council, 1965), together with an average carrying capacity of one beast per 10 hectares, and a liveweight production of 400 kg in 4 years, one can arrive at a net loss of approximately 50-200g of these nutrients/hectare/annum from grazing lands in the Dalrymple Shire in north Queensland. Quite clearly, nutrient losses of this magnitude are unimportant.

3. Water movement

Through their effects on soil structure, soil organisms exert a significant influence on infiltration and runoff rates. Because of the large range in body size, soil organisms influence soil structure and water movement in different ways. The very small soil organisms such as bacteria, secrete mucilages which bind small soil particles together, thereby effectively increasing soil porosity and water-holding capacity. The main influence of larger soil organisms is through the creation of macropores connected to the soil surface. The size and number of these soil macropores within a given area effectively control the steady-state infiltration rate.

The influence of microorganisms on water movement in and on soils has not received much attention. Mott *et al.* (1979) found significant reductions in organic carbon, hydraulic conductivity and sorptivity in bare soils compared with grassed soils in a tallgrass pasture near Katherine. In a savanna woodland near Charters Towers, Holt *et al.* (1996a and 1996b) found significantly lower organic carbon, soil microbial biomass and unsaturated hydraulic conductivities in bare areas compared with grassed areas. In each case overgrazing had resulted in the appearance of the bare areas. Microorganisms also form intimate associations with surface soils to form crusts which in most cases appear to improve infiltration (Eldridge and Greene, 1994).

As discussed in the Nutrient Fluxes section, termites are ubiquitous in Australian tropical landscapes. Not only do they influence nutrient cycling processes but they also affect the water storage and transmission properties of soils. Holt *et al.* (1996a) showed that a reduction in the biomass and diversity of detritivorous termites caused by heavy grazing pressure over a period of six years at two sites near Charters Towers, north Queensland, caused a 70% decline in unsaturated soil hydraulic conductivities and a 40% decline in steady state flows. Changes in soil hydraulic properties of this magnitude obviously have dramatic implications for soil water storage, erosion and pasture productivity. Although there are no other published studies of the influence of termite activity on the hydraulic properties of Australia's tropical soils, significant advances have been made in the semi-arid regions of Africa. Studies in northern Burkina Faso showed that cumulative infiltration amounts, soil water content and porosity were higher on experimental plots with termites compared to plots without termites (Mando *et al.*, 1996). By placing mulch on severely crusted soils and thereby stimulating termite activity, Mando (1997) was able to significantly improve the soil structure and hydraulic properties of degraded soils. These termite induced changes in soil properties were sufficient for the development of natural vegetation on previously severely degraded and bare soils.

There are a few studies which have examined the effects of grazing on run off and soil erosion in northern Australia (discussed above), but none of these studies documented changes in the biological properties of soils (McIvor *et al.* 1995; Scanlan *et al.*, 1996; Prove and Hicks, 1990).

4. Influence of grazing, clearing, fire and drought on soil organisms

4.1. Grazing

In addition to reducing ground cover and increasing runoff, erosion and soil nutrient loss, poor grazing management can have a negative effect on soil organisms and soil fertility levels generally. A decline in the biomass and diversity of soil organisms as a direct result of grazing pressure has already occurred in some northern Australian savannas. Partly degraded native pastures in northern Australia were shown to have a significantly lower soil microbial biomass than non-degraded pastures (Holt, 1997). Associated with this reduction in soil microbial biomass was a decreased activity in the ammonification enzymes amidase and peptidase, indicating that the N mineralization potential, and hence soil nitrogen availability, would also be decreased. Thus the limited information available suggests that heavy grazing reduces microbial biomass and activity which in turn negatively affects soil nutrient supply, soil structure and water infiltration.

Again, there are very few studies on the effects of grazing on termite populations. Holt *et al.* (1996a) found that heavy grazing of native pastures at two sites near Charters Towers reduced the abundance and diversity of termites. In contrast, Birkill (1985) found that the density of mounds built by the termite *A. vitiosus* were significantly higher in heavily grazed paddocks compared with lightly grazed paddocks. She concluded that the increase in termite populations was due to the ability of this termite to utilize cattle dung as a food resource. The density of *Nasutitermes longipennis* mounds in a grazing exclosure near Townsville increased after three years a zero fire, zero grazing treatment (Holt, 1988). The contrasting results of these few studies suggests that the effects of grazing on termites may be species dependent. In general, available evidence suggests that a reduction in termite activity will have a significant effect on nutrient availability and pasture production. Future studies should aim to quantify the role of termites in the nitrogen economy of grazing lands, and to determine the grazing pressures at which the important activities of termites remain unaffected.

4.2. Clearing

The effects of clearing of tropical native woodland on soil organisms is also relatively unknown. Holt and Coventry (1988) noted a reduction in the density and diversity of mound-building termites following the clearing of native woodland and establishment of *Urochloa* pasture near Charters Towers. They attributed the disappearance of harvester termites from the newly established pasture to the lack of acceptable food resources. A study at Balfes Creek, near Charters Towers showed that tree clearing results in higher soil temperatures (Gillard *et al.*, 1989). Because of its effect on soil temperatures, tree clearing may also have an indirect effect on termite populations as Holt (unpublished) found that several species of termites common to the Charters Towers region were unable to survive temperatures above 45°C for more than 30 minutes. High soil temperatures coupled with low soil moistures also reduces the activity of soil microorganisms as reflected in soil respiration rates (Holt, 1987: Holt *et al*, 1990).

4.3. Fire

Repeated burning may depress organic matter levels of some soils, with an associated decline in exchange capacities. Burning of native pastures for two years at Cardigan, near Charters Towers, caused a 30% decline in soil microbial biomass (MB) levels (Holt, unpublished). Since MB is largely responsible for the mineralization of nutrients in organic matter, it is likely that a decline in MB will be associated with a reduction in the nutrient recycling capacity of soils that are continuously burnt.

With the exception of the study by Holt (1988), discussed above, no information on the effects of fire on termite populations in tropical Australia is available. Since most of the termites found in northern Australia are detritus feeders (ie. feed on leaf litter, twigs, dung, bark and dry grass) it is probable that removal of their food resource by burning will have a negative effect on their survival. It is also probable that drought, because of its effect in reducing food supply for the termites, will have a similar negative effect on populations.

5. Soil organisms as indicators of catchment health

Over recent years there has been much discussion centred around the potential of soil organisms as bioindicators of environmental impact. The most commonly used bioindicators are population parameters of specific groups of organisms e.g. earthworms, ants and other soil faunal groups, or some index of activity e.g respiration, enzyme activity, cellulose decomposition etc. These have all been used as an indicator of the state of a ecosystem. With the exception of a preliminary study on the potential of soil microbial biomass (MB) as an indicator of pasture state and possible transition (Holt *et al.*, 1996), there are virtually no studies of bioindicators in the tropical savannas of Australia.

A range of soil invertebrates have been considered as indicators of condition or state, but caution must be used when interpreting results. Most researchers agree that much basic research is still needed before invertebrates can successfully be used as indicators of state (Paoletti *et al.*, 1991). Most bioindicators are used to distinguish states (or condition) of a system. As such they reflect the physical properties of that system e.g. qualitative/quantitative aspects of the herbage layer or soil surface. If the need is for diagnosis of state, then often visual indicators (e.g. herbage attributes, soil crusts) are a simpler and easier tool than having to recognize specific faunal assemblages.

If the need is for an indicator to warn of a potential transition to a poorer state, then state indicators as mentioned above are of little use. The work of Holt *et al.* (1996) showed that MB may have some use as an indicator of potential transition, ie. it may allow the risk of pasture degradation under a range of environmental and management parameters to be assessed. For this type of indicator to be successful, critical levels of MB need to be established for identifiable land condition states, ie. thresholds for MB.

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ATTACHMENT 1 — LOCATION OF EXPERIMENTAL WORK

Experimental Site and Soils	**Reference**
Katherine, NT - red earths	Wetselaar and Norman (1960) Wetselaar and Norman (1963) Norman and Wetselaar (1960) Mott *et al.* (1979) Birkill (1985)
Kimberly, WA	Hingston and Gailitis (1976)
Charters Towers, QLD	Probert (1976)
Groote Eylandt, NT	Langkamp *et al.* (1982)
Alligator River, NT	Noller *et al.* (1985)
Balfes Ck, QLD - red and yellow earths	Probert and Williams (1986) Coventry *et al.* (1988) Gillard *et al.* (1989) Holt and Coventry (1988) Congdon *et al.* (1993)
Lansdown, QLD - solodics	Holt (1987) Holt (1988) Holt *et al.* (1990) Congdon *et al.* (1993)
Hillgrove, QLD - euchrozems	Holt *et al.* (1996a) Holt *et al.* (1996b) Holt (1997) Ash *et al.* (1995)
Lakeview and Allan Hills, QLD yellow earths	Holt *et al.* (1996b) Holt (1997)
Cardigan, QLD - neutral red duplex	Ash *et al.* (1995) McIvor *et al.* (1995) Hicks (1989) Prove and Hicks (1990) Hicks (1992) Holt *et al.* (1996a) Holt *et al.* (1996b) Holt (1997)
Charters Towers region, QLD	Scanlan *et al.* (1996)
Kangaroo Hills, QLD - solodics	Prove and Ciesiolka (pers com)

Most studies referred to in the review have been conducted in the Charters Towers (north Queensland) and Katherine (NT) regions. The earth soils of these regions are widely disatributed in northern Australia and might be viewed as representative. The northwest of WA is poorly represented.

ATTACHMENT 2 — CURRENT RESEARCH

Agency and Investigator(s)	Project Title	Research Site
Fraunhofer Institute for Atmospheric Research (Dr H. Papen), University of Adelaide (Dr I. Singleton), CSIRO Land and Water (Dr J. Holt). Funded by German Ministry of Education, Science; Research and Technology (BMBF)	N_2O emissions from savanna soils (aspects of N cycling)	Cardigan and Hillgrove, north Queensland
QDPI (Dr P. O'Reagain). Funded by Drought Regional Initiative (Canberra) and GBRMPA	The effect of grazing management on soil and nutrient loss in the tropical savannas of north Queensland.	Wombiana, north Queensland