THE GREAT BARRIER REEF

SCIENCE, USE AND MANAGEMENT

A NATIONAL CONFERENCE

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THE GREAT BARRIER REEF SCIENCE, USE AND MANAGEMENT

A National Conference

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VOLUME 1

Invited Papers

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James Cook University of North Queensland
Townsville, Queensland, Australia

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CRC Reef Research Centre

GREAT BARRIER REEF
MARINE PARK AUTHORITY

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CONTENTS

Preface 1

INTRODUCTORY SESSION

Partnerships and collaboration: management of the Great Barrier Reef World Heritage Area, past, present and future ***I McPhail*** 5

Advances in scientific research on the Great Barrier Reef since 1983 ***R Reichelt*** 9

SESSION 1

Land use influence and nearshore processes and pressures

Keynote Paper: Run-off from the land to the rivers and the sea ***R Wasson*** 23

Sources of material in river discharge ***G Rayment*and D Neil*** 42

Terrestrial inputs of nutrients and suspended sediments to the Great Barrier Reef lagoon ***A Mitchell and M Furnas**** 59

Marine plants as bioindicators to infer source, transport and fate of nutrients on the Great Barrier Reef ***B Dennison*** (abstract only) 72

SESSION 2

Pressures and effects on the Great Barrier Reef lagoon

Keynote Paper: Biological oceanography of the Great Barrier Reef ***M Furnas* and A Mitchell*** 75

Soft-bottom benthic communities and processes in the Great Barrier Reef lagoon ***D Alongi*** (Paper not presented) 88

Impacts on and responses of seagrasses in the Great Barrier Reef - issues for management ***W Lee Long* and R Coles*** 101

The effects of prawn trawl fisheries on Great Barrier Reef seabed habitats ***R Pitcher*, C Burridge, T Wassenberg and I Poiner*** 107

Endangered and charismatic megafauna ***H Marsh*, P Arnold, C Limpus, A Birtles, B Breen, J Robins and R Williams*** 124

SESSION 3

Pressures on reefs, islands and cays

Keynote Paper: Issue-driven research for managing the Great Barrier Reef: progress and future directions ***T Done*, L Bode, R Coles, C Crossland, U Engelhardt, M Furnas and K Woolfe*** 141

Population and community dynamics of corals: implications for management of the Great Barrier Reef ***T Hughes*** (abstract only) 151

Environmental implicaions of waste-water management on resort islands of the Great Barrier Reef ***R Volker*, M Gallagher and A Johnston*** 152

Threats, status, trends and management of seabirds on the Great Barrier Reef ***K Hulsman*, P O'Neill, T Stokes and M Warnett*** 164

The effects of line fishing on the Great Barrier Reef: available evidence and future directions ***B Mapstone*, C Davies and J Robertson*** 178

SESSION 4 . . . . . .

Large-scale phenomena and organism response

Keynote Paper: Massive corals: grand archives of Australian paleoclimate ***M Gagan*, S Anker, L Ayliffe, D Barnes, J Chappell, D Hopley, P Isdale, J Lough and M McCulloch*** 195

Coral bleaching: implications for the Great Barrier Reef Marine Park ***O Hoegh-Guldberg*, R Berkelmans and J Oliver*** 210

Geoscience issues on the Great Barrier Reef: time scales for reef and shelf processes ***D Johnson*, P Larcombe, B Carter, A Orpin, P Ridd and K Woolfe*** 225

Organism level response of corals to increased nutrients concentrations ***D Yellowlees*** (abstract only) 242

A review of the possible causes and consequences of outbreaks of the crown-of-thorns starfish *(Acanthaster planci)* on the Great Barrier Reef - an Australian perspective ***U Engelhardt* and B Lassig*** 243

Physical oceanography ***E Wolanski and B King**** 260

ADDITIONAL SESSION . . . . . .

Management-science links

Catchment management links to the Great Barrier Reef ***C Robson*** (presented by D Begbie) 269

Effects of sugarcane growing on the environment ***H Bonanno*** (presented by I Ballantyne) 286

The marine tourism initiative towards use management in the Great Barrier Reef ***E Green*** 292

Fisheries management in the Great Barrier Reef region ***J Tanzer*, M Elmer and T Healy*** 298

SESSION 5 . . . . . .

People and the Reef

Keynote Paper: Science brokering and managing uncertainty ***P Cullen*** 309

Science and tourism infrastructure on the Great Barrier Reef: learning from experience or just 'muddling through'? ***G Inglis*** 319

Understanding Great Barrier Reef economics ***S Driml*, T Hundloe and R Blamey*** 335

Understanding the tourist market ***P Pearce*, G Moscardo and B Woods*** 343

Understanding visitors and use through social sciences research ***M Fenton and D Benzaken*** (abstract only, not presented) 353

SESSION 6

Reef connectedness

Keynote Paper: Connectivity and the replenishment of fish populations on coral reefs ***P Doherty*** (abstract only) 357

On the assumption of larval dispersal among reefs: caution advised ***G Jones*** (abstract only) 358

Genetic evidence for connectivity, past and present: implications for management ***J Benzie*** (abstract only) 359

Patterns of coral diversity within the Great Barrier Reef ***C Veron*** (abstract only) 360

Larval transport modelling in the Great Barrier Reef ***M James*, L Mason and L Bode*** 361

SESSION 7

Managing the Great Barrier Reef World Heritage Area

Keynote Paper: Can the Great Barrier Reef World Heritage Area be managed sustainably? ***I Lowe*** (abstract only) 379

The changing roles of aboriginal people in the management of the Great Barrier Reef. ***N Pearson and A Leibler*** (Presented by A Tanner, abstract only) 380

State of the Great Barrier Reef World Heritage Area report ***J Oliver*** (abstract only) 381

The Great Barrier Reef: multiple-use marine park and world heritage site ***P Valentine*, T Webb, H Marsh and P Lucas*** 382

Community involvement in the management of the Great Barrier Reef ***D Tarte* and E Hegerl*** 396

Throughout this table of contents* indicates, in the case of a multi authored paper, the person who presented the paper at the conference.

PREFACE

The Great Barrier Reef is a marine ecosystem that is recognised worldwide for its unique biological and physical features. It is by far the largest single collection of coral reefs in the world and biologically supports one of the most diverse ecosystems known.

The Great Barrier Reef Marine Park includes most of the Great Barrier Reef region and the Reef was added to the World Heritage List in 1981. The Great Barrier Reef Marine Park is a multiple-use protected area with zoning plans and permits for different activities being the main tools for Reef management. The Great Barrier Reef region supports direct economic activity estimated to be worth in excess of $1 billion annually to Australia. Demands are rapidly increasing for information about, and access to, the Reef and its resources by tourists, other recreational users, commercial fishing and mariculture industries.

The large and growing economic and social values of the Great Barrier Reef demand an improved scientific knowledge base to allow Reef users and managers to make more informed decisions, so that benefits can be maximised in a sustainable manner and costs minimised, while preserving the Reef's unique biological and physical features. The 25 year Strategic Plan for the Great Barrier Reef World Heritage Area, with both 5 year and 25 year objectives, has been developed recently by a process involving all users and interest groups.

Knowledge about the Great Barrier Reef from natural, social and economic research is an essential part of decision making for ecologically sustainable development. In the early 1970s, research effort in the Great Barrier Reef underwent a major shift – essentially from earlier expedition-type enterprises to institutionally based projects and programs. The Great Barrier Reef Conference held in Townsville in 1983 captures a summary of this work and provides a valuable baseline of information. But much of the early information comprised small bites or building blocks of vital knowledge with little integration possible across scientific disciplines. Physical and natural science predominated with minor mention of social, economic and engineering research.

Thirteen years later, ideas on reef management and use have changed considerably, as has the knowledge from research. The present Conference sought to examine two key questions:

Firstly, how reef science has adapted to reflect these changes.

Secondly, what we have learnt in recent years that will enable sustainable reef-based industries and economic activity, and provide an improved scientific basis for management and decision making of the Great Barrier Reef as a World Heritage Area.

The Conference provides a review of major scientific findings and concepts over the last decade, purposely integrating information across research on key issues. The mixture of keynote, invited and contributed papers provides a good basis of record and discussion. Putting 'people' into the equation through enhanced social science research is a notable step forward, along with higher effort in engineering research. However, research on economics and indigenous use/involvement remain under represented.

The work of the Organising Committee (Jan Crossland, Dave Yellowlees, Terry Done, Don Alcock, Jon Brodie, Peter Valentine, Kirsten Duke, Peter McGinnity) and graduate students; the sponsors – and the enthusiastic response of authors – ensured that the Conference delivered and recorded a new information base useful to existing and future Reef researchers, managers and users, and conservation and other interest groups.

Chris Crossland
Chair, Organising Committee

INTRODUCTORY SESSION

Chair: Chris Crossland

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Partnerships and collaboration: management of the Great Barrier Reef World Heritage Area, past, present and future
I McPhail

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Advances in scientific research on the Great Barrier Reef since 1983
R Reichelt

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Partnerships and collaboration: management of the Great Barrier Reef World Heritage Area, past, present and future

Ian McPhail
Great Barrier Reef Marine Park Authority, PO Box 1379, Townsville Qld 4810

To claim the ability to manage a natural system has more than a touch of hubris about it. We are reminded by David Suzuki that humans do not manage natural systems, they can only attempt to manage the activities and impacts of humans in and on that system.

No more is this true than in the management of the Great Barrier Reef. Whatever the sweep and cycle of natural events in recent geological time, the European settlers found the reef in its present stage of scale and abundance. After Captain Cook committed one of the first recorded incidences of anchor damage, increasingly intensive human use has been made of the system, beyond the first assumed light impacts of the indigenous populations. This increase is seemingly exponential, and it is only in the last decade that trends thought to be slow, have now accelerated to the point of creating major challenge.

The Great Barrier Reef is iconic, it is Australia's first and the world's largest world heritage area. Although by no means a closed system - it is part of a massive hemispheric circulation - and by no means complete in biogeographical terms it approximates closer a bioregional arrangement for management purposes than any other portion of this country. In spite of recent debates the Great Barrier Reef Marine Park is not a national park, it is a physical and political province. In Australia, areas established for conservation have more often than not been remnants and not always the best examples of their vegetation or other characteristics - the Great Barrier Reef is a province that includes practically all of the reefal areas, and the cross shelf components of coast, lagoon, reefs and the open ocean to seaward. Much will be discussed about the characteristics of the natural systems and their life forms in the region this week, and the threats and opportunities that are identified by science.

The biodiversity, natural beauty and high productivity of the system means that the Great Barrier Reef Marine Park is also a fully functioning portion of the Australian economy. In legislation, it is established for multiple use; reasonable use is a statutory right. Within its very large 350 000 square kilometre area, spreading along 2 000 kilometres of the Queensland coastline, there is an approximately $700 million to $1 billion per annum vessel based tourism industry, a $250 million dollar commercial fishing industry, and a large recreational boating and fishing activity. The continued interest in the development of further integrated resorts on islands and the coast brings not only the issues of immediate environmental impact but collateral pressures. Along the coast of the Great Barrier Reef are six of Australia's bulk export ports, and some 2 000 large vessels a year transit the region. Although residential populations are growing off a low base, some of this country's fastest growing urban areas are in tropical north Queensland. Indigenous groups are claiming the right to be involved in management, based on their long association with the region and also in such issues as traditional hunting rights, and in broader issues of fishing and by-catch. Adjacent to the coast, and located on modified flood plains and wetlands is the canegrowing industry, Australia's second largest export crop by value. Clearance of native vegetation for pastoral purposes adds to the dynamic of the downstream effects of land use, making the whole issue of water quality one of great concern.

This pattern of growth is all occurring within or beside the Great Barrier Reef World Heritage area. In spite of sectional argument, World Heritage Areas in Australia are managed to a level far above the average in most other parts of the world, yet this should not divert from the recognition that management is increasingly being, or indeed should be, subjected to standards that are appropriately stringent.

Add to this real and immediate challenges in the decline of vulnerable species, and the jurisdictional complexity of the region, then the phrases ecologically sustainable development and the precautionary principle are being put to the test. Indeed, though these concepts are increasingly appearing in legislation and properly so, they are essentially qualitative and are often the source of debate in their application. I understand in this conference Valentine will address this topic, and argue that in a world heritage area such as

the Great Barrier Reef, management might be better served by the introduction of more direct instruments, such as best or highest practice requirements.

Given the over-riding obligation to conserve the World Heritage Area, the political and the jurisdictional dimensions, the complex use patterns which frequently compete and displace, the need for equity and fairness in access, no extra-political body such as the Marine Park Authority could manage without a national consensus that the Great Barrier Reef was worth conserving, strong political support and fully functioning and working relationships with the many parties that have an interest in the use or the management of the region. The Marine Park Authority is celebrating its 20 years of existence, with the slogan 'Twenty Years of Partnerships'. That these partnerships should be eternally amicable is about as wishful as believing marriages are, but they have proven to be strong and enduring. Nevertheless the nature of the relationships requires constant attention, and re-structuring to meet changing demands. Indeed the increasing change in use and pressures being placed on the region mean also that compartmentalised interests, with limited involvement by one group in the activities of others, should be long gone. The conservation movement is not the only interest area that becomes broadly involved with others. Displacement and equity issues bring commercial and recreational fishers into debate, mangrove clearance brings the conservation and fishing sectors together, recreational boat owners feel displaced at crowded reefs and islands.

Certainly one of the outstanding achievements has been the negotiation between groups of the 'A 25 Year Strategic Plan for the Great Barrier Reef World Heritage Area', a stakeholder agreement about the short and long-term objectives for sustainable management. It was always intended that this document would be living and dynamic, and an audit of its application mid-way through the implementation of its five year objectives has been commenced internally, later to include stakeholders reports on their stewardship. Flowing from this, from the statutory cross-sectoral and cross-jurisdictional Great Barrier Reef Consultative Committee and from the strongly consultative nature of the legislation the Authority has established sectoral and regional advisory mechanisms. Some need further development such as those with the tourist industry, indigenous interests and the conservation movement, but they all represent a culture of contact that has proved enduring even through some testing periods.

Chapter 4 of the Strategic Plan speaks of the role of research as an objective to obtain and disseminate accurate and timely information which will help decision makers and maximise community confidence in decisions made in regard to the Great Barrier Reef World Heritage Area.

Organised scientific activity is of relative recency, amongst the first forays being the conduct of Great Barrier Reef expeditions in the inter-war period, and the establishment of research stations by the Universities of Sydney and Queensland and the Australian Museum. Like other uses the growth in inquiry into the reef and its users has also seemingly increased exponentially. Certainly the increase from the Yonge expedition of the twenties to the effort of today is significant. The foundation of the James Cook University and the establishment of the Australian Institute of Marine Science have been absolutely critical to the understanding of the reef. Australian Institute of Marine Science has established itself as the pre-eminent public sector marine research institution, with an increasing national presence, and demonstrates the clear benefits of a specialised arrangement for research into the marine environment.

The technology of scientific inquiry has changed dramatically. Cartography, hydrography, position fixing, combined with GIS and computer simulation mean that powerful new tools have improved both opportunity and analytical capacity enormously.

Science holds a dual status in the management regime. First, through its contribution to the corpus of knowledge that is available for application to decisions on the management of the Marine Park. Second,as an industry or use in its own right.

The Authority has held from its origins that credible management must be grounded in good information. It has invested relative to its resources very heavily in information and its interpretation. Authority scientists led by such as Gilmour, Kinsey, Craik, Kenchington and others, have made distinguished contributions on their own behalf. Brodie, Engelhardt and

Benzaken are continuing that tradition. However, as the management tasks have become increasingly complex, the Authority has correspondingly become a purchaser of research. The need for information is a core requirement of the Marine Park Authority, but the conduct of research is not in itself a best use of resources. The Authority's research and monitoring section concentrates on identifying areas of needed research, brokering and interpreting the results in management terms, and maintaining or accessing important databases. They are often research managers. As well the Authority has considerable needs in the unglamorous field of monitoring, essential for the establishment of trends.

In the post-war period the long-standing scientific activity was augmented by the growth of James Cook University and the establishment of the Australian Institute of Marine Science. In more recent times, the University of Central Queensland has begun to contribute. This development of a locus for marine science in the region led in 1993 to the Marine Park Authority combining with James Cook University, the Australian Institute of Marine Science, the Queensland Government through the Department of Primary Industry and tourism industry partners to establish the CRCfor the Ecologically Sustainable Development of the Great Barrier Reef - whose long title is directly targeted at information for management. The Authority contributes $680 000 annually to the CRC and $1M raised from 75% of the first dollar of the Environmental Management Charge collected from commercial tour operators. Most of the effort is not so-called applied research, but it is increasingly focussed on the issues that the Authority has developed as principal policy and management areas. I look forward to Terry Done's paper on issues-related research later in the week. Importantly, the CRC is also directing attention to social and economic aspects of reef use. Resource management requires an understanding of users, and the demands, values and perceptions that individuals bring. A knowledge of the fundamentals of the biological and physical characteristics of the region is unarguable, but essentially the authority is managing the people who seek to use the natural asset. Both in-house and with the CRC Reef Research Centre, much work on behaviour and economics has been instituted. Already, material as diverse as work by Done of Australian Institute of Marine Science on biophysical regions and hemispheric systems, informs the Authority of broad connectivities and creates the basis for the identification of representative areas as the starting point for public consideration, through to detailed analysis of environmental impacts of moored or anchored structures, and predicting the behaviour of animals such as the crown-of-thorns starfish. Management needs are complex and the list of research required is equally diverse and rich.

Research however is also a use, and is required to be permitted within the Marine Park. I am sure that all science managers are aware that science can be thoroughly political. The assumption that experimentation is justified wholly by the right to inquire has probably never been true, and has probably never been publicly espoused. It is true however that scientists originally demurred at being subject to a permit regime in the Great Barrier Reef Marine Park. Scientific experiment was seen to be unarguable, and of course beneficial and benign. This does not suggest that universities and research institutions did not have or have not developed ethics bodies and protocols. However, experience in the last two years has shown that public scrutiny of experimentation in the World Heritage Area suggests that many are not convinced of the beneficial value or the ethical correctness of some projects. Recently the Authority and the CRC agreed on an Effects of Line Fishing Experiment. Its objectives were clear, to provide management information on the sustainable levels of exploitation of fish stocks. The background purpose was also very direct. As demand for reef fish expands, particularly with the live fish trade, there should be no possibility of the collapse of stocks and the collateral impacts on the natural system. Because it involved a rezoning, the experimental design was given extensive public discussion, and then debated in parliament. This and other projects, though internally well designed, had presentational features that became negatives, while at the same time issues related to experimentation in World Heritage areas emerged. Much of the public argument was based on fundamentalist objections to using green zones, but some was disturbingly anti-science. As is the nature of such debates, collateral accusations about the use of explosives and poisons in fish research became national news items and had to be handled.

Prior to this debate the Authority had already commenced planning for an ethical study. This was not to be a second guessing of university ethics procedures, but to examine the particular question of experimentation within a World Heritage Area. This may be broadened, in that the Authority is aware of an approach to the Academy of Science to

examine the generic issue of experimentation in world heritage areas. World Heritage designation is no longer a passive indicator of global acceptance of the outstanding natural values of a region. Through the World Heritage Convention and the World Heritage Properties Conservation Act, interested groups are requiring evidence that management is meeting the objectives of the convention. Already in Australia there have been some major court cases while in this region a major development project is being challenged on world heritage terms. The line fishing experiment was evaluated by the Authority in the context of the National Estate, and it has been referred to the Australian Heritage Commission and designated under the Environment Protection (Impact of Proposals) Act. All in all, a stark indication that vital scientific activity must now be managed in a much more complex social environment, and is certainly not accepted by the community as being immune solely by reason of prospective benefit. Experimental design will need to be considered in terms of prudent and desirable alternatives, question whether the benefits of the research justify any environmental impacts, and researchers will need to be sensitive to public presentational issues. This should not be interpreted as a form of Authority oversight but as a recognition that protocols in many areas of experimental science have changed with time as a consequence of changes in community awareness, and that world heritage areas seemingly are now part of this shift.

Let me stress however, that inquiry both as a source of management information and as a use of the Great Barrier Reef Marine Park is vital. In the last 13 years we have been able to move from informed opinion on management matters to information-based decisions. Intense internecine scientific arguments over such topics as crown-of-thorns starfish are converging, although by no means resolved, and certainly the management context is somewhat clearer. Knowledge of dugong, their number, behaviour and habitat status is available to aid what will be fiercely contested management decisions. Monitoring and modelling are providing insights into topics as widespread as larval dispersal and the movement of flood plumes in the Great Barrier Reef lagoon. More information allows decisions to be based on hard evidence, thoroughly grounded arguments are needed when dealing with industries and users who may be displaced or have their activities modified.

In the decade ahead, the increased pressures of use make the products of scientific inquiry of continuing necessity. Long standing relationships with James Cook University and the Australian Institute of Marine Science have created strong historic linkages, while the CRC Reef Research Centre not only provides for funds leveraging but also formal collaborative arrangement. Similarly GBRMPA, James Cook University and the Australian Institute of Marine Science operate formally as INTROMARC a commercial research and training application facility.

Thirteen years ago the Marine Park Authority's need for information on the natural system was a major strategic requirement. Many of the relationships with scientists and institutions were forged as much by common origins and interests of the scientists as by any formal structures. A steady stream of research results influenced the policy directions that the Authority adopted. Today both the need and the relationships remain, but collaboration on an institutional basis has become increasingly formalised. The Authority has structured its programs around a set of critical issues, and is reflecting these through its requests to the CRC Reef Research Centre in particular. Also the information needs to the Authority have spread beyond the physical and biological sciences into economics and social issues. In twelve years' time, what will the structure of collaboration look like? In part this will be as much a function of the universities and research institutions themselves as the Authority. Trends in the funding of research and the shape of institutions are beyond my commentary, however there are two polar demands. One, that curiosity led, basic investigation of the components of this massive, exciting, complex and little-understood eco system will and must always be a fundamental activity. There is endless opportunity for the motivated inquirer, and each fragment of evidence forms one of the building blocks of understanding of what we are dealing with. Secondly, as basic knowledge expands, Terry Done and others will continue to develop a cosmology of the reef. The sweeping relationships of the hemispheric systems, the linkages to the Indo-Pacific realm, the connectivities within the system which will enable the community to decide on the level of protection that they will afford to this superb work of nature. In the words found at the end of many research papers, 'More work needs to be done'. None of us will exhaust the questions in our lifetimes.

Advances in scientific research on the Great Barrier Reef since 1983

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ABSTRACT

Marine science in Australia is critically important for providing the knowledge needed to protect and use what is the world's largest single ocean territory. Advances in scientific research on the Great Barrier Reef have been driven by technological advances, changes in our major research institutions, and recent focusing of research towards strategically important problems of interest to industry, government and the community through the Cooperative Research Centre for Ecologically Sustainable Development of the Great Barrier Reef.
Some examples of technology developments include:

- GPS and remote sensing allow accurate site location and mapping. Reliable vessels, including the high speed tourist vessels, permit easy access to the entire Great Barrier Reef. The expeditionary days are over.

- Scientific instrument advances have boosted chemistry studies (Fourier Transform Mass Spectrometry and NMRs), genetic studies (2D-PAGE electrophoresis), biological oceanography (*Trichodesmium* counter), geomorphology (swath mapping sonar, deep ocean drilling) and physical oceanography (Doppler current meters, wave radar, automatic weather stations, turbidity loggers)

There has been marked increase in the diversity of research effort through institutional growth at James Cook University, the Australian Institute of Marine Science, the Great Barrier Reef Marine Park Authority, the Museum of Tropical Queensland and the chain of island research stations. In addition, there is a significant new player – the Cooperative Research Centre for Ecologically Sustainable Development of the Great Barrier Reef.

As research efforts have advanced, new ideas (the dogma of tomorrow?) have emerged. Some of these include a new understanding of the importance of the coastal trapping phenomenon, an appreciation of the long term changes in species abundance across a spectrum that includes corals, reef fish and even the crown-of-thorns starfish, and increased knowledge of the impact of major natural disturbances such as tropical cyclones and new information on the geological age and growth of the Great Barrier Reef. While understanding of the Great Barrier Reef as one the world's great Large Marine Ecosystems has advanced considerably since 1983, our ability to forecast human impact is still weak. A good understanding of the ways in which living reef systems (e.g. corals and fish) are replenished will likely take a further 5 years of research. Long term changes in productivity and coastal inputs and impacts on the Great Barrier Reef are also only beginning to be understood.

Major problems confronting coral reef researchers are the relatively high cost, and hence restricted resources, available for critically important mapping and monitoring work, development of more effective and useful techniques for risk assessment of impacts on coral reefs, and development of autonomous sensors for more components of the reef system (especially the living components), which are needed as input to predictive models of the whole system. While the Reef CRC has generated new focus and research interest, a major long term goal of research should be to service the information requirements of the 25 Year Strategic Plan for the Great Barrier Reef. Its creation has been a visionary act that warrants pursuit.

As environmental information becomes more readily available, it will be ideas and models that will be in shortest supply.

INTRODUCTION

The first Great Barrier Reef Conference was held in 1983 here at James Cook University, hosted by the University and the Australian Institute of Marine Science. The Institute had reached its planned staffing level only a year or two previously, the Authority had yet to finish its planning processes, and JCU was considerably smaller than it is today.

John Bunt, who was then Director of AIMS, was one of the opening speakers and he talked about the origins of the interest in coral reef research, the Australian Coral Reef Society, and the dual roles for the Australian Institute of Marine Science and the Great Barrier Reef Marine Park Authority.

John Bunt also spoke about the last really major injection of public funds into marine science, back in 1979, the public concern for the health of the Reef, and about the question that has driven much of the scientific research on the Great Barrier Reef since that time. The question was '**What controls growth, maintenance and change in the Great Barrier Reef**?'

Things have changed dramatically in Australian science over the last 13 years – R&D managers now use a different vocabulary of management jargon. The talk now is about project management skills, specific research objectives, milestones, performance indicators, best practice, ISO 9000, earnings targets, cost recovery, pricing and charging policies, efficiency audits and corporate governance. Coming from a science background I often ask myself if all this business oriented approach and management-speak is necessary to get the science done. The answer seems to be an unequivocal yes – because science is driven by people and funding, and to secure the funding it is vitally important to be strongly linked to those who are buying the research – mainly the taxpayer (government) and industry. Just as scientific discoveries can influence society, so does scientific culture track that of society.

Establishing strategic priorities, building links to users of research, and commercialising of intellectual property are more important to publicly funded research agencies and Universities than they used to be.

Since the 1983 conference we have seen a strong collaborative relationship develop between the University, AIMS and the Authority. Since then the Queensland Museum has established a branch here and all of us are looking forward to further growth with the completed Pandora exhibit in the second stage of the Museum of Tropical Queensland.

On the world stage we have seen the Earth Summit in Rio (which saw among other things the birth of the Global Ocean Observing System program which will eventually produce systems that make synoptic maps of the oceans' currents the way that meteorologists map winds, clouds and rain.). We now have international agreements on biodiversity and climate change; the UN Convention on the Law of the Sea has come into force, and recently we've seen the birth of the International Coral Reef Initiative.

Today, the Great Barrier Reef remains in peak condition while coral reefs in most other places are showing signs of wear and tear from human impacts. As public access to the full extent of the Great Barrier Reef becomes possible through the use of high speed vessels, the potential for pressure on our own coral reefs is mounting and the demand is increasing for tighter and more watchful control of the users of the Reef. As control is applied, the users will demand higher standards of proof that restrictions are necessary. The need for high quality science and engineering is greater than ever.

Advances in scientific research on the Great Barrier Reef have been driven by technological advances, changes in our major research institutions, and recent focussing of research towards strategically important problems of interest to industry, government and the community. The Cooperative Research Centre for Ecologically Sustainable Development of the Great Barrier Reef (or the 'Reef CRC' as we call it) is a partnership fostered by

government and industry and designed to steer research towards the most important problems confronting the Great Barrier Reef – that is, building the knowledge we need for its conservation and sustainable use.

In this paper I want to provide some background and context for the conference in relation to the national marine science effort, highlight changes in technology and understanding since the last conference, and finally try to guess where science is heading on the Great Barrier Reef by mentioning a few gaps in our efforts.

Marine science in Australia

Australia's Ocean Territory is filled with natural wonders, valuable resources and ecosystems that are beautiful and diverse, both physically and genetically.

Conservation of our marine resources is a national responsibility which is now written into international law. In fact this is now written into a number of international instruments and the occasional collision between them, or problem of interpretation, will keep the legal profession secure for the foreseeable future.

Extract from UN Convention on the Law of the Sea, Part xii.

> **Article 192**
> **General obligation**
>
> States have the obligation to protect and preserve the marine environment.
>
> **Article 193**
> **Sovereign right of States to exploit their natural resources**
>
> States have the sovereign right to exploit their natural resources pursuant to their environmental policies and in accordance with their duty to protect and preserve the marine environment.

Exploitation of resources is mentioned in the article right next to the one on protection and preservation. This seems to be near the nub of ecologically sustainable development.

The ESD of the EEZ is of great importance to our tourism and fishing industries, but there are differing views in society about what this really means. It's likely to be a matter of long-running debate – partly because the meaning of sustainability is highly arguable and partly because we know relatively so little about the vast expanse of Australia's Ocean Territory.

Globally, the marine economy is worth around US $1000 bn (Bennett 1996). Australia's slice of this action is estimated roughly to be about A$40 billion, and the Australian Marine Industries and Sciences Council reported recently that growth in the marine sector has been running at 8% per year for a number of years. At this rate the Australian marine sector could be worth more than A$100 bn by 2010.

By any measure, both our marine environment and marine industries are valuable to Australia. Science and technology have vital roles to play in support of both conservation and industry development. The knowledge needed to use marine resources without destroying them, and to protect them where necessary, can come only from world-class science and engineering efforts.

The size of the task for scientists and engineers to generate the knowledge Australia requires to protect and use its marine resources is daunting. Already there is a considerable effort being put into the job. There is currently intense interest, generated by the National Commission of Audit report, on the number of government agencies involved in various sectors. Of all the areas in our economy, the marine sector is among the most diverse.

To illustrate the point with an international example – look at the United Nations. In the UN there are 14 large, separate agencies working on marine issues such as atomic energy, food, agriculture, labour, maritime law and pollution, navigation, safety at sea, ocean dumping, transporting hazardous waste, meteorology, conservation and cross-agency coordination.

Table 1. United Nations and other specialised agencies dealing with the oceans

DPCSD	Department for Policy Coordination and Sustainable Development
IAEA	International Atomic Energy Agency
FAO	Food and Agriculture Organisation – sustainable development
ILO	International Labour Organisation
IMO	International Maritime Organisation
IOC	Intergovernmental Oceanographic Commission of UNESCO
WHO	World Health Organisation
WMO	World Meteorological Organisation
World Bank (GEF)	Global Environment Facility World Bank
UNCTAD	Trade law – navigation
UNDP	United Nations Development Programme
SEED	UNDP – Sustainable Development and Environment Division
UNEP	United Nations Environment Programme
UNIDO	United Nations Industrial Development Organisation

Within Australia we have similar diversity. Interest in the marine sector comes from the general community who enjoy the marine environment as tourists, sailors and recreational fishing enthusiasts; from government policy developers and decision makers; from educators and students; and from a huge variety of industries, including tourism, offshore oil and gas, fisheries, pharmaceutical's, ship building and engineering, and environmental consultants.
There are at least 8 federal portfolios with an interest in marine science and technology with 20 separate groups conducting targeted work of one form or another – and this is only at the federal level, and does not count the Universities and Colleges, nor does it count the States' fisheries and environmental research labs. With such diversity of interest it is important that a strong effort go into coordination and cooperation.

By 1992, national expenditure on marine science and technology was running at over $200 million and by now would likely be considerably more than this. Remember that this expenditure is serving a huge array of customers. Some of these customers have common interests, and some research efforts use shared infrastructure. To coordinate this scientific effort where necessary, there are several federal groups working to ensure there is no wasteful duplication. The two main ones are the Commonwealth Heads of Marine Agencies (HOMA), currently chaired by Dr John Zillman of the Bureau of Meteorology, and the Coordinating Committee on Science and Technology (CCST), which is effectively an Inter Departmental Committee.

However, given the diversity of issues arising within the marine sector, it is hard to be confident that the best possible coordination is achieved between the various government departments which are implementing a diverse set of policies covering everything from ocean dumping to safety of life at sea and navigation conventions.

Quite recently, the government has drawn attention to the size and value of our ocean territories and the need to develop a coordinated policy for all issues relating to the oceans. The **Ocean Policy** is expected to take at least a year to develop, and is being coordinated through the federal Environment portfolio. At the same time, a group working within the Science and Technology portfolio is developing a **Marine Science and Technology Plan for Australia**.

Both of these initiatives are in their early stages, but should be of great benefit to Australia.

Research on the Great Barrier Reef: times have changed

The Great Barrier Reef epitomises marine diversity and natural beauty. Last week the US President, Mr Clinton, called it the *'biggest, best managed protected marine and coastal area in the world'.*

The approach to conducting research on the Great Barrier Reef has changed since the first Conference. Researchers did not have a good map of the Reef back in '83. Satellite-based navigation had not yet become common-place, and where it was available it could be downright dangerous because the maps of reef locations had considerable errors in them. So the SatNav could put you in the right location (plus or minus a few hundred metres), but the reef on the chart might have been a kilometre or two in another direction, or worse, right underneath you.

Through sustained funding of hydrographic survey, remote sensing, the island research stations, the AIMS research vessels, remote logging devices and weather stations, and the broad scale ecological monitoring work, scientists now have a much more synoptic picture of the entire Reef.

In 1989, the Australian Marine Science and Technologies Committee published a review of tropical marine science (Dartnall 1989)

The shallow water communities of corals and fishes are now fairly well known – but not mapped in their entirety. The taxonomy of corals was a glaring gap in our knowledge of coral reefs until the 1980s. Since the 1983 Conference, this gap has largely been filled by the work of Veron, Wallace, Pichon and their co-workers.

The broadscale oceanography is now much better understood after a long -term effort by Pickard, Stark, Andrews, Wolanski, Bode, Black, Massel and Burrage. Their efforts have ranged from studies of the large-scale fluctuations in the East Australia Current to the small-scale impact of waves on coral structures.

Links between these physicists and experts in other disciplines have produced new knowledge about the nutrient cycling of the Great Barrier Reef and the impact of cyclones on coral communities. Understanding such huge natural phenomena is absolutely essential if the impact of human activities on the Reef is to be understood.

In the field of ecology there has been a steady growth in knowledge across a huge range of topics but with few singular landmarks, but one that captured everyone's imagination is the phenomenon of mass coral spawning. The fairyland images of countless eggs drifting upward like an inverted snowstorm were popularised in natural history, Attenborough-style television productions and are known now to many Australians. Since that spectacular phenomenon was first documented it has triggered a range of diverse research projects including studies of the chemical composition of coral eggs and physical modelling of the upwelling and downwelling currents that lead to the formation of linear slicks of drifting eggs.

A few years ago, it was the AIMS broad-scale surveys that detected the new outbreaks of crown-of-thorns starfish now appearing again in the northern regions after an absence of 15 years. This has enabled the Authority to mount fine scale studies to determine the extent of outbreaks in time to alert tourist operators and the general public. As well as covering a very large area, the tracking of major events such as populations of crown of thorns starfish has to be done over a significant time period. It is the detailed ecological information and long time series of data on coral reef fish collected by Williams, Doherty, Russ, Choat and their co-workers that enable the Marine Park Authority to predict how the fish communities will change on reefs that are affected by the crown of thorns starfish.

Effects of Line Fishing

On the subject of fish: A major experiment on the effects of line fishing received government approval last week, amid considerable publicity, and with consternation from some quarters.

The controversy surrounding the experiment brought into focus a few important issues:

1. The public holds the Great Barrier Reef in the highest possible regard and will not tolerate any possible threat of damage to their national icon whether they live in Mackay, Melbourne or Perth;

2. The questions being asked of scientists about managing the resources of the Reef are getting increasingly more difficult to answer without large scale studies such as the Effects of Line Fishing – manipulative experiments are a critically important tool and need not be highly destructive in their impact;

3. Natural Resource managers (Marine Parks and Fisheries in this case) have long recognised the need for good consultation among the stakeholders in the resource, but the public consultation will in future need to include some public review of the ethics of scientific experiments on the environment;

4. Finally, it is clear that managing access to natural resources remains one of the greatest unresolved issues for the Australian people, perhaps for the whole world. Judging from comments I heard on talk-back radio last week, the general public is still divided on the issue of how much of the environment should be zoned for sustainable but multiple use rather than zoned as 'no admission by humans'.

It's worth noting that resource use conflicts are not restricted to the Great Barrier Reef – they are everywhere. Native title, coastal developments, community versus commercial use of natural resources, and so on. As a society we are still coming to grips with how to manage common property resources in a comprehensive way.

Technology developments

Many aspects of science and engineering are either technology-driven or lead to new technologies being developed.

Since the 1983 Conference there has been a number of developments that have had a profound impact on how reef research is done.

For example, Global Positioning Systems and satellite-based remote sensing allow accurate site location and mapping. Reliable vessels, including the high speed tourist vessels, permit easy access to the entire Great Barrier Reef. The expeditionary days of Sir Maurice Yonge are well and truly over. The island field stations, which I regard as vitally important research infrastructure in the region, are no longer the remote base-camps they used to be. Today there are modern accommodation and laboratories located as close as possible to the reef, providing essential teaching and research facilities and help further the aim of 'taking the lab into the field' and should be supported as National Facilities.

Scientific instrument advances have boosted

chemistry studies (Fourier Transform Mass Spectrometry and Nuclear Magnetic Resonance instruments),

genetic studies (2D-polyacrylamide gel electrophoresis, microsatellites and automatic sequencing),

biological oceanography (AIMS Workshop has built *Trichodesmium* counter that uses laser to excite fluorescence in the algal cells of interest, giving new capability to measure ocean productivity),

geomorphology (swath mapping sonar, deep ocean drilling) and

physical oceanography (Doppler current meters, JCU's wave radar, automatic weather stations, turbidity loggers)

In addition to development of new instruments, there is a variety of technologies that were once rare but are now commonplace. Almost every scientist has access to a personal computer, and my finance manager at AIMS thinks that every chemist has an HPLC machine as well. Sophisticated tools such as mass spectrometers are much more readily available than they were.

Diversity and growth of research effort

There has been marked increase in the diversity of research effort through institutional growth at James Cook University, the Australian Institute of Marine Science, the Great Barrier Reef Marine Park Authority, the Museum of Tropical Queensland and the chain of island research stations. In addition, there is a significant new player - the Cooperative Research Centre for Ecologically Sustainable Development of the Great Barrier Reef. The CRC started in 1993 and signalled a new phase in the degree of cooperation among researchers studying the world's greatest reef system, and a major advance in linking research output to users of the research.

New ideas and understanding

While our understanding of the Great Barrier Reef as one of the world's great Large Marine Ecosystems has advanced considerably since 1983, our ability to forecast human impact is still weak. We know much more about processes that happen on the reef. And through the deep ocean drilling program, we even know much more about how the Reef came to be where it is. But we still find it very difficult to make accurate predictions about long term change on the Reef.

Nevertheless, there are some new ideas emerging (call them the dogma of tomorrow?) that is changing our basic understanding of the Great Barrier Reef.

For example, there is a rapidly growing understanding of the importance of the coastal trapping phenomenon. Research on the reef and elsewhere is showing that there is good news and bad news associated with water runoff from land. The good news is that where the reef is offshore, it is relatively safe from this impact. The bad news is that the impact is likely to felt more acutely along the coast because there are a number of physical phenomena that lead to pollution and sediments running off the land to be trapped in the coastal zone.

It is the inshore fringing reefs and other habitats that are most exposed to most risk from land-based pollution and silting effects.

Since 1983, another idea to gain currency is that of the Large Marine Ecosystem. This expression recognises the fact that it is the regional current patterns that join parts of the reef together, and which makes it important to understand the regional patterns in how coral reefs are replenished after disturbance. A good understanding of the ways in which the parts of the Great Barrier Reef (e.g. corals and fish) are replenished will likely take at least another 5 years of research.

As our time series of observations grows longer, we now appreciate the huge effect that a single catastrophic event like a cyclone can have on the Reef. Ecologists no longer think much about long term stable equilibria. They understand now the importance of high frequency, short term processes, occasional large scale catastrophes, and the need to gain long term data about the Reef to understand it properly.

Problems, gaps and opportunities

Major **problems** confronting coral reef researchers are:

- the relatively high cost, and hence restricted resources, available for critically important mapping and monitoring work,
- development of more effective and useful techniques for risk assessment of impacts on coral reefs, and
- development of autonomous sensors for more components of the reef system (especially the living components), which are needed as input to predictive models of the whole system.

As information becomes more readily available, it will be ideas and models that will be in shortest supply.

What about **major gaps**?

This is a difficult question because every good scientist has far more questions than answers, and begins every morning by reciting 'How little we know, how little we know'.

In my view it is critically important to capture the knowledge of reef systems now held by a few scientific experts and make it accessible to scientists from other disciplines. Coral taxonomy is an example where there are very few people who have a comprehensive knowledge across the whole field. If they were to leave coral research to become highly paid business consultants, reef research could be in trouble.

The funding pressure on the basic work of Museums and Universities is partly responsible. But so is the trend in basic strategic science away from systematics and taxonomy towards areas where more immediate users of the research results can be identified (and asked to pay research costs). There is a serious market failure when it comes to building and capturing such basic knowledge.

Regarding **the future**, I think the field is wide open.

There are **great opportunities** to extend research in both science, engineering and technology development on the Great Barrier Reef. To name just a few, I would list:

improving the basic tools for automated data gathering (especially biological data), developing data standards for spatial mapping, and sharing resource mapping data via the Internet;

modelling sites under pressure, or potential pressure, from human impact (taking the OECD approach of pressure-state-response) – this could be done perhaps hand-in-hand with the idea of a Ready Response Group for the Great Barrier Reef which is overseen by the Marine Park Authority and the Maritime Safety Authority, and could swing into action at the site of either natural events like cyclones or human-induced catastrophes like ship grounding;

extending basic research in both the life sciences and the earth sciences into the inter-reefal and deep ocean areas of the Great Barrier Reef Marine Park, which have been a little 'out of sight, and out of mind';

developing improved risk assessment models for the Great Barrier Reef, incorporating ecosystem value' state variables of the sort now being developed by Terry Done at AIMS.

25 year objective:

Advances on some or all of these fronts would greatly assist us fulfil the 25 Year Objective which is spelled out in the Research and Monitoring Chapter of the Great Barrier Reef World Heritage Area Strategic Plan:

'To obtain and disseminate accurate and timely information which will help decision makers and maximise community confidence in decisions made regarding the Great Barrier Reef World Heritage Area.'

While the Reef CRC has generated new focus and research interest, a major long term goal of research should be to service the information requirements of this Strategic Plan. Its creation was a visionary act, and its objectives warrant the most vigorous pursuit.

At the Australian Institute of Marine Science, we have recently re-examined where we are heading, reviewed our role and the major types of research that we undertake.
We regard our mission in life to be 'to generate the knowledge to support the sustainable use and protection of the marine environment through innovative, world-class scientific and technological research'.

Our research falls under one or more of 5 major banners:

Understanding the Ocean Environment;
Characterising Marine Biodiversity;
Identifying valuable marine living resources;

Supporting Ecologically Sustainable Development by understanding and documenting natural changes and human impacts; and finally
Developing advanced instruments and techniques for the marine sector.

Directions for reef science

I've talked about changes since 1983, and the new links between researchers and users of research results. These links were flagged by John Bunt in his speech back in 1983. These relate to science application, but what is happening to the underlying philosophies and dogmas that drive scientific endeavour?

Scientific thinking shifts over time, some call it science 'fads' and some call it epistemological advance. Whatever you call it, a new 'reality' has settled over those who study ecosystems.

The popularisation of complex system behaviour through writings on the 3 C's: catastrophes, chaos and complexity has had a sobering effect on the ecologists who sought fundamental laws of the universe in the complicated workings of ecosystems. 'There goes my Nobel Prize' I hear you say.

Murray Gell-Mann wrote recently that in ecology we are dealing with a system that is half-way between the cold order of absolute zero, and the heated randomness one finds at the centre of the sun. In Gell-Mann's terms, when we try to understand coral reefs we are dealing with a system with very high Algorithmic Information Content. They are about as complex as complex systems get.

This is not to say that the behaviour of coral reef systems is completely unpredictable, but it does imply that deducing whole system behaviour from the bottomup is probably at best a waste of time and at worst impossible (that is, not able to be simulated by computer). Instead we adopt a scaled approach. (This is a bit like the approach taken by physicists using renormalisation theory to make the mathematical description of complex, multi-scale physical systems amenable to computation.)

As with any scientific challenge, the hard bit is to ask the right question. In modelling terms this means that you have to select an interesting 'grain' or 'scale'. Then in making measurements, formulating testing and using models for prediction you need to decide how much the level of 'grain' below the one you are working on is relevant.

As I think Roger Lewin once wrote many years ago in New Scientist, **far better to have an approximate answer to the right question than an extremely precise answer to the wrong question.**

Instead of starting with the molecules of the reef and working up, the future lies in building sets of models of how the reef works, but at different scales, and choosing scales of interest to the modeller. **The challenge is to build models that can accept observations of the real system, which generate predictions that can be tested against reality in some way, and which are making predictions of use to someone.**

On a different tack, having mentioned molecules just now, I should say that those who are trawling through the molecules of the Great Barrier Reef are doing so for another reason. The work on molecules with unusual chemical properties may not produce predictions of whole system behaviour, but has already revealed chemicals and medicines of great benefit to the public owners of the Reef.

How reef science has adapted to changes in management and use of the reef

The emerging need in coral reef science is to turn our detailed knowledge of how a reef works into useful information for those whose job it is to protect the reef for future generations, or for those who want to run a commercial operation on the reef without damaging it in any way.

Some of the tools are falling into place now. For example, GIS technology is developing steadily, and the visualisation tools now available (such IBM's DX Explorer) make it possible to display complicated scientific model outputs in easily interpretable 'movies' of the system.

A key step in this process will be for us to develop the capacity to gather broad scale geographic information cheaply and quickly (and the physicists and chemists are well ahead of the ecologists on this one), and then make those data accessible to system models developed on behalf of users. The use of underwater video recording and PC-based data analysis tools have helped enormously, but we have a long way to go.

CONCLUSION

Future researchers will have radically improved access to information, regardless of who wins the 'internet browser wars', whether the Network Computer and Hollow Network become standards, and regardless of whether Bill Gates joins forces with Rupert Murdoch to form a company with a bottom line bigger than Japan's GDP.

Information will be as valuable as it always has been, but its ready availability will boost the **importance of the analyst**, the synthesisers of information and the idea-generators, those who filter information and turn it into something useful.

Earlier I singled out (at the risk of offending others by omission) some areas of research that have advanced significantly since 1983. A common feature was that in every case there were scientists involved from the Australian Institute of Marine Science and James Cook University. The core business of AIMS is research, and the core business of JCU is teaching, but our common interests are clear and the high degree of cooperation has been remarkably effective.

Linking this powerful research combination with the Great Barrier Reef Marine Park Authority has been highly productive and put Australia at the forefront of tropical marine research and resource management. Each party brings something different to the table. It's no accident that the Global Coral Reef Monitoring Network is based here at AIMS in Townsville, and I think it is appropriate that now the International Coral Reef Initiative (mentioned by President Clinton during his recent visit) will also be based here in Australia.

A few years ago the creation of the CRC scheme created an opportunity to bring the user community into the picture, steering research towards high priority areas for the users of the Great Barrier Reef and drawing in significant industry funding for coral reef research.

Provided we can also protect the 'public good' research effort, and I am sure we can, the recent advent of the Reef CRC signals a new phase of cooperative research on the Great Barrier Reef, a partnership that includes not only the researchers but also the primary users of the research results.

Based on its performance so far, I predict that by the time a third Great Barrier Reef Conference is convened, commentators will be reporting tremendous advances arising from the CRC's research results.

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SESSION 1

Land use influence and nearshore processes and pressures

Chair: Jon Brodie

Rapporteur: Andrew Johnson

•

Keynote Paper:
Run-off from the land to the rivers and the sea
R Wasson

•

Sources of material in river discharge
G Rayment* and DT Neil

•

Terrestrial inputs of nutrients and suspended sediments to the Great Barrier Reef lagoon
A Mitchell and MFurnas*

•

Marine plants as bioindicators to infer source, transport and fate of nutrients on the Great Barrier Reef
B Dennison
(abstract only)

•

Run-off from the land to the rivers and the sea

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ABSTRACT

It is believed that run-off from the land is carrying contaminants that are beginning to damage the Great Barrier Reef. Worldwide experience indicates that coral reefs are being damaged by land-based contaminants, and so it is wise to reduce the quantities of these materials leaving the coastal rivers. If reduction is to be accomplished, basic questions must be answered: how much sediment and nutrient is being discharged beyond the coast, what are the sources of the material, how does land use effect these discharges, and where does the material go once it reaches the Great Barrier Reef lagoon? This paper reviews our current answers to these questions, raises doubts about the degree to which we can accurately answer them, and concludes that to achieve reductions a more sophisticated appreciation of catchment processes will be necessary.

INTRODUCTION

This paper reviews our current understanding of how much water, sediment and nutrients are reaching the Great Barrier Reef lagoon from the adjacent land (figure 1); the principal sources of this material, and their relationship to land use in the catchments; and how far the material travels in the Great Barrier Reef lagoon. The paper concludes with observations on the management of the Great Barrier Reef lagoon catchments and the use of scientific knowledge.

Marine and coastal ecosystems around the world are being degraded by land-based pollution by inorganic sediments, organic matter, inorganic nutrients, toxic pollutants, freshwater storage on land which reduces both total and episodic discharges to the sea, and land cover changes that increase the discharge of freshwater to the sea (Bernal and Holligan 1992). Estuaries, lagoons, mangroves, corals, seagrass and salt marsh habitats and geomorphic features occur in the Great Barrier Reef lagoon, and so the movement of materials from the land to the sea is not only of significance for coral reefs. For example, mangroves are sensitive to salinity variations caused by changed freshwater inputs, with implications for coastal stability, recreational amenity, and spawning for various animals (Fortes 1988).

There have been many statements about, and analyses of, the biological and physical impacts in the Great Barrier Reef lagoon of land-based pollutants, (e.g. Bell 1991; Jones and Tirendi 1989; Bird 1973; Pringle 1986; Bell and Elmetri 1993; Baldwin 1990; Hopley et al. 1990; Hopley 1988; Hopley et al. 1991; Belperio 1983, 1988; Larcombe and Woolfe 1995; Harris 1995; Kinsey 1991), but many have been ambiguous in their results. The most complete analysis of Australia's marine environment (Zann 1995) concludes:

> The most serious issues in Australia's marine environment stem from poor catchment use, and therefore declining water quality. Increased levels of nutrients and sediments are the major problems.
>
> The most serious consequences of these are the die-back of seagrasses in temperate Australia and threats to inshore corals in the wet tropics. (p.96)

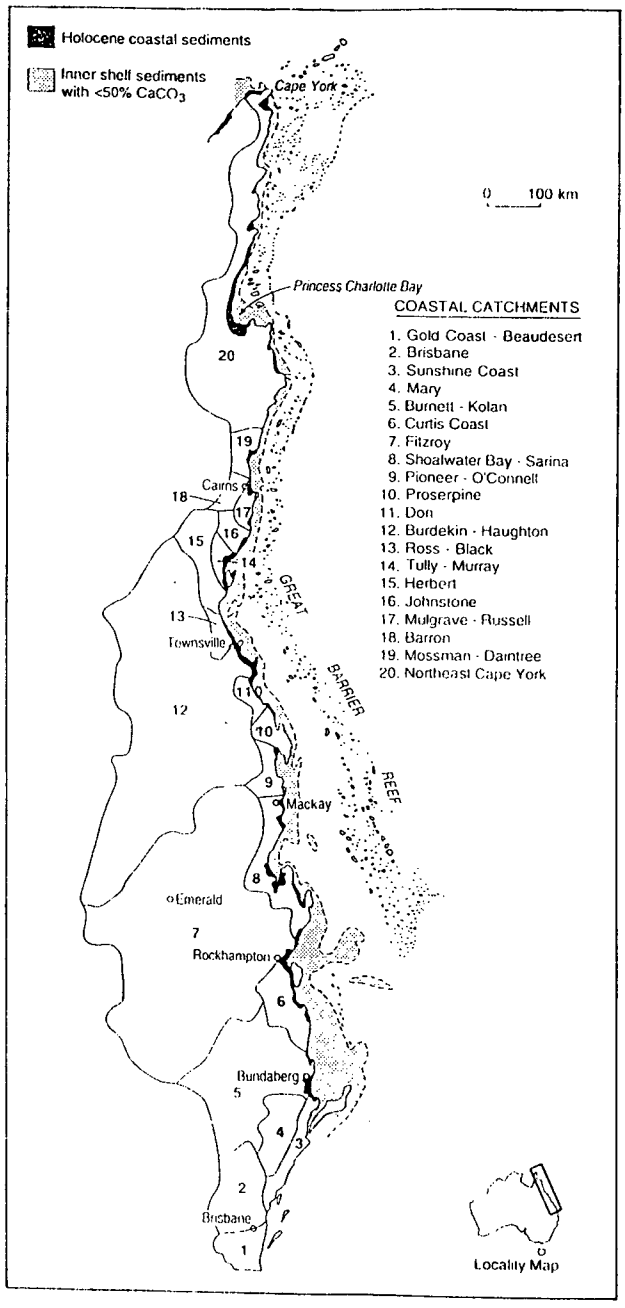


Figure 1. The Great Barrier Reef lagoon and adjacent catchments

Reference to Hopley (1981), Hopley et al. (1990) and Baldwin (1990) will illustrate Zann's (1995) conclusion. Sediments have dramatically affected some nearshore corals. Mangroves have been damaged by sedimentation from adjacent agricultural land, freshwater pulses have also damaged corals and mangroves, and nutrients have the potential to do widespread damage to corals. In 1990, Baldwin concluded:

> Nutrient levels in inshore Great Barrier Reef waters are reaching levels that have caused detrimental effects to corals elsewhere, though the evidence of damage to coral communities in the Marine Park is still primarily circumstantial. (p.1)

The risk to the ecosystems of the Great Barrier Reef lagoon is therefore demonstrated in some cases and not in others. Under these circumstances of uncertainty, it is prudent to continue to search for the effects of land-based pollution, and to reduce the pollution loads so as to avoid the impacts seen on reef and mangrove systems in other parts of the world. To reduce the pollution loads, emphasis needs to be on the management of sources of sediment and nutrients within the catchments discharging to the Great Barrier Reef lagoon.

Discharges to the Great Barrier Reef lagoon

Freshwater

For the purposes of monitoring and reporting the water resources of Australia, the continent is divided into 13 drainage divisions (Australian Water Resources Council 1987). The North-East Coast Division extends from the NSW–Queensland border to near the tip of Cape York, and includes all catchments draining onto the coast. This Division has an area of 451,000 km^2, a mean annual outflow to the sea of 83,900 x 103 Ml, and a specific outflow of 0.186 x 103 Ml/km^2. This specific outflow is the second highest after Tasmania, and along with the other tropical Divisions (Gulf of Carpentaria and Timor Sea) yields most freshwater to the Australian coast.

The southern-most catchments in the North-East Coast Division are not adjacent to the Great Barrier Reef lagoon, but water and transported constituents from these few southern catchments probably move north into the Great Barrier Reef lagoon. Therefore, this Drainage Division is a reasonable approximation to the area that drains to the Great Barrier Reef lagoon.

Forty-six catchments are listed by the Australian Water Resources Council (1987) as draining the Drainage Division, although this list does not include a large number of small catchments. The smallest in the list is 115 km^2 in area (Whitsunday Island) and the largest is 143,000 km^2 in area (Fitzroy River). On average, the specific discharge is highest for the small catchments, a well known hydrologic phenomenon where the run-off ratio (run-off/precipitation) is greatest in small catchments.

Although it might be expected that conversion from native vegetation to the current land uses would increase the run-off ratio, and that any increase to the density of the drainage network would increase the peaks of flood hydrographs, there are no analyses of data from the Great Barrier Reef lagoon catchments relevant to the issue. It has been shown that by combining measurements of Sr/Ca and $d^{18}O$ in corals, river run-off to reefs can be quantified (McCulloch et al. 1994). If long enough coral records are analysed, it should be possible to investigate changes to run-off to the Great Barrier Reef lagoon from before European settlement.

Suspended sediments

The first estimate of the fluvial sediment discharge to the entire Great Barrier Reef lagoon was by Belperio (1983) who applied to all Great Barrier Reef lagoon catchments a relationship between sediment loads and discharge derived for the Burdekin River (Belperio 1979). This approach assumes that there is a constant relationship between load and discharge in all Great Barrier Reef lagoon catchments, and that the area of catchment is the only variable useful for prediction of sediment yield.

Moss et al. (1993) developed two simple statistical models to estimate the quantities of sediment reaching the Great Barrier Reef lagoon. Model 1 depends entirely on flow-weighted in-stream concentrations (125 kg/Ml northern catchments and 250 kg/Ml in the south) and annual average stream discharge. In-stream concentrations are based on data from the region, resulting from daily or frequent samplings during the wet season. In this approach, all factors that influence erosion and sediment transport (such as land use, erodibility, etc.) are subsumed by two variables. Model 2 is more elaborate, allowing for the effects of land use, catchment erosion rate, and delivery ratio (catchment yield/total erosion). Sediment exports from each land use category in a catchment were calculated separately, using published erosion plot and small catchment data, then summed. These exports were corrected by applying a delivery ratio of 0.1, derived from a global compilation of relationships between delivery ratio and catchment area. The annual discharge term in Model 2 is expressed as specific yield (i.e. Ml/km^2) to reduce the effect of large variations of annual flow volumes between catchments.

Model 1 outputs were calibrated by comparison with available measured loads, giving the best estimates in the view of Moss et al. (1993). Model 2 outputs were calibrated using the

outputs of Model 1, and increased for sediments by a factor of 1.5. Model 2 is physically more realistic than Model 1, but the additional parameters of Model 2 do not seem to add to its veracity. An obvious problem with Model 2 lies in the use of a single delivery ratio for land use areas of widely differing size, given that the ratio usually shows a strong inverse relationship with catchment area.

Neil and Yu (1995, 1996) have developed another statistical model based on mean annual catchment run-off and suspended sediment concentration data from six catchments discharging to the Great Barrier Reef lagoon. A rating curve method was used, corrected for bias created by back transformation of the log-linear relationship, to calculate mean annual sediment yield using daily streamflow data. Neil and Yu then calculate the Unit Sediment Yield (USY) as the sediment yield (t) per unit area of catchment (km^2) per unit run-off (mm) per unit time (yr). USY is strongly correlated with mean annual catchment run-off allowing Neil and Yu to calculate sediment yields from all Great Barrier Reef lagoon catchments without making arbitrary choices of concentration.

The results of these calculations are summarised in table 1. The total yield to the Great Barrier Reef lagoon calculated by Belperio and Neil and Yu (for their current case) are indistinguishable at about 27.5x106 t/yr, giving a mean specific yield of 61 $t/km^2/yr$. Despite the essentially identical total yields, there are some marked variations between calculated yields from individual catchments. This is most evident by comparing the proportion of the total yield produced by the largest catchments. The Fitzroy, Burdekin–Kolan and NE Cape

York catchments constitute 80% of the total area draining to the Great Barrier Reef lagoon. These catchments produce 54% of the total yield estimated by Belperio (1983), 50% of the total estimated by Moss et al. (1993), and 83% of the total estimated by Neil and Yu (1996). These differences are also clear when expressed as specific yield. In the case of the Fitzroy catchment, the specific yield is 15 $t/km^2/yr$ from Belperio (1983), 12 $t/km^2/yr$ from Moss et al. (1993), and 73 $t/km^2/yr$ from Neil and Yu (1996).

In attempting to assess the veracity of these various estimates, two criteria will be used: physical reality of the model; and the agreement between estimated and measured yields. As already noted, Model 2 of Moss et al. (1983) is the most physically realistic of their models, and Belperio's (1983) estimates are based on data from only one river. The model of Neil and Yu (1996) is superior to Model 1 of Moss et al. because it does not rely on an arbitrary assignment of concentrations to northern and southern catchments. The Neil and Yu model also most closely agrees with measured loads from the region. The average specific yield for the entire Drainage Division, according to Neil and Yu, is 62 $t/km^2/yr$. Moss et al. estimated a value of 34 $t/km^2/yr$. Almost all measured yields in this area come from catchments smaller than 1000 km^2 (Wasson 1994), and the smallest catchment in table 1 is 2020 km^2.

Therefore, to compare measured and estimated yields, a regression equation relating catchment area and mean annual sediment yield in NE Queensland (Wasson 1994) has been used to estimate yields for catchments of 2000 and 3000 km^2 in area. the mean of these estimates is 38 $t/km^2/yr$. The average specific yield, for all catchments between 2000 and 3000 km^2, calculated by Neil and Yu is 51 $t/km^2/yr$. From the estimates of Moss et al, the specific yield for these catchments averages 177 $t/km^2/yr$, and from Belperio 417 $t/km^2/yr$.

While the extrapolation of the power law equation of Wasson (1994) has probably underestimated the yield from catchments 2000 to 3000 km^2 in area, the estimate of Neil and Yu is closest to the 'measured' yields derived from this equation. The estimates by Belperio and Moss et al. are too high.

An additional estimate of the suspended sediment yield to the Great Barrier Reef lagoon is by Harris (1995 and pers. comm.). He assembled all measured yields and calculated a total yield by multiplying the area of similar catchments by representative measured yields for these areas. By this means, Harris estimated a mean annual yield of 86 x 106 t/yr, a figure three times higher than that of Neil and Yu.

Table 1. Estimated sediment yields to the Great Barrier Reef lagoon

Catchment	Area (km^2)	1	2	3	4	5
	Average Sediment Yield (t/yr x 106)					
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	1.210	0.573	0.138	0.435	3.2
5 Burnett–Kolan	39470	1.760	0.724	0.641	2.381	3.7
6 Curtis Coast	9225	0.550	0.374	0.133	0.476	3.6
7 Fitzroy	142645	2.200	1.774	2.570	10.466	4.1
8 Shoalwater Bay–Sarina	11270	0.220	0.924	0.166	0.568	3.4
9 Pioneer–O'Connell	3925	1.540	0.657	0.064	0.240	3.8
10 Proserpine	2485	0.110	0.349	0.039	0.132	3.4
11 Don	3985	0.550	0.175	0.057	0.225	3.9
12 Burdekin–Haughton	133510	3.520	2.711	2.116	8.520	4.0
13 Ross–Black	2890	0.550	0.265	0.043	0.133	3.1
14 Tully–Murray	2825	1.870	0.660	0.069	0.124	1.8
15 Herbert	10130	1.430	0.624	0.155	0.536	3.5
16 Johnstone	2330	1.540	0.582	0.056	0.159	2.8
17 Mulgrave–Russell	2020	1.430	0.521	0.050	0.137	2.7
18 Barron	2175	0.330	0.137	0.035	0.094	2.7
19 Mossman–Daintree	2615	1.320	0.528	0.060	0.096	1.6
20 Northeast Cape York	43300	7.260	2.387	0.649	2.008	3.1
TOTALS	450,515	27.39	15.25	7.35	28.03	

1 Belperio (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 Yu (1996)

Wasson et al. (1996) estimated that each year on average 302 x 106 t of suspended sediment is delivered to the coast of Australia. This estimate includes the results of Harris, and needs to be reduced to include the better estimate by Neil and Yu. The total yield to the Australian coast is now considered to be 244 x 106 t/yr, of which the best estimate of yield to the Great Barrier Reef lagoon (28.03 x 106 t/yr) is about 11% from an area that is about 11% of the land that drains to the Australian coast. This area produces 22% of the water that reaches the coast as run-off.

Phosphorus

Of the investigations so far considered, only that by Moss et al. (1993) has estimated phosphorus yield to the entire Great Barrier Reef lagoon. Using Model 1, they estimated an average annual yield of Total P (TP) of 12.2 x 103 t/yr. Model 2, which employs more parameters, estimates a yield of 10.5 x 103 t/yr of TP. While it is not clear from Moss et al. (1993) how well their flow weighted in-stream concentrations of sediment and nutrients represent both floods and baseflow, two values for all catchments is unlikely to be representative of the wide range of flow conditions experienced in the region. Given that most phosphorus is moved attached to particulates wherever there are claying soils (Tiessen 1995), and that most TP is moved during a few large floods, it is most likely that the TP estimates of Moss et al. are underestimated. The comparison of sediment yields in the previous section suggests the same conclusion.

Furnas et al. (1995) estimated the TP yields to the northern Great Barrier Reef by measuring point source discharges and in-stream concentrations in the South Johnstone River, paying particular attention to floods, and multiplying the mean discharge-weighted concentration of P for this river by the average annual discharge for each river. These authors grouped the rivers draining to the northern Great Barrier Reef lagoon into those entering the Tully Box

(Dunk Island to Cape Grafton) and the Cairns Box (Cape Grafton to Cape Tribulation) (table 2).

Mitchell et al. (1996) have used the results of more detailed river sampling to estimate yields of TP for some of the same rivers, and these results are also shown in table 2.

Cosser (1988), using a version of the flow – concentration – unit area relationship derived for the South Pine River in southeastern Queensland (Cosser 1989), estimated the TP yield to the Cairns Section of the Great Barrier Reef lagoon. Estimates for individual rivers are shown in table 2, and the total annual yield for this section was estimated at 9357 t/yr.

It is evident from table 2 that the estimates by Cosser are the highest, and those of Moss et al. are much higher than those of Furnas et al, and higher than most made by Mitchell et al. Furnas et al. note that their sampling is inadequate to resolve flood transports, and so the large loads of P moved with sediment are not well represented in their estimates. Mitchell et al. have included at least one large event in their sampling, but still they estimate yields less than those of Moss et al. which, it was earlier argued, are likely to be underestimates. It is difficult to assess the accuracy of the estimates by Cosser because they are based on a relationship for only one river, slightly modified for northern conditions.

Furnas et al. (1995) note that the average P concentration on sediment is 0.03 to 0.04% in north Queensland streams. Taking the estimate of Neil and Yu of suspended sediment yields in conjunction with this concentration estimate results in a still lower estimate of P yield, (table 2); although this is really an estimate of particulate P which is likely to be about a third lower than TP according to the measurements of Mitchell et al. (1996). Also, it takes no account of enrichment in the fine particle sizes that preferentially constitute catchment yield.

The results in table 2 differ by a factor of up to 36, but most differ by factors between 5 and 10. A better comparison is between estimates based upon similar techniques, that is between that by Furnas et al. (1995) and Mitchell et al. (1996). the estimates differ by a factor of $\leq$ 4. Therefore, the TP yield to the Great Barrier Reef lagoon is uncertain by a factor of about four. The ongoing river monitoring program is the only way of making better estimates.

Table 2. Estimated TP yields to the Great Barrier Reef lagoon

	1	2	3	4	5
Catchment	TP Yield (t/yr)				
14 Tully	528	168	124		
15	499	302	135		
16 Box	466	38	105		1977
17	417		68		3003
TOTALS	**1910**		**432**	**286–382**	
18 Cairns	110	64	32		422
19 Box	423		161		1643
TOTALS	**533**		**193**	**57–76**	**2065**

1 Moss et al. (1993) Model 1
2 Mitchell et al. (1996)
3 Furnas et al. (1995), table 23
4 0.03 to 0.04% of Suspended Sediment yield from Neil and Yu (1996)
5 Cosser (1988)

Nitrogen

Moss et al. (1993) used their Model 1 to calculate a Total N (TN) yield to the Great Barrier Reef lagoon of 90 x 103 t/yr, and their Model 2 provided on estimate of 73.5 x 103 t/yr. Based on measured in-stream concentrations in the region, Furnas et al. (1995) estimated a TN yield to the Tully and Cairns Boxes of 4386 t/yr and 1947 t/yr respectively. Mitchell et al. (1996) estimated a TN yield for several of the rivers investigated by Furnas et al. and Moss et al.

The comparable results are included in table 3. As in the case of TP, the estimates by Moss et al. are generally higher than others, by as much as an order of magnitude. A comparison of the results based upon in-stream concentrations from the rivers of interest indicates that the loads are different by a factor of ≤ 3. Once again, the river monitoring program is essential to reduce this uncertainty.

Table 3. Estimated TN yields to the Great Barrier Reef lagoon

Catchment	1	2	3
	TN Yield (t/yr)		
14 Tully	4225	1258	2142
15	3995	1370	2701
16	3728	1069	353
17 Box	3335	689	
TOTALS	**15283**	**4386**	
18 Cairns	3380	321	690
19 Box	878	1626	
TOTALS	**4258**	1947	
12	15184		6842
7	9937		5346

1 Moss et al. (1993) – Model 1
2 Furnas et al. (1995)
3 Mitchell et al. (1996)

Catchment sources

If loads of sediment, P and N are to be reduced so that damage to the ecosystems of the Great Barrier Reef lagoon is minimised, catchment management is required that properly targets the most important sources of these materials. Analyses of sources and pathways through catchments broadly fall into three categories: simple often black-box descriptions suitable for simple statistical or numerical models; elaborately parameterised numerical models; empirical–deductive investigations designed to identify sources and pathways. Investigations in the catchments of the Great Barrier Reef lagoon fall almost entirely into the first category, but some are being undertaken in the third category.

The role of land use

Neither Belperio (1983) nor Model 1 of Moss et al. (1993) take land use into account. Model 2 of Moss et al. uses exports derived from sediment yield measurements and from plot yields combined with soil nutrient concentrations. Model 2 generates sediment and nutrients exports from measured areas of different land uses. All of the complexity of pathways between sources and river mouths is assumed to be accounted for by means of a series of corrections: delivery ratio, enrichment ratio, dissolved N compensation factor, and annual run-off rate correction factor.

Even if the correction factors appropriately account for the delivery process, there is no way of deconvolving these factors to identify sources and pathways for management purposes. Of course Moss et al. aimed to estimate yields, but it might be tempting to take the formulation of Model 2 as a guide to the significance of land uses as sources of sediments and nutrients. Such an approach would be unwise because there is no independent test of this formulation, and, from the comparison with other estimates, those by Moss et al. appear to be too high.

A potentially very useful approach to estimating the role of land use is to determine change since European settlement. The author (with C. Barnes and J. Olley) is currently taking this approach in the Herbert catchment using sedimentary deposits. Neil and Yu (1996) have used a modelling approach to the same problem, and have used the land use increase factors of Moss et al. (1993) which indicate that grazing increases specific sediment yield over pristine conditions by a factor of 4, and cropping increases it by a factor of 10. For soils with the same P and N concentrations, grazing and cropping increase nutrient yield by the same factors, according to the formulation of Moss et al. (1993). The results of calculations

by Neil and Yu are in table 1, indicating that the current sediment yield of 28 x 106 t/yr is about 3.8 times that prior to European settlement. This compares with a factor 5 or more according to Moss et al. (1993).

Moss et al. (1993) conclude that 84% of the total sediment yield to the Great Barrier Reef lagoon comes from grazing land. Neil and Yu (1996) estimate that 26% of the total yield is attributable to natural processes, 66% from grazing land use, and 8% from cropping. Neil and Yu then question the validity of the increase factors used by Moss et al. (1993), suggesting that a factor of 20–25 may be more appropriate for cropping. They also make the important point that dams have not been considered in the analyses, structures that reduce sediment and nutrient yields.

While much has been made of the link between fertiliser management and nutrient concentrations in rivers, research currently underway is the first likely to demonstrate if a link exists. Mitchell et al. (1996), for example, report early results of studies that suggest N leaching may be reduced by fertiliser management.

Material budgets

The conclusions reached about the role of land use in mobilising sediment and nutrients are based upon correlations between exports (on plots or in small experimental catchments) and land use types. Plots produce unambiguous results, but small catchments do not. A yield of sediment or nutrients is measured in a stream, and the source of the material could be any part of the catchment upstream of the point of measurement – including the ground surface occupied by various land uses, or the channel walls and bed. A material budget is required to deconvolve the sources of yields measured in rivers, or a source tracer.

Cameron McNamara (1985) produced a model-based budget for the South Johnstone River catchment, suggesting that > 80% of soil eroded from cane paddocks remains in farm channels. Arakel et al. (1989) linked evidence of river sedimentation with expansion of cane-land since 1976. They calculated a gross erosion rate of 823,000 t/yr and river deposition of 100,000 t/yr. Adopting the sediment yield estimate of Neil and Yu, of 159,000 t/yr, about 69% of the gross erosion is stored on-farm. The sediment delivery ratio for this catchment is therefore 19%. The figures supplied by Cameron McNamara and Arakel et al. provided no estimates of channel erosion or of slope deposition. Prosser (1996) used aerial photographs and field surveys of sediment and erosion volumes to produce a more complete sediment budget for the Johnstone River catchment. His estimates are for the whole catchment and a 1 km^2 sub-catchment for an intense storm period in March 1996, and for the whole catchment between 1942 and 1983. These budgets, and that by Arakel et al. (supplemented by this author with the catchment yield value of Neil and Yu) are set out in table 4.

The most accurate budget is for the 1 km^2 Coventry Creek, a banana plantation within the Johnstone River catchment. Most sediment was moved from hillslopes at a rate equivalent to 2000 t/km^2, and a further 5% from gullies on recently formed plantation. Only 1–3% of the sediment was trapped at the base of hillslopes in the riparian zone, and 10–15% was deposited in channels. The high sediment delivery ratio (SDR) of 85% is the result of an efficient system where hillslopes lead directly to channels without intervening alluvial flats.

For the same erosion event, the sediment budget for the entire Johnstone River is much less certain (column 2, table 4). About 110,000 t of material cannot be accounted for, perhaps because the cropland erosion estimate is based on extrapolation giving a quantity that is too high. The catchment yield of 193,000 t is that reported by Mitchell et al. (1996) resulting from intense measurements of in-stream concentration of sediment. The budget for the entire catchment between 1942 and 1983 is again uncertain, probably because the cropland erosion rate is overestimated by short-term plot studies, and it is not possible to directly scale from plots to hillslope delivery of streams (1. Prosser pers. comm.).

Despite the uncertainties, these budgets are worthwhile because they force the analyst to attempt to quantify all of the sources and stores rather than assume a system structure dictated by the need for a simple statistical model. On the basis of the data in table 4, channel erosion does not appear to be a significant source of sediment within the Johnstone

River catchment. This is not surprising given that it is a small and relatively steep catchment with a small floodplain.

Table 4. Johnstone River sediment budgets

Budget Components	1 (t)	2 (103 t)	3 (106 t)	4 (103 t/yr)
Sources				
Cropland erosion	1800	560	70	823
Riverbank erosion	90	?	3.8	
TOTALS	**1890**	**>560**	**73.8**	
Stores				
Slope deposition	30	?	?	
Channel deposition	290			
-small tributaries		90	0.7	564
-tributaries			1.1	
-main channel		80	7.7	100
Floodplain deposition		80	0.7	
TOTALS	**320**	**>250**	**>10.2**	
Yield				
Export from catchment	1600	200	6.5	159
Unaccounted	30	>110	57.1	
Sediment Delivery Ratio (%)	85	<34	<9	19

1 Coventry Creek (1 km^2) – March 1996 (Prosser 1996)
2 Johnstone River catchment (2330 km^2) – March 1996 (Prosser 1996)
3 Johnstone River catchment – 1942 to 1983 (Prosser 1996)
4 Johnstone River catchment – annual budget (Arakel et al. 1989)

The Herbert River may be different. In the vicinity of Halifax, the river has been moving laterally between catchment 2 and 3 m/yr since 1883 (Ian Drummond and Associates 1993). In this one reach of 4 km, about 60,000 t/yr of sediment has been eroded, representing 11% of the estimate by Neil and Yu of the current annual yield of the Herbert River. Other reaches upstream of Ingham are also eroding, and so it is clear that channel erosion in the Herbert catchment is a greater contributor to sediment yield than is the case in the Johnstone River catchment.

The largest catchments rise in the semi-arid landscape above the Great Escarpment that separates the coastal plain from the hinterland. This applies to the Herbert, Burdekin, and Fitzroy catchments in particular. These upland areas are grazed and gullied, and main channel erosion appears to be active. Using data supplied by C. Ciesolka (pers. comm.) and Prove (1992) for the Kangaroo Hills area of the upper Burdekin catchment, in sub-catchments of 0.03 to 0.31 km^2 it can be shown that sheet and rill erosion yields 260 $t/km^2/yr$ from grazed land, minor gully and sheet erosion produces 420 $t/km^2/yr$, and severely gullied areas yield on average 1830 $t/km^2/yr$. Wasson (1994) showed that gully density (km/km^2) accounts for 53% of the between-catchment variance in sediment yield. These results suggest that, in the Kangaroo Hills and similar areas, gullies produce about twice as much sediment as sheet and rill erosion. This contrasts with a factor of 8 between sheet and rill erosion and gully erosion in the Southern Tablelands of NSW and the ACT (Wasson 1994).

The role of channel erosion as a source of sediment (and particulate nutrients) remains uncertain for the Great Barrier Reef lagoon catchments. The Johnstone River catchment appears to be dominated by slope erosion, whereas in the drier catchments channel erosion may be much more significant. Given that the best available estimates of sediment yield to the Great Barrier Reef lagoon by Neil and Yu (1996) indicate that the drier (and larger) catchments yield the vast majority of material, channel erosion needs to be examined seriously.

Turning now to nutrients, Moss et al. (1993) presented some of their findings as a nutrient budget while Furnas et al. (1995) constructed formal nutrient budgets for the northern Great Barrier Reef lagoon. Moss et al. concluded that diffuse loads of both P and N are dominant except in urban catchments in the Gold Coast–Beaudesert and Brisbane areas where point source discharges are significant. It is not possible to deconvolve source information from the Model 1 results of Moss et al, and Model 2 indicates that grazing produces most N and P because it occupies the largest fraction of the Great Barrier Reef lagoon catchments.

Moss et al. compare total annual diffuse-source N and P exports with annual inputs of fertilisers. According to their calculations, around Mackay and in far north Queensland, annual N fertiliser inputs exceed annual exports. Only in the lightly cropped Fitzroy region did exports exceed inputs. Phosphorus results show similar features except in the Don, Burdekin–Haughton, Ross–Black catchments where exports of P exceed fertiliser inputs. This comparison is of curiosity value only, and Moss et al. reach no conclusions about the effect of fertiliser inputs on nutrient exports. This is a sensible outcome because, depending on nutrient sources, fertiliser inputs may (or may not) be irrelevant to the yields to the Great Barrier Reef lagoon. For example, if channel banks in the dry parts of the large catchments are significant sources of P (as has been shown in parts of southeastern Australia, Wasson et al. 1996), then fertiliser P can only be contributing a tiny fraction of the yield. But this is speculation until catchment-based nutrient budgets are available.

Furnas et al. (1995) constructed nutrient budgets for their Cairns and Tully Boxes (table 5). They recognise that the river inputs are underestimated because their concentration data did not include sufficient results from flood events. Yet the overall result is very suggestive: fixation of atmospheric N by *Trichodesmium* is potentially the largest input component, and rainfall inputs are of similar magnitude to sewage inputs except in the Tully Box where rainfall TN input is very high. These results confirm those of Moss et al. that sewage inputs to the Great Barrier Reef lagoon are overall trivial, although they may be locally important.

Table 5. Nutrient input budgets for the northern Great Barrier Reef lagoon (from Furnas et al. 1995)

Sources	Cairns Box		Tully Box	
	TP (t/yr)	TN (t/yr)	TP (t/yr)	TN (t/yr)
Sewage	70	19	37	142
Rivers	214	157	477	4906
Rainfall	68	84	90	1547
Upwelling	124–400	53–85	263–641	1138–2773
Trichodesmium	-	140–6500	-	2634–121900
Reef fixation	-	89	-	1257

Land use and water quality

The material budgets presented in the last section are critically important to provide a basis for catchment management. Most of the analyses aimed at estimating yields to the Great Barrier Reef lagoon are based on near-black box models which provide little real understanding of processes inside catchments. The material budgets are examples of empirical–deductive investigations, and only Mitchell et al. (1996) are planning the use of an elaborate numerical model.

In the literature on the maritime effect of land-based pollutants, there is an assumption that land use is a key explanatory variable of rates of transport. This assumption has been partially vindicated by Neil (1995) and Neil and Yu (1996), but in the drier catchments it is likely that landform components are at least as important. As a guide to the possible role of land use and other factors in controlling the movement of particulates through catchments, a brief summary of relevant literature follows.

Catchments

A catchment is an 'area of land from which rainfall or snowmelt flows into a stream, lake, reservoir, etc.' (Lo 1992). A single large catchment is a hierarchy of smaller catchments (sometimes called sub-catchments) each one of which is defined as the contributing area

upstream of a particular point on a stream channel. The smallest catchment is that which extends from the upstream tip of a headwater channel to the drainage divide; an area that is generally less than one hectare, and consists of hillslopes and in some cases, an unchannelled depression through which water moves to the head of the channel downstream. All other sub-catchments contain channels, hillslopes, and alluvial flats such as floodplains, terraces and fans. Channels and alluvial flats become larger, and hillslopes often become longer and gentler and more disconnected from channels, with distance downstream.

It is therefore likely that the link between land use and water quality will vary with position in a catchment, because of variation in the connectivity between hillslopes, floodplains, and channels.

There is a systematic change downstream between stream order and mean valley-side slope length and mean maximum slope angle (Arnett and Conacher 1973). As order increases, and therefore catchment area, mean maximum slope angle increases to a peak at fifth order (approximately 10 km^2) and then declines. Mean slope length increases to at least sixth order (approximately 60 km^2). Rates of soil loss increase as a power function with slope gradient and length, showing that hillslopes in this particular case near Brisbane, erode fastest adjacent to fifth order channels; assuming identical vegetation cover and climate for all sub-catchments. However, as seen in the work of Richards (1977) and Bhowmik and Stall (1979), alluvial flats intervene between hillslopes and channels increasingly between second and fifth order channels. Despite a maximum sheet and rill erosion rate on hillslopes adjacent to fifth order channels, the sediment from these slopes reaches a channel only at those locations where a channel adjoins or undercuts a hillslope, or where the alluvial flats narrow. A highly erosive land use on a hillslope in a fifth order valley reach, may produce a large yield of sediment, but this yield will not have a water quality impact. By contrast, the cultivated slopes in Bamboo Creek catchment (in the Johnstone catchment) are connected directly to first-order channels. These channels drain more than 50% of the entire 13 km^2 catchment (Prosser 1996).

Large catchment regularities

The systematic variation in fluvial landforms, and in connectivity between landforms, along a catchment drainage network, shows that not all land use can affect water quality. These observations also show that there should be large scale regularities in the transport of materials along the drainage network. The most general analysis of these regularities has been performed by Dedkov and Mozzherin (1984) and Mozzherin (1994). These authors argue that under natural conditions, in plains and deforested mountains, specific sediment yield increases as catchment area increases (figure 2). By contrast, in treeless mountainous areas, specific sediment yield decreases with catchment area under natural conditions (figure 2). The specific sediment yield at any point in a catchment is the difference between the total mobilised material minus the stored material upstream. Increasing specific yield can only be the result of increasing input of sediments from downstream sources, the most likely of which are channels. A decreasing specific yield with catchment are implies that most sediment is derived from the headwaters and storage of sediment in alluvial flats and channels increases downstream. When disturbed, both system types display decreasing yield with catchment area, showing that in both cases it is the source zone that responds most to clearing and grazing.

These results are intuitively sensible because of the systematic variations along drainage networks already discussed. The source area hillslopes are on average steeper than those further downstream, and they are connected to channels directly. Therefore, when cleared and/or grazed, the source areas are likely to respond more than other parts of a catchment. Areas of sediment storage increase in size downstream, and so trap more and more mobilised material downstream.

In figure 2, the size of the yield change resulting from disturbance is largest in the smallest (source area) catchments because of the combined effect of mobilisation and storage. This representation is supported by Mozzherin's (1994) global synthesis which shows that the difference in specific sediment yield between intense and less intense agricultural land use, is greatest in small catchments (table 6).

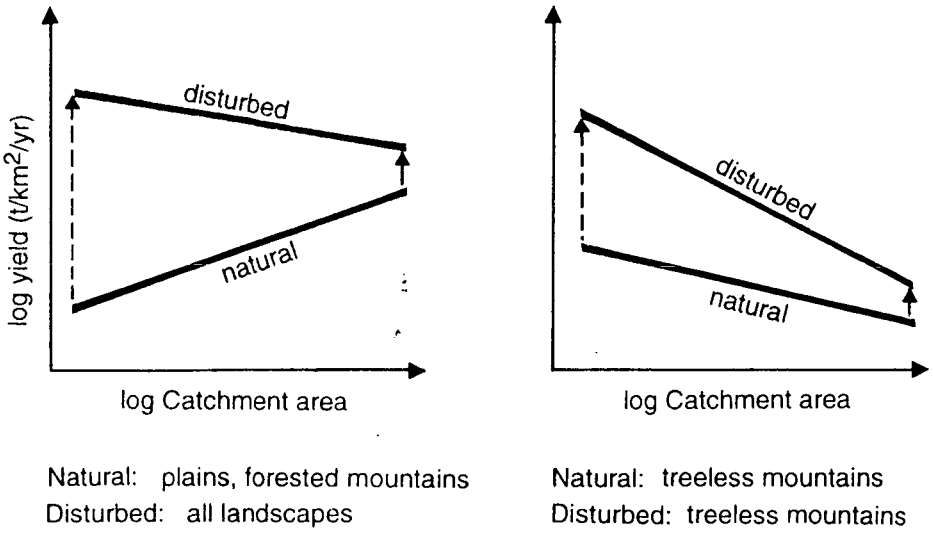


Figure 2. Global relationships between mean annual specific sediment yield and catchment area. Based on Dedkov and Mozzherin (1984).

Table 6. Dependence of specific sediment yield (tonnes/km^2/yr) on intensity of land use, for catchments of different area in the world's temperate climate zone

Intensity of land use	Catchment area <1000 km^2	1000–5000 km^2	5000–25000 km^2	>25000 km^2
Weak	6	6	6	8
Strong	115	108	76	37

In Australia, Wasson et al. (1996) have documented a similar result. Twelve estimates of the increase in yield following disturbance are available from Australia, based on: comparison of plot and catchment yield from near-natural woodland or grassland, and cultivated, grazed, salt-scalded and gullied areas; and stratigraphically based estimates from lakes. The data are plotted in figure 3 where two lines are shown. The bottom line shows that as catchment area increases, the multiple of natural sediment yield (that is the increased of disturbed over natural) decreases. The top line joins data, from intensely gullied landscapes, with the general line. The summary data from table 6 are also shown for comparison with the Australian data.

A schematic representation of these observations is depicted in figure 4. Here a change of vegetation cover in the uplands (source zone) is reflected along the long-profile of the main river. In the smallest headwater sub-catchment, above the smallest headwater channels, the response to disturbance is a rapid increase of erosion rate, initially slowed by the structural stability of the soil, derived largely form its organic content.

Within the channel network, the response is delayed by the travel time of sediment from upstream, and if channel erosion also contributes other pulses of sediment downstream then the yield response curve at position 2 will fall as gully extension and channel bank erosion slow to reach a new quasi-equilibrium (Srikanthan and Wasson 1993). At position 3, the response is even more delayed and the magnitude of the response (the multiple in figure 3) is small. At position 4, there is no response at all, either because the pulse of sediment has not reached that position in 200 years, or the pulse has been lost by overbank or in-channel deposition. This discussion has shown that continuity of sediment transfer through a catchment does not occur because of storage as alluvium, or as colluvium on hillslopes. This lack of continuity is most readily expressed as a sediment delivery ratio (SDR) (Walling 1983), which decreases as catchment area increases.

The earlier discussion of material budgets indicates their usefulness in analysing the regularities of catchment fluxes. However, estimating all of the terms for a material budget for a large catchment is difficult and expensive. An alternative is to use environmental (not applied) tracers of sediment source. Surface soils are labelled by the fallout of radionuclide tracers 137Cs (a product of nuclear weapons testing) and 210 Pb (a natural product of decay of the Uranium Series).

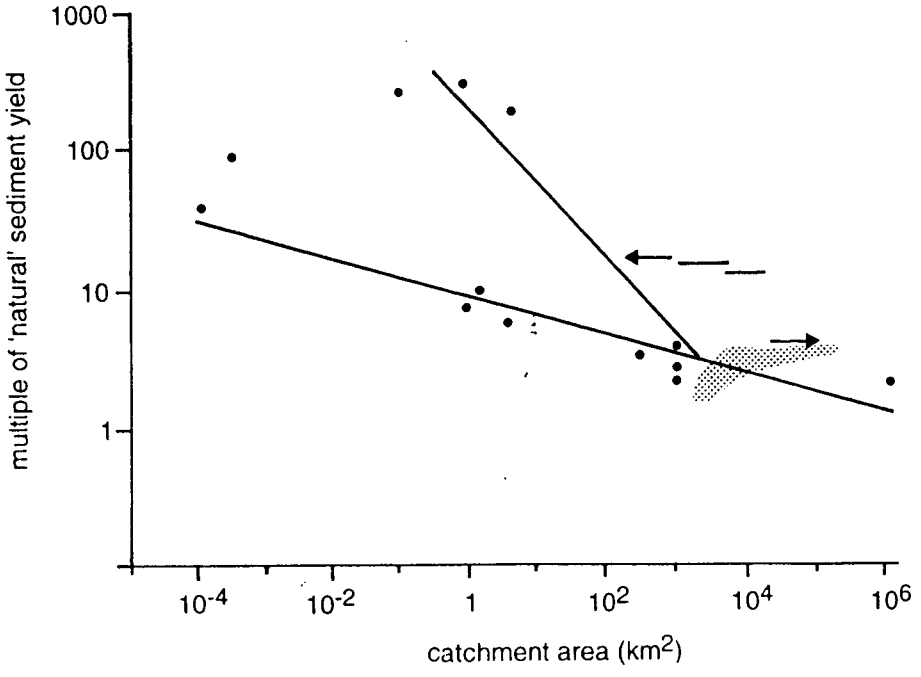


Figure 3. Spatial scale dependence of the increase (or multiple) of natural sediment yields caused by land use (lower line) and gullying (upper line), from Wasson et al. (1996). Calculated increases for the Great Barrier Reef lagoon catchments, from Neil and Yu (1996) and table 1, all lie in the area of hatching. Mozzherin's (1994) multiples for the global temperate zone are shown as small horizontal lines.

These radionuclides are at their highest concentrations in the top few centimetres of soil. If diluted by unlabelled soil during transport, their concentrations in river sediments fall

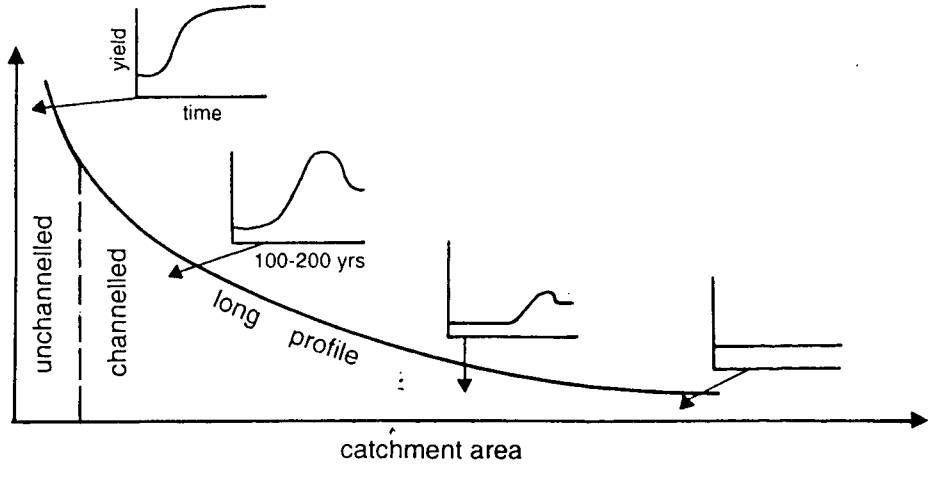


Figure 4. Schematic representation of the downstream responses to clearing, cropping or grazing in the headwaters of a catchment. The vertical axis is a rate of sediment transport, either from a hillslope or along a channel.

dramatically. The major source of unlabelled soil is channel and gully walls below the depth of radionuclide penetration (Wallbrink and Murray 1993).Using this reasoning, Wallbrink et al, (1996) estimated that about 90% of the suspended sediment in transport in the lower Murrumbidgee River comes from channel and gully erosion, with the main channel supplying little of this material. In the Upper Murrumbidgee catchment, Wallbrink and Fogarty (in prep.) have used this technique to show that in the Molonglo River, 96 $\pm$ 11% of the fine sediment in transport comes from channel and gully erosion. Radionuclides can also be used to estimate travel times.

Erosion, sediment transport, land use and land management

From the discussion so far, it should be clear that land use is only one of many factors that influence sediment and particulate nutrient transport through a catchment. In small upland catchments, the between hillslope variance of yields is high (coefficient of variation of 478% in the southeast Uplands of Australia), and decreases with catchment area (Wasson 1994). Most of the variance of yields from hillslopes < 10-1 km^2 in area (that is, from experimental plots) is the result of land use (Edwards 1987). Land use plays a subsidiary role in small gullied catchments, but in small unchannelled pland catchments, land use once again is a significant factor in sediment yields.

In medium area catchments, that is between 3 and 321 km^2 in the Adelaide Hills, mean annual specific yield correlates most strongly with the area of horticulture and orchards (Wasson 1994). The most intensive land uses therefore stand out in this analysis, once the effect of catchment size is removed by using specific yield as the independent variable. For catchments greater than 1000 km^2 , data are insufficient to determine correlations between sediment yields and land use. It is highly unlikely that land use is a useful explanatory variable at this spatial scale, given the powerful attenuation of sediment transport in large catchments by storage.

All of the preceding discussion has centred on the role of land use, as reflected in land cover, on erosion and sediment transport. There has been no discussion of the effect of differences in the way particular land uses are managed. While there is a large body of literature on the effects of minimum tillage, row crop management, terracing, etc., on offsite loss of soil and nutrients, only recently has there been any attempt to determine the water quality impacts. In Australia, the impacts are usually judged by extrapolation from plot studies to larger catchments, a procedure which the discussion so far would indicate is not warranted. Currently, therefore, little of value can be concluded about the effect of land management on water quality.

Sediment and nutrient dispersal in the Great Barrier Reef lagoon

Sediments and nutrients nearing the end of their journey through the Great Barrier Reef lagoon catchments have a very high probability of being deposited either on the floodplains, deltas, or fan-deltas of the coastal zone. Gauging of rivers is usually carried out inland from the coast, and so the estimated quantities of sediments and nutrients that are thought to leave the coast are overestimated; some of this material remains on the coast. Based on 14C and 137Cs, Belperio (1983) estimated coastal progradation rates in the Burdekin delta and the Townsville coastal plain. The delta has been prograding at rates of 1–4 m/yr over the last 6000 years, with vertical accumulation rates of 1–8 mm/yr. On the Townsville coastal plain, progradation has been 0–1 m/yr (Belperio 1983; Carter et al. 1993), and vertical accumulation rates are not well known. The rates generally decrease northward away from the principal source of sediment in the Burdekin River. In the Herbert fan-delta, unpublished results show progradation rates of 1 m/yr and vertical accumulation of 1 mm/yr.

Offshore a mud prism is a continuation of chenier plains and tidal flats, and tapers over an average distance of about 10 km Larcombe and Woolfe (1995) and Carter et al. (1993). This mud prism underlies the innershelf area of Belperio (1983) where the carbonate content of the surface sediments is <30% (see figure 1). This innershelf area is thought of as the area of greatest terrigenous impact both since sea-level stabilised 6500 years BP and since European settlement (Johnson 1995).

The seaward zonation of the shelf according to carbonate content (0–20 m depth <30% carbonate; 20–40 m depth 30–80% carbonate, 40–80 m depth >80% carbonate) suggests a simple exponentially decreasing sedimentation rate of land-derived materials. That the coral reefs on the outer shelf (40–80 m depth of water) have been little affected by terrigenous sediment seems clear from their essentially zero non-carbonate content. But the distribution of carbonate and clastic sediments landward of the outer shelf is not a simple result of fluvial inputs to a passive waterbody.

Gagan et al. (1990) and Gagan et al. (1988) showed that offshore from the Johnstone River, cyclone Winifred in February 1986 produced a mixed terrigenous-carbonate storm layer extending 30 km offshore into water up to 43 m deep; that is, to the boundary between the mid and outer shelf. The inner shelf part of the storm layer was formed by fluvial sediment carried seaward in buoyant flood plumes, resuspension and settling of inner-shelf sediment, and resuspension and shoreward transport of mid-shelf sediment. From mass balance calculations, Gagan et al. (1990) showed that 10–30% of the upper centimetre of storm layer comprises carbonate-rich mid-shelf mud. From the same calculations, the fluvial input from the Johnstone River declines exponentially from 60% of the top centimetre at the coast to 0% at about 10 km. The Johnstone contribution to the entire storm layer is minor.

Gagan (1990) used Belperio's (1983) estimate of Johnstone River sediment yield, 210Pb based sedimentation rates for the last 100 years, and stratigraphically based estimates of sedimentation rates for the last 6500 years to calculate the redistribution of terrestrial sediment on the shelf. By comparing 210Pb and stratigraphically based rates of sedimentation with the yield estimate, Gagan showed that there are high accumulation rates 2.5 to 7 km offshore where sediment is preferentially stored on a timescale of 100 years. This excess deposition results from resuspension and offshore transport of inner shelf deposits, but this is not sufficient to explain the excess. Some additional sediment must be moving shoreward from the mid-shelf, a conclusion already discussed.

On a time scale of 6500 years, Gagan (1990) concludes that only 10% of the fluvial sediment from the Johnstone River remains immediately offshore. The other 90% is transported away, presumably adding to the inner shelf mud prism to the north.

These conclusions imply that particulate contaminants derived from the land will be moved considerable distances both offshore and alongshore within decades. According to most authors, river-derived material rarely reaches the Great Barrier Reef, but fine particulate material is apparently moved towards the Great Barrier Reef during episodic resuspension events. There does not appear to be any impediment to dissolved nutrients reaching any part of the Great Barrier Reef lagoon.

Concluding remarks

A considerable amount of effort has been expended to make progressively better estimates of the fluvial inputs to the Great Barrier Reef lagoon of suspended sediments, phosphorus and nitrogen. This work must continue because current estimates differ by factors that are unacceptably large; and the natural variability of the rivers in the region means that monitoring over many years is essential if realistic yields are to be estimated. The existing measurement programs are likely to improve our understanding of the amounts of material reaching the Great Barrier Reef lagoon, and with appropriate investigations within catchments will guide efforts at catchment management.

This effort will only be of real value if a greater understanding is gained of the dispersion of land-based materials within the Great Barrier Reef lagoon. This should not only include dispersion to the corals, but should include effects on mangrove, saltmarsh and seagrass ecosystems. These are more likely to be impacted then the outer shelf. Yet our understanding of the impacts in the Great Barrier Reef are ambiguous, and the warnings of Lough and Barnes (1995) should be repeated – reef performance is highly variable at time scales much longer than decades. Just as the fluvial inputs vary widely, so does the reef. A long-term view by means of monitoring and the use of sedimentary archives is essential.

If the catchments are to be managed to reduce fluvial inputs to the Great Barrier Reef lagoon, then we must at least do the following: estimate material budgets that provide a

synoptic view of sources; estimate the likely impact of management strategies to determine if they are environmentally useful, and economically and socially feasible; be prepared to change strategies based on new scientific findings. Wasson et al. (1996) challenged the currently applied conceptual models of the sources and pathways of particulates in Australia catchments. Many of the models used to estimate yields adopt a formulation imported from a different environment. If these formulations are used to guide catchment management it is possible that a lot of effort will be spent for little gain. Even if the formulations are correct, and in the Johnstone they may be, the effect of economically and socially feasible management strategies may not be large at the coast. If the full effect of European settlement has already been expressed in yields at river mouths (cf figure 3), and yields have increased by a factor of ≤ 4, how much change is required in the catchments to reduce this factor?

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Sources of material in river discharge

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ABSTRACT

The types of materials in river discharges to the Great Barrier Reef Marine Park include eroded soil particles, remobilised stream sediments, nutrients such as nitrogen (N) and phosphorus (P), pesticide residues and heavy metals. Apart from pesticides and other manufactured compounds, these materials occur naturally in the 425,000 km^2 of land drained by Queensland's east-coastal rivers from Cape York to the Mary. These catchments support many land uses, typically dominated by grazing, forestry and canelands. Whilst important economically, other land uses and urban regions occupy only relatively small areas. Examples are provided. There is evidence, supported by current annual inputs of around 80,000 tonnes of fertiliser N and 17,000 tonnes of fertiliser P, that long-term cropping of soils used for sugarcane and horticulture have raised levels of fertility. In contrast, nutrients are being depleted in the grazing lands through removal in primary produce. Soil erosion during storms and floods is a major source to rivers of N and P, and probably heavy metals and pesticide residues. Green cane trash blanketing in the sugar industry and zero or limited tillage practices in the grain industry have significantly reduced erosion losses, while retaining around 25-30% of ground cover lowers both run-off and soil erosion in grazing lands. Estimates are given of nutrient and pesticide inputs and of materials lost via rivers on a regional or catchment basis. The amount and frequency of acid discharges from acid sulfate soils known to exist in low-lying coastal areas are unclear.

INTRODUCTION

The Great Barrier Reef (GBR) and the Great Barrier Reef Marine Park (GBRMP) lie close to the eastern coastline of Queensland, a land mass with rich and diverse natural resources. Soils, rivers, forests, climatic conditions, mineral resources, transport facilities and population densities suit a wide range of agricultural, pastoral, horticultural, mining, and urban pursuits. All of these, plus commercial and recreational fishing, make important contributions to the state's economy, buoyed further by expansions in tourism, towns and rural industries such as sugarcane, cotton, and tropical fruits.

Over the past 25 years there have been increasing calls for water resources and river catchments to be used and managed sustainably for present and future generations. The need applies across Australia (e.g. Kelleher 1988; Anon 1993a; Anon 1994a; Anon 1995a,b; Taylor 1996) and internationally (e.g. UNEP 1995). No longer is it possible to ignore proven or possible adverse downstream impacts of land use, particularly in the vicinity of the GBR. Zann (1995) concluded, mostly on anecdotal evidence, that about 80% of the contaminants in marine and estuarine environments are sourced from the land.

While the community debates what resource sustainability and conservation values need to be achieved, water continues to cycle in the environment. This water dissolves or physically transports chemicals, eroded soil, stream sediments, litter, etc to new locations. Factors such as weather conditions, catchment size, land use practices, run-off volume, riparian conditions, the fertility of eroding soils, the types and amounts of agricultural chemicals used, and the habits and actions of animals all influence what is transported by rivers and how far it moves. This paper provides background information on Queensland's coastal rivers, soil fertility and land use practices. It also compares materials entering these catchments with those contained in water moving to the sea. Most attention is given to nutrients, suspended solids, pesticide residues, heavy metals, and acidity from acid sulfate soils.

River Catchments, Soils and Land Use

Easterly flowing streams in Queensland, except for the Burdekin, Fitzroy, Burnett and Herbert River systems, have relatively short courses. Typically, the rivers descend rapidly in their upper reaches, then slow as they approach the coast.

Rivers such as the Daintree, Mossman, Barron, North Johnstone, and Herbert Rivers, all on the Wet Tropical Coast, consistently flow year round (Hausler 1991). In contrast, most of the remaining rivers cease flowing in dry seasons, although in times of flood, flows can increase up to hundreds of times the long-term mean annual flow. Water storages including farm dams, barrages and major dams make important contributions to standing freshwater reserves and, in the case of the latter two, to stream flows in dry seasons (Anon 1992; Anon 1993b,c; Anon 1994b; Anon 1995c,d). The Mulgrave-Russell, Johnstone, and Tully Catchments have the highest mean annual run-off, each exceeding 2,000 mm (Hausler 1991).

Soils of the region have been described and evaluated for their physical and chemical characteristics and land-use suitability (e.g. Murtha 1986). At the profile scale, surface layers almost always exhibit higher levels of total nitrogen (N) and phosphorus (P) than do corresponding sub-surface layers. The few soil fertility maps that are available show wide variations in the bicarbonate-extractable P status of surface soils from the Fitzroy (Ahern et al. 1994) and Burdekin River (Ahern 1988; Rayment 1989; Ahern et al. 1994) catchments. Sub-catchments of the Fitzroy also vary in surface soil P fertility (Table 1), but corresponding data for total soil P reserves have not been compiled.

Table 1. Distribution patterns (expressed as % of sub-catchment area surveyed) of bicarbonate-extractable P in surface soils (0-10 cm) from major tributaries of much of the Fitzroy Catchment, Central Queensland (Baker et al. 1995).

Sub-catchment	Area ('106 ha)	Percent of area in six bicarbonate-extractable P ranges (mg P/kg)					
		<4	4-6	6-9	10-15	16-25	>25
Comet	1.4	4	7	38	24	15	12
Dawson	2.6	6	17	21	25	25	7
Fitzroy	1.1	2	36	28	10	16	8
Isaac	2.2	7	23	24	17	18	10
McKenzie	1.3	12	21	13	24	17	14
Nogoa	2.9	12	20	21	27	15	4

Holocene-age sulfidic sediments on which acid sulfate soils (ASS) form following oxidation have an extensive distribution (at least 1.2 x 106 ha) along the Australian coastline (Kawalec 1973; White et al. 1996; Crossland 1996). Associations between such soils and the occurrence of mangroves, *Melaleuca* paperback trees and coastal wetlands are well accepted (McGarity 1989; Melville et al. 1993). In southern Queensland, the mapping of areas of ASS risk has commenced (Powell and Ahern 1996), but less is known of their distribution and associated risks in north Queensland.

Russell and Hales (1993) reported the clearing for development of around 1200 ha of *Melaleuca* communities in the Johnstone River/Ninds Creek Catchment between 1951 and 1992. This suggests circumstances amenable to the formation of ASS. Moreover, broadacre developments on ASS can release large quantities of sulfuric acid into coastal streams (White et al. 1996), resulting in highly acidic waters, the mobilisation of aluminium (Al) and iron (Fe), and consequent harm to aquatic biota. The acid is neutralised naturally by seawater if good mixing occurs.

One limitation of the soil chemical databases accumulated over the past 20-30 years is the 'pooling' of contemporary with older data. That is, changes in soil chemical fertility over time are usually ignored. However, there is evidence that the chemical fertility of at least some soils of the region have changed significantly. For example, a mean value of acid-extractable P of 26 mg P/kg can be derived from the 1938 data of Kerr and von Stieglitz (1939) for north Queensland canelands. This is only 40% of the 1991 mean of 65 mg P/kg reported by Reghenzani (1993) for the same soil depth, soil test and cane-growing region. Results from a survey of soils used for commercial vegetable production in Queensland

(Table 2) suggest that excessive inputs of nutrients have been a regular feature of vegetable production practices across the state, when contrasted with analytical data for similar Queensland soils and the soil fertility ratings of Rayment and Bruce (1984).

Table 2. Air dry soil values of pH, nitrate-nitrogen (NO_3-N), phosphorus (P), potassium (K) and sulfur (S) __ arithmetic means and ranges __ in soils (0-10 cm) below Queensland vegetables at harvest time for three district of coastal Queensland (Rayment 1994).

Location	pH (1:5 H_2O)	NO_3-N mg N/kg	Bicarb-P mg P/kg	Acid-P1 mg P/kg	Total-P %P	Total-K %K	Total-S %S
Atherton/Mareeba District (n=29)							
	5.9	40	111	246	0.137	0.483	0.032
	4.4-6.9	1-130	18-382	15-1669	0.04-0.43	0.003-1.91	0.01-0.10
Ayr/Bowen (n=15)							
	6.7	35	185	417	0.098	1.29	0.02
	5.7-7.8	1-150	83-389	79-834	0.04-0.14	0.95-1.64	0.014-0.03
Bundaberg/Gympie (n=18)							
	5.6	36	84	99	0.076	0.234	0.04
	4.5-7.2	3-150	30-147	21-190	0.05-0.11	0.003-0.93	0.01-0.07

1 This soil P test was used by Kerr and von Stieglitz (1939) and Reghenzani (1993)

Apart from the few studies already mentioned, serious attempts to systematically identify high fertility, nutrient sensitive soils across Queensland's coastal zone are lacking. High risk areas with respect to adverse impacts on river water quality would be expected to have elevated levels of nutrients (N and P in particular), either naturally occurring or supplied as fertilisers. Concurrently, these areas would be susceptible to water erosion and/or the leaching of nutrients.

Land use practices mostly reflect climatic conditions, topography, soil fertility and/or the availability of water. Proximity or accessibility to processing facilities and markets are additional considerations.

Statistics compiled by Pringle (1991) for the periods 1897, 1944-45, and 1983-84, show progressive increases in total areas being cropped. For example, there was a trebling in the area under cane during the period 1951 to 1988 (Pulsford 1991). Indeed, 'waves' of land development have been a feature of agricultural expansion in the coastal zone, shown numerically in Table 3 as the increase in potential sediment yield for seven phases of development in the Tully Catchment since 1866 (Neil 1995).

Table 3. Increases in potential sediment yield, expressed in percentage terms, for seven 'waves' of land use change in the Tully Catchment, North Queensland. (Total increase from 1900-1990 was 120%; Neil (1995)).

Phase	Time	Land use change	Increase in potential sediment yield
1	1866-74	Cane growing - limited area	negligible
2	1880-85	Cane growing - limited area	negligible
3	1900-20	Banana growing	2.5%
4	1924-31	Cane growing & town establishment	20% (excludes town establishment)
5	1931-58	Cane growing - gradual increase	31%
6	1958-67	Improved pasture	26%
7	1967-90	Cane growing - banana growing	13%

Table 4. Prominent land uses1 in selected Queensland catchments draining to or near to the Great Barrier Marine Park (Areas compiled mainly by P. Bloesch (DNR) using data from a range of sources, including Anon (1993a), satellite imagery interpretations of M. Grundy (DNR), and data from DPI-Forestry, and DNR-Lands).

Catchment	Area	% of catchment								
	'000 ha	Timber	Pristine	Graz-ing	Sugar	Banana s/ fruits	Vege	Grain	Other crops	Urban
Daintree	213	37.7	31.7	26.7	1.8	0.04	0.03	0	0	2.0
Mossman	49	30.4	11.0	44.6	10.0	0.07	0	0	0	3.9
Barron	218	36.4	2.0	47.7	2.1	0.55	0.80	3.2	0.18	6.9
Mul/Russel l	202	16.9	25.1	38.9	13.1	0.15	0.02	0	0	5.8
Johnstone	233	25.3	12.8	41.6	14.8	0.89	0.01	0	0.20	4.4
Tully	169	62.5	2.1	20.7	9.6	1.53	0	0	0	3.7
Murray	114	32.9	27.3	29.6	6.1	0.88	0.02	0	0.01	3.3
Herbert	1,013	9.5	9.7	71.1	6.6	0	0	0	0.36	2.7
Black	108	18.0	9.3	67.4	0.7	0	0.40	0	0.04	4.2
Haughton	365	0.8	10.8	74.0	10.4	0.36	0.05	0	0.10	3.5
Burdekin	12,986	1.0	1.3	94.8	0.2	0.01	0.04	0.5	0.22	2.0
Don	389	0.2	2.6	91.3	1.1	0.05	1.63	0	0.03	3.1
Proserpine	249	9.6	4.0	74.6	7.5	0	0	0	0.01	4.3
O'Connell	244	7.6	4.4	70.5	11.1	0	0	0	0	6.5
Pioneer	149	22.7	6.1	48.5	17.9	0	0	0	0.05	4.7
Plane	267	4.3	2.9	67.4	21.0	0	0	0	0	4.4
Fitzroy	15,264	6.7	2.3	87.5	0	0.01	0	2.0	1.27	0.2
Baffle	386	12.2	4.4	75.9	0.4	0.09	0.03	0	0.34	6.7
Kolan	298	12.5	0	79.0	4.5	0.05	0.04	0	0.18	3.8
Burnett	3,315	12.9	0.4	79.9	0.8	0.11	0.05	1.6	1.03	3.2
Burrum	334	26.9	6.3	53.4	8.8	0.02	0.08	0	0	4.5
Mary	960	28.3	0.6	64.5	1.2	0.03	0.03	0	0.60	4.8

1 Timber includes State forests and timber reserves; Pristine includes National Parks, National Park (scientific), Conservation Parks and Resource Reserves; Other crops include cotton, sunflower, peanuts, irrigated forage crops, etc.; Urban includes roads, railways, watercourses, dwellings, and aquaculture.

By 1928, cattle were well distributed across the extensive grazing lands of Queensland (Hancock 1964) and still are. Indeed, extensive grazing is the major land in Queensland's coastal catchments adjacent to the GBRMP, accounting for over 85% of total land use in the Fitzroy, Don and Burdekin Catchments (Table 4). Timber forestry (exotic and native State forests and timber reserves) is the next most common land use, accounting for over 25% of the land area in 8 of the 22 catchments listed in Table 4.

Sugarcane, which has been grown for over 100 years in some areas, is the most important crop on an area farmed basis, but only in the Mossman, Mulgrave/Russell, Johnstone, Haughton, O'Connell, Pioneer and Plane Catchments does it occupy 10% or more of the total catchment area (Table 4). Areas committed to bananas and fruit trees are expanding in the tropical north, but apart from the Tully Catchment, they collectively occupy <1% of any catchment. Vegetable cropping is another minor land use, while grain crops are restricted to relatively small portions (on a percentage basis) of the Barron, Burdekin, Burnett and Fitzroy Catchments. Seasonal conditions and market prospects affect the actual areas planted to grains (O'Connell 1995). Cotton is grown, often with irrigation, in the Fitzroy (24,000 ha) and Burnett (1,300 ha) Catchments.

Material Inputs

Human activities are unequivocally associated with the presence of pesticide residues and other manufactured compounds in river discharges. However, this is not true for naturally occurring materials, added or mobilised by human activities and land-management practices interacting with the environment.

Fertiliser usage in coastal Queensland is dominated by the sugar industry (Pulsford 1991, 1993). In 1990, for example, some 59, 3.3, 3.0, 11.2 and 6.6 thousand tonnes of N were used on sugarcane, fruits, vegetables, field crops and pastures, respectively, in coastal catchments from the Mary to the Daintree. Corresponding quantities of P were 7.4, 0.65, 1.0, 1.8, and 2.6. It is obvious from the examples given in Table 5 that catchment ratings based on total annual inputs of fertiliser N and P differ from those based on nutrient inputs per hectare and as ratios against annual run-off volume. Across all catchments, the average fertiliser N to fertiliser P mass ratio is 6.2:1. The average ratio for the 12 catchments listed in Table 5 (the top 12 catchments on an N supplied basis) is 7.8:1. Whether or not the wide differences in the ratios based on nutrient inputs with run-off volumes have any value is unclear, although Pulsford (1993) has suggested that they might provide a measure of the relative importance of each catchment in contributing nutrients to the GBRMP.

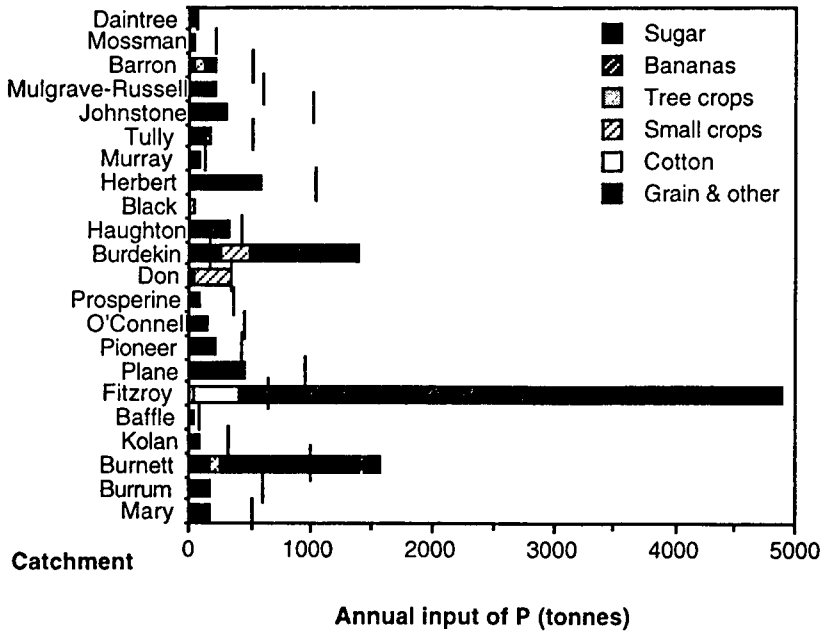
It is instructive to evaluate relationships between quantities of fertiliser used in the various catchments and the quantity which would be used if recommended rates of application were followed by all growers. The product of recommended rates of N and P for the various crop and pasture types (these were obtained from a variety of sources, including Calcino (1994) for sugarcane) and the area under each crop/pasture type was used to estimate the total possible annual input for each catchment, given its land use. These results (Figure 1) are compared with estimates of actual fertiliser sales in 1990 for each catchment (Pulsford 1993).

Table 5 Fertiliser nutrients (N and P) applied in 1990, and equivalent inputs expressed on a catchment area basis and as a ratio with mean run-off for catchments receiving the most nitrogen and draining to or near to the Great Barrier Reef Marine Park (compiled from Pulsford 1993).

Catchment	Nitrogen			Phosphorus		
	Quantity used *tonnes N*	N input /ha	kg N /1000 ML of run-off	Quantity used *tonnes P*	P input /ha	kg P /1000 ML of run-off
Mul/Russell	4720	23.4	1.13	605	3.00	0.14
Johnstone	7300	31.3	1.55	1700	7.30	0.36
Herbert	9800	9.7	1.96	1330	1.31	0.27
Haughton	8805	24.1	11.65	613	1.68	0.81
Burdekin	3180	0.24	0.31	256	0.02	0.03
Proserpine	3040	12.2	2.12	459	1.85	0.32
O'Connell	4390	18.0	2.63	539	2.21	0.32
Pioneer	5490	36.8	5.52	648	4.35	0.65
Plane	7685	28.8	5.61	995	3.73	0.73
Fitzroy	7290	0.51	1.02	786	0.06	0.11
Burnett	4545	1.37	2.61	1160	0.35	0.67
Burrum	2970	8.89	4.14	650	1.95	0.91

For N fertilisers, actual application rates are generally lower then recommended (Figure 1) . The major exception is the Haughton where applications exceed recommendations by about 27%. A very different pattern emerges with P. Catchments dominated by sugar production appear to 'overuse' P (by > 250% in the Burrum, Kolan, O'Connell, Johnstone and Mossman catchments). In contrast, where field crops are grown, P fertilisers may be 'under-utilised', particularly in the Burdekin and Fitzroy Catchments. The implications of these discrepancies are that (i) P inputs to some cropping catchments could be decreased; and (ii) there exists considerable scope for increases in the application of P (by a factor of 6 (Burdekin) and of 7 (Fitzroy)), which would be within the bounds of recommended

agronomic practice. Such increases could have important implications for future water quality in these catchments, as P loadings could increase.



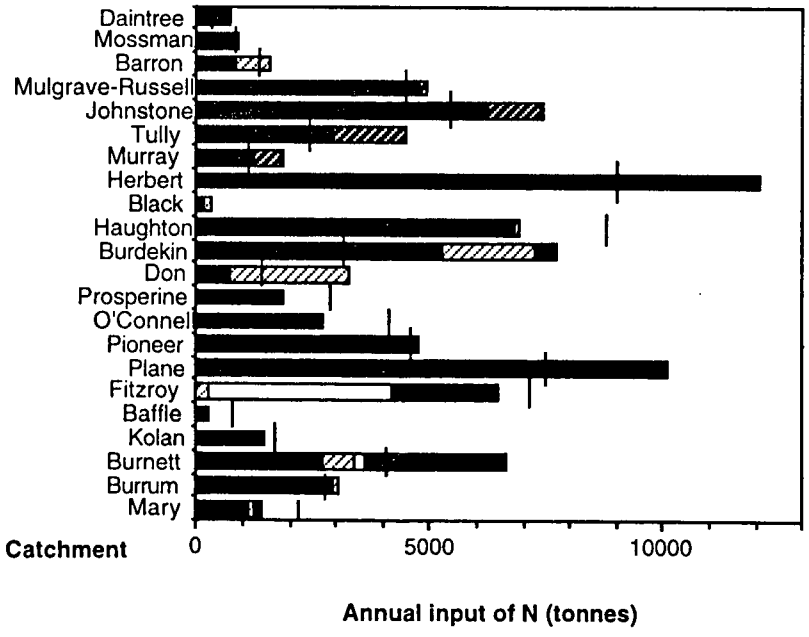


Figure 1. Fertiliser N and P used in 1990 (Pulsford 1993) on a catchment basis (vertical lines) and estimated usage based on conservative applications rates.

Pesticides used to control pests and diseases of plants and animals and to control weeds have a long history of use in the coastal zone. There is little reliable knowledge of the quantities of these chemicals used in time past, but introduction dates and other details are available. As examples, lindane was introduced in 1946 and withdrawn in 1987; DDT was introduced in the early 1950s and withdrawn in the early 1970s; dieldrin was introduced in the late 1950s with permits needed after 1987; while heptachlor was introduced in the 1960s, with restricted usage since 1987. Types and contemporary quantities of pesticides now used in the Queensland Sugar Industry are available (Hamilton and Haydon 1996), together with environmental-fate profiles for the various pesticides. Chloropyrifos is the most used insecticide, but five herbicides (atrazine > diuron > 2,4,D > glyphosate > ametryn) each have greater usage (Table 6).

Table 6 Estimated annual quantities (kg a.i.) on a regional basis of herbicides, insecticides and fungicides most used in Queensland for sugarcane production (Hamilton and Haydon 1996).

Pesticide group and active ingredient	Regional catchment groupings					Total
	North	Herbert	Burdekin	Central	South	
Herbicides						
Atrazine	107594	33804	46480	116011	27696	331000
Diuron	34264	16718	7884	108691	29889	197000
2,4,D	50260	28237	13168	41103	8789	141000
Glyphosate	10267	4388	10052	53830	7088	85600
Ametryn	8688	2208	11768	51113	2205	76000
Insecticides						
Chlorpyrifos	25653	3104	538	20967	24767	74500
Ethoprophos					4751	4750
Aldicarb					1582	1580
Heptachlor	1134					1134
Fungicides						
MEMC	742	400	472	378	312	1890

Nutrient heavy metals, particularly copper (Cu) and zinc (Zn) are supplied to crops (2-10 kg Cu/ha; 7-10 kg Zn/ha) pastures (2 kg Cu/ha; 2 kg Zn/ha) and sugarcane (10 kg Cu/ha; 10 kg Zn/ha) when deficiencies of these nutrients are suspected (Rayment and Hamilton, unpublished data; Calcino 1994). Over time, these heavy metals can accumulate in soils as can contaminant heavy metals such as cadmium (Cd) and lead (Pb). For example, total concentrations of Cd in 190 surface soils from commercial vegetable farms in Queensland ranged in 1990/91 from 0.016-2.08 mg Cd/kg dry weight (G.A. Barry, unpublished data). Moreover, Rayment (1995) has estimated that the cropping lands of coastal Queensland, received up to 340 g Cd/ha as a contaminant in P fertilisers to 1990. In contrast, cropping lands of the Fitzroy Catchment have received an average of only 3 g Cd/ha from P fertilisers. It follows that variable concentrations of heavy metals can be expected in soils with different cropping histories, as is apparent from Table 7. Soil type is a further variable as demonstrated by Reghenzani (1993) for 0.1M hydrochloric acid extractable levels of Zn. For north Queensland canelands, which had a mean value of 1.91 0.15 mg Zn/kg, the order was basaltic soils > organic and alluvial soils > beach ridge and granite soils > metamorphic derived soils.

World rivers typically contain about 0.07 g Cd/L (Boyle et al. 1976), a concentration only sometimes supported by data for freshwaters tabulated by Fleischer et al. (1974). Locally (near Townsville), Cd concentrations in waterways as high as 30 and 12 g Cd/L have been reported (Anon 1986), while the same report suggests that undesirable Cd fluxes can occur at point sources elsewhere in the state. It is known that a high portion of the Cd found in coastal and estuarine waters is associated with particulates (WHO 1985), and these elevated concentrations may reflect the stripping of Cd from mineral particulates suspended in the water column.

Heavy metals may be transported by the atmosphere for hundreds of kilometres from sites of emission (Alloway 1990; Rayment 1995), the dispersion facilitated by thermal currents and winds. International examples for Cd transport are: forest fires, 0.03-2 ng/kg dust; vegetation, 2.7-36 ng/kg dust; and sea spray, 0.001-0.003 ng/kg. The extent to which such emissions may contaminate Queensland rivers and soils is unknown.

Table 7. Examples of mean concentrations of total heavy metals in southern Queensland canelands (0-10 cm) together with comparative data from similar soils nearby (Rayment, Barry & Jeffrey, unpublished data).

Sugar region	Site history	As *mg/kg*	Cd	Co	Cr	Cu	Ni	Pb	Zn
Maryborough	Cane	5	0.048	21	51	18	11	19	21
	No cane	4	<0.01	<6	31	11	<10	13	<12
Bundaberg	Cane	5	0.06	27	135	28	49	21	52
	No cane	5	<0.01	7	70	16	19	16	25

Material Movement and Exports

The erosion of soils by water and the collapse of stream-banks during periods of high stream flows are major pathways for the entry of materials to waterways. For example, annual soil losses in row crop sugarcane from the Johnstone River Catchment near Innisfail of <50 to 500 t/ha (average of 150 t/ha) have been measured (Prove 1988; Prove et al. 1995). Sallaway (1979) reported soil losses under lower rainfall conditions near Mackay of 42 to 227 t/ha. Cumulative top-soil losses in canelands of up to 1.5 m had already occurred in the Childers area by the early 1970s (Sullivan and Sallaway 1994). These losses are now being lowered to insignificant rates (e.g. 13.5-15.1 t/ha/yr) by moving cane assignments to erosion-resistant lands, and by the adoption by canegrowers of modern soil conservation measures. These measures include the implementation of soil conservation plans and green cane trash blanketing (Sullivan and Sallaway 1994; Prove et al. 1995).

At Emerald, Central Queensland Highlands, an estimated 1,440 tonnes of suspended sediments were mobilised in a drain immediately downstream of an irrigated cotton site following a storm event that generated a total flow of 1,200 ML (Simpson et al., unpublished data). Average soil loss estimates (really weighted) of 1.3-9.0 t/ha/yr have been derived by Elliott et al. (1996) from 137caesium activity at a small number of sites across Queensland's cultivated cropping lands.

Ciesiolka (1987) has reviewed the limited knowledge on soil loss in the grazing lands of Australia. For example, Belperio (1977) estimated 0.3 t/ha/yr soil loss in the Burdekin River Catchment. In the same catchment near Charters Towers, soil losses measured as sedimentation in dams was positively correlated with the degree of gullying. Measurements (Ciesiolka 1976) showed that 0.9, 1.6 and 27-30 t/ha/yr were moved from catchments with minor gully erosion, one active gully, and with severe gully erosion, respectively. Overseas data supports local observations that the maintenance of good ground cover (at least 25-30%;) can markedly reduce both soil losses and run-off volumes (Ciesiolka 1987; M. Silburn, personal communication; G. Rayment, unpublished report). While beneficial from a soil erosion viewpoint, reductions in stream flow associated with pasture improvement may be seen as a disbenefit by other users of the catchment (Ford 1991).
Given that a really weighted average soil erosion rates for Queensland grazing lands appear to range from zero to 4.1 t/ha/yr (Elliott et al. 1996), the development of grazing lands for cultivated cropping will add to soil erosion losses. This is particularly so for the Fitzroy and Burdekin Catchments.

Relationships between pasture management and both soil and nutrient losses from a grazed speargrass site in Queensland are summarised in Table 8. This table shows that around half the N and over 90% of the P were transported off-site as particulate material. The percentage for N is similar to the percentage transported as particulates in the lower Herbert River during flooding associated with Cyclone Sadie but is over 30% lower than was measured across the full hydrograph in the Johnstone Catchment, also during the Cyclone Sadie floods (Mitchell et al. 1996). For P, the percentages associated with river-carried

particulates during the Cyclone Sadie floods in the Herbert and Johnstone Rivers were 81 and 95, respectively. The variance in these data sets, particularly for N, is difficult to explain but could be due to analytical techniques and/or to the inclusion of very fine soil particles in run-off samples from the speargrass pasture and in filtered water samples from the Herbert River.

Table 8. Soil and nutrient losses measured as a consequence of run-off from one storm event of 92.4 mm (February 1994) on a grazed native speargrass pasture in a thinned ironbark woodland in Queensland (M. Silburn, unpublished data).

Item	Treatment		
	Bare	Grazed	Exclosure
Cover (%)	6	70	87
Run-off (mm)	35	14	2.1
Total soil loss (t/ha)	22	0.3	0.03
Total N loss (kg/ha)	15	2	0.1
% of total N loss in run-off water & fine sediment	53		
% of total N in eroded soil (coarse sediment)	47		
Total P loss (kg/ha)	4.3	0.3	0.02
% of total P in run-off water & fine sediment	8		
% P of total P in eroded soil (coarse sediment)	92		

While it is important to identify sediment source areas in specific catchments, understanding delivery to the coast requires consideration of in-stream sediment loads. These are much more difficult to attribute to specific land uses than is the case for erosion studies. Crude estimates of the role of land use in determining in-stream sediment loads in the GBR region can be made using general relationships between stream water quality and catchment characteristics derived from the literature. The relationships can then be applied to known patterns of land use.

While assumptions regarding the increase in stream sediment concentrations are subject to discussion and debate, they are at least transparent and can be readily modified as knowledge increases. To estimate the role of land use in the main agricultural catchments discharging to the GBRMP, we have made the simple assumptions that grazing increases suspended sediment concentrations by a factor of 4, cropping by a factor of 15, and urbanisation by a factor of 4. Some justification of these assumptions can be found in the results of Neil and Fogarty (1991), Neil (1994) and others. If anything, these factors are probably conservative.

Based on these assumptions and the land use patterns of the early 1990s, we agree with Moss et al. (1993) that the dominant source of sediment in rivers draining to the GBR region is from grazing lands (Figure 2). Cropping lands are likely to be a more important source in the major sugar catchments (Mulgrave-Russell, Johnstone, Tully, Pioneer, Plane), although even in these areas grazing is significant. While urban areas are a relatively small proportion of all of these catchments, the estimated sediment yield response to urbanisation suggests that the contribution of this minor land use represents a significant proportion of natural yields. Natural sediment yields are calculated as unity (Figure 2) in this analysis. Thus, the horizontal scale of Figure 2 provides an estimate of the present sediment yield of each catchment, relative to the pre-European (natural) rate.

The greatest increases in estimated sediment yields have occurred in the Plane, Pioneer, O'Connell, Haughton and Johnstone catchments, apparently determined by the combination of a relatively large proportion of the catchment under crops and/or a small proportion of the natural vegetation retained. The importance of sediments sourced from grazing areas poses particular problems of management and mitigation of sediment input to the GBR lagoon, given the extensive areas involved, much lower monetary returns per unit area, and a climate of greater variability, strongly influenced by *El Nino* conditions.

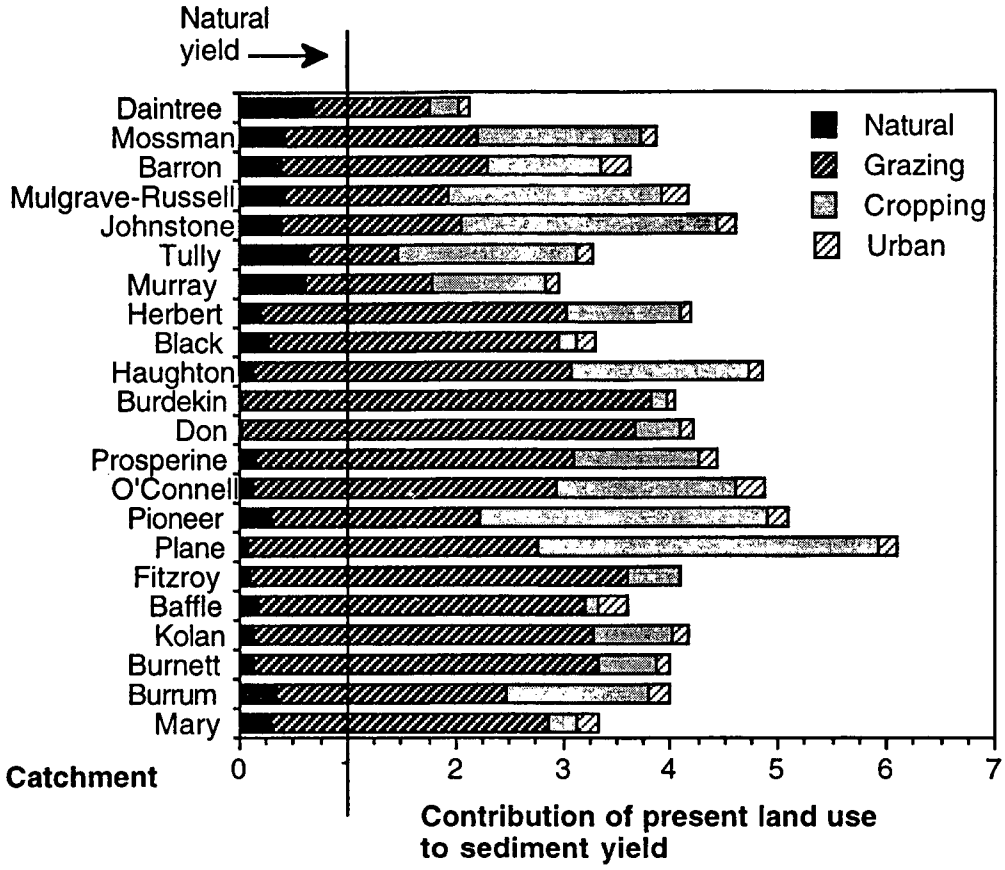


Figure 2. Relative contributions by present land uses to estimated sediment yields on a catchment basis, where unity represents the estimated pre-European (natural) sediment yield, 2 represents a two-fold increase, etc.

Within-region variation in sediment yield at catchment scale is generally related to land use. However, over larger areas of varying climate, the effect of rainfall on vegetative cover, and hence erosion rates, must be taken into account. One approach to this problem for the GBR region is that of Neil and Yu (1995, 1996). They developed an empirical relationship between catchment run-off (a readily available correlate of rainfall) and unit sediment yield (a 'true' measure of flow-weighted suspended sediment concentration) to predict sediment yields from GBR catchments. (Figure 3).

Estimates from the modelling (Figure 3) show that most of the sediment discharged to the GBR Lagoon comes from the Fitzroy and Burdekin Catchments. Moreover, the amounts are considerably higher (Table 9) than those reported by Belperio (1983) and Moss et al. (1993), reflecting the importance of model parameters on the outcome, particularly for large catchments. Sediment yields (and sediment concentrations) from the humid tropics catchments are much lower than those from the large, seasonally wet-dry catchments.

Table 9. Estimates from simple models of mean annual exports of suspended sediments (million tonnes/y) from a selection of Queensland coastal catchments.

Catchment	Belperio (1983)	Moss et al. (1992)	Neil and Yu (1996)
Johnstone	1.5	0.6	0.2
Burdekin/Haughton	3.5	2.7	8.4
Fitzroy	2.2	1.8	10.3
Burnett/Kolan	1.7	0.8	2.4

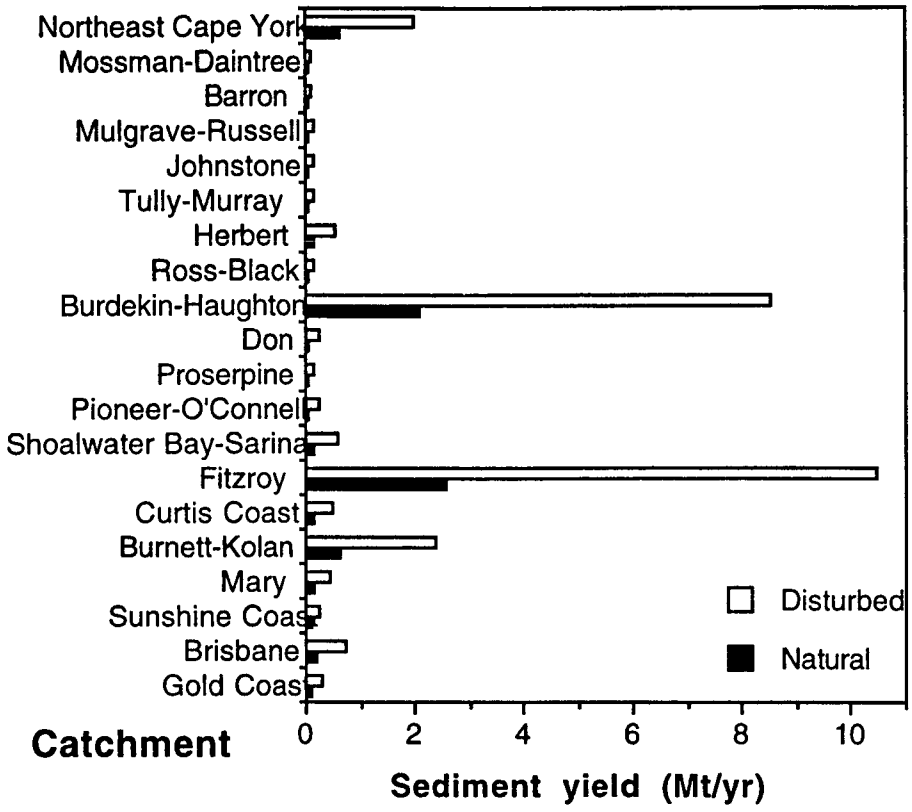


Figure 3. Comparative estimates of sediment yields from Queensland's east coastal catchments prior to European settlement (natural) and as a consequence of land use conditions in the 1990s (disturbed) (Neil and Yu 1995; 1996).

Because the estimates in Figure 3 are calibrated on data from the Burdekin-Barron area, errors are likely to be greatest moving both north and south from these catchments. This is likely to be most pertinent to the estimates for northeast Cape York and the Fitzroy. However, although further data are required to test the validity of and/or refine the model, its ability to estimate the sediment rating curve parameters for the streams on which it is based (Neil and Yu, 1996) encourages some confidence in the estimates.

With an intensification in the monitoring of water quality, particularly in rivers of the Wet Tropical Coast, reliable estimates of river nutrient concentrations and fluxes are emerging. For example, in one four day event associated with Cyclone Sadie, the South Johnstone River at South Johnstone transported 67,000 tonnes of suspended sediment, 343 tonnes of N and 104 tonnes of P (a N:P mass ratio of about 3.3:1). The sediment, N and P loads were around 5 (14,000 tonnes), 1.7 and 3.5 times those of the prior two, relatively dry years even though the water discharged during the cyclone (112,000 ML) was only about one-sixth of that of the preceding two years (Hunter et al. 1996). The authors noted the high erosivity of rainfall and run-off during cyclonic and similar events. Average wet season export fluxes of N and P for six north Queensland rivers, derived by Mitchell et al. (1996) from water quality monitoring data, are in the order: Burdekin > Fitzroy > Herbert > Tully > Barron > South Johnstone. On a unit area basis, greatest losses were associated with the Tully and South Johnstone Rivers.

Only limited monitoring of pesticide residues has occurred in river systems draining to the GBR lagoon. Even less is known of the ability of Queensland rivers to transport pesticide residues and metabolites from upstream locations to the sea. The fact that significant quantities of pesticides can be lost by volatilisation and to groundwater (e.g. Gerritse 1990) complicates the issue. For example, Bauld et al. (1995) have confirmed, from samplings in 1992 and 1993, the presence (30 to 76%) of low concentrations of atrazine in groundwaters of the Burdekin River Delta and in the Burdekin River Irrigation Area, which suggests that

this environmentally mobile herbicide is likely to move in surface waters draining the same land systems.

In the 1990s, atrazine was occasionally detected in surface waters and sediment samples from the Burdekin / Haughton / Barratta Creeks area of north Queensland (G. Rayment and H. Hunter, unpublished data) and in two mussel and two mud crab samples from the Johnstone River (Russell et al. 1996). Noble et al. (1995) also detected traces of atrazine (up to 0.4 g/L) in the Fitzroy River at Riverslea in 1995, suggesting a wide distribution of this herbicide in the rivers of coastal Queensland. The herbicide 2,4-D has also been detected in waters from the Burdekin / Haughton / Barratta Creeks area, and was the most detected herbicide in aquatic fauna from the Daintree and Johnstone Rivers (Russell et al. 1996). In addition, traces of 2,4-D were detected in water samples taken throughout the Johnstone Catchment, while residues of atrazine occurred only at sites in the lower catchment (Hunter 1996; H. Hunter, personal communication) where sugarcane is grown.

There is improving knowledge of pesticide movement and partitioning between suspended sediment and water fractions for irrigated cotton in the Fitzroy Catchment. While findings are awaiting publication, it is clear that the types and concentrations of pesticides moving off-site in drainage water varies with hydrology, the crop's growth cycle and with the active ingredient involved. For example, at concentrations of 3 and 15 g/L of endosulfan (early and mid-season concentrations in drainage water), one storm event with a flow of 1,200 ML could mobilise 3.6-18 kg endosulfan (B. Simpson et al., unpublished data). Similar information is needed for other cropping systems in order to develop appropriate strategies to minimise pesticide transport in waterways.

Studies to identify the extent to which heavy metals are moving to coastal waters are lacking, although Moss and Bennett (1991) have reported concentrations of six heavy metals (Cd, Cr, Cu, Hg, Ni, Pb) in stream sediments from six rivers of the Wet Tropics. The basaltic nature of the catchment was given as the reason for generally higher concentrations of most metals found in the South Johnstone and Johnstone Rivers. These authors also noted, with examples, that sediment levels above background are often detected in or near to urban areas.

As most heavy metals are either firmly attached to soil and sediment surfaces or are contained within the soil/sediment matrix, soil erosion and sediment mobilisation will be major movement pathways. Others are air-borne vapours and particulates from industrial emissions, fires and wind erosion of soils. The unknown amounts of sulfuric acidity draining from actual ASS in Queensland's coastal region can also be expected to mobilise heavy metals in affected soils and stream sediments (White et al. 1996). However, evidence (e.g. Russell et al. 1996) that heavy metals in aquatic fauna from coastal rivers do at times reach concentrations that violate Australia's Food Standard Code does not confirm that the metals were of anthropogenic origin.

Brodie (1991) has already reported on sewage discharges and other urban influences on parts of the GBR lagoon. At that time, loads of N and P to local waterways from Port Douglas to Mackay were estimated at 1,077 and 292 tonnes/yr, respectively. More recent discharge data from the Department of Environment, mostly from near-coastal sewage treatment plants and for catchments from the Endeavour River at Cooktown to the Burnett at Bundaberg, total 1,970 and 460 tonnes/yr of N and P respectively. On a mass basis, the ratios of N:P of both data sets approximate 4:1.

While drainage through artificial wetlands and other measures are being taken to minimise the release of nutrients and other substances contained in effluents, there have been increases since the early 1990s in discharges to waterways from aquaculture. Present estimates of discharges of N and P from the Wet Tropics region to the Bundaberg area are around 180-360 and 20-35 tonnes/yr, respectively. Although these loadings are relatively low at present, the aquaculture industry is in its infancy. With expected expansion over the next 20 years or so, the contributions of N and P to streams could be considerable if control measures are not implemented, due to the very large discharge volumes involved.

It warrants noting that the grazing lands and grain cropping lands, particularly those that are not fertilised to any significant extent, are being slowly depleted of nutrients through the removal of produce such as livestock, wheat and sorghum. Averaged over the four year period 1979/80-1982/83, there was an estimated annual P removal from the Fitzroy Catchment of about 2,400 tonnes in beef cattle and grain combined. The average annual P fertiliser input for the same period was less than 9% of this figure. While this degree of nutrient deficit is unsustainable in the long term, the observation does suggest that river nutrient levels in this and in similar catchments will very slowly decline, when sourced primarily from eroding soil particles.

CONCLUSIONS

Knowledge of historical and present inputs of nutrients, pesticides, heavy metals, etc on a catchment basis, combined with modelling and monitoring of a range of water quality parameters, have greatly enhanced awareness of the types and amounts of materials that have or might enter river systems discharging to the GBRMP. Clearly, early estimates of sediment loads and nutrient fluxes (Belperio 1983; Moss et al. 1993) in some of these rivers are being refined by monitoring and more robust modelling. Knowledge of areas of particular land use is also improving. Nevertheless, the 'big-picture' outcome of Moss et al. (1993) that grazing lands in the Burdekin and Fitzroy Catchments are the major sources of suspended sediments and nutrients moving to the GBR Lagoon has not changed.

The need now is to integrate and better utilise the information we already have in formulating better catchment management strategies. Condition and trend monitoring, combined with process and decision support modelling, is needed, along with targeted research in a number of areas. These areas include soil hydrology, sediment transport, the use of 'tracers' in sediment records, the assimilative and recovery capacity of rivers affected by excess nutrients, heavy metals, pesticide residues, acid discharges, effluent disposal and the like. Efforts to minimise adverse downstream effects are a high priority, but there is little to be gained from research solely focused on deriving more precise estimates of N and P fluxes.

Finally, it would help with natural resource planning if statistics on animal numbers, grain production, fertiliser use and the like were aggregated on a catchment basis in order to better resolve the connection between inputs and exports. The example of P depletion in the Fitzroy Catchment, independent of any losses to the river, is a stark reminder that many accepted land use practices are not sustainable in the long term.

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Terrestrial inputs of nutrients and suspended sediments to the GBR lagoon

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ABSTRACT

Terrestrial runoff is the largest source of nutrients and sediments to the GBR likely to be affected by human activities. River flows are highly variable over seasonal, inter-annual and event-related time scales. The diverse range of catchments discharging to the GBR encompass extremes of rainfall variability, ranging between recurrent wet-season flows in rivers of the wet tropics to irregular episodic floods in dry tropical rivers. Material fluxes from catchments are related to catchment rainfall, through leaching, sheet runoff and erosion processes. Intense rainfall events cause high levels of soil erosion, typically observed as sharp peaks in suspended sediment and particulate nutrient concentrations. In contrast, dissolved nutrient fluxes exhibit a complex range of behaviours (dilution, enhancement) in relation to river flow rates.

Average annual freshwater runoff to the GBR lagoon is estimated to be close to 40 km^3 (range 12-120 km^3). Based on average monthly flows and monthly means of nutrient concentrations derived from sampling in a number of rivers, we estimate annual riverine N, P and Si inputs of 33,000 t, 2,400 t and 72,000 t, respectively. More precise estimates await the development of improved rating curves, particularly for flood events in large rivers of the dry tropics. Recent in-situ suspended sediment measurements suggest that particulate nutrient fluxes will differ significantly between wet and dry catchment rivers.

Introduction

Nutrients and sediments enter the GBR lagoon from a number of sources (Furnas et al. 1995). Terrestrial runoff is the major source which is likely to be affected by human activities. The extent to which inputs of terrestrially derived nutrients and suspended sediments have changed since European settlement of the region (Moss et al. 1992), or are affecting the GBR ecosystems remains unresolved and a subject of considerable discussion (e.g. Bell and Gabric 1990; Kinsey 1991; Bell 1992; Wachenfeld 1995). A number of estimates of river nutrient and sediment inputs have been made in recent years (Belperio 1983; Cosser 1989; Moss et al. 1992; Furnas et al. 1995; Neil and Yu 1995; Furnas *et al.* 1996a, b). All are broad-scale extrapolations from measurements in a relatively small number of catchments. The most comprehensive dataset available on river nutrient and suspended sediment concentrations is the recently-reviewed sampling program of AIMS (Furnas et al. 1996a, b).

Water discharge patterns

A total of 33 river basins with an aggregate catchment area of 411,000 km^2 drain eastward into the GBR. Using long-term discharge data for 12 of these rivers (Lough 1992; additional data courtesy of DNR; Table 1), representing 77% of the total watershed area, Furnas et al. (1996b) estimated that the average annual terrestrial freshwater input to the GBR is close to 42 km^3. The largest freshwater discharge occurred in 1974 (120 km^3 estimated), while the lowest annual flow occurred in 1987 (11.7 km^3 estimated).

A conspicuous feature of this discharge is the very high inter-annual, seasonal and event-coupled variability of flow (Furnas et al. 1996b). Seasonal variability is related to the monsoonal climate of north Queensland, with a 'wet' summer and 'dry' winter. Over decadal time scales, regional rainfall and river discharge is also modulated by fluctuations in the strength and duration of the summer monsoon which, in turn, are coupled to ENSO climate variability (Lough, 1992; 1993). The largest variations are associated with tropical cyclones and monsoonal rain depressions, resulting in periods of very heavy rainfall and dramatic changes in river discharge on a day-to-day and often hourly basis (e.g. Yu, 1995; Mitchell et al., 1996).

Rainfall and runoff vary considerably between river basins draining to the GBR. Most rivers of the wet tropics drain small catchments with low inter-annual variability of rainfall (Brunt 1970; Anon. 1978) and are characterised by multiple, short-duration flow events each year. In contrast, rivers of the dry tropics include a number of large to very large catchments subject to extended drought periods. Discharge from the two largest rivers, the Burdekin and Fitzroy, typifically occurs as one or two small annual flows, but occasionally as a very large flood event which may last for several weeks and greatly exceeds the combined discharge from all other regional rivers (Furnas et al. 1996b). These large floods have a significant impact on salinity, nutrient and freshwater dynamics over large areas of the GBR shelf (e.g. Wolanski and van Senden 1984; Brodie and Furnas 1995).

For the purpose of comparing statistics derived from wet and dry catchment, the 'wet tropics' rivers are regarded as the catchments between the Daintree and Herbert Rivers, inclusive. It should be noted that both the Barron and the Herbert Rivers have mixed wet and dry catchment areas and relatively high coefficients of variability in annual discharge. This band of 'wet' rivers drains just 10% of the total gauged catchment area listed in Table 1, but on average contributes 42% to the total gauged discharge. Over a 24 year period considered herein, the combined annual discharge from these wet catchments was relatively constant, varying by a factor of 6 between years.

Overall variability in discharge to the GBR shelf is largely driven by year-to-year differences in discharge from the Burdekin and Fitzroy Rivers. For example, during 1974 and 1991, the two wettest years in this period (Table 1), the combined discharge of the Burdekin and Fitzroy Rivers represented 71 and 77% respectively of the total annual gauged discharge. Conversely, during 1992 and 1987, the two years with the lowest overall gauged discharge, the contribution to the total annual discharge by the Burdekin and Fitzroy Rivers together was just 11.7 and 12.4% respectively. Over the 24 year period examined, combined annual discharge from these two dry-catchment rivers varied by a factor of 86 between years.

Seasonal and Event-related Variability of Nutrient Concentrations in Rivers

Nutrient and suspended sediment concentrations vary significantly between river systems, between seasons and within seasons in relation to catchment type and streamflow dynamics. Details of these dynamics and their implications for estimates of annual river nutrient fluxes have been presented in a number of publications (Mitchell et al. 1991; Mitchell and Furnas 1994; Furnas et al. 1995, 1996a, b; Mitchell et al. 1995). Data from two rivers, the Tully River in the wet tropics and Burdekin River in the dry tropics illustrate these findings (Figure 1).

Seasonal peak concentrations of dissolved inorganic nitrogen (DIN = NO_2 + NO_3 + NH_4) and less often, dissolved inorganic phosphorus (DIP as PO_4) typically occur during the first significant flow event of each summer wet season (Figure 1a, b - N shown only). DIN concentrations in these 'first-flush' peaks, often exceed 40 µM (= 560 µg N L^{-1}); reflecting the mobility of oxidized N (and to a lesser extent P) stocks built up in catchment soils during the dry season. Thereafter, DIN and PO_4 concentrations in river waters progressively decline over the course of the wet season, as leachable N and P stocks are exhausted. Concentrations of dissolved organic nitrogen (DON) and phosphorus (DOP) remain low and relatively constant through the year. There is a tendency for DON to decline with increasing discharge, suggesting relatively constant input from the watershed and dilution during major flood events. Seasonal and event-related trends for DOP are not well defined at this stage.

In contrast, concentrations of particulate nitrogen (PN) and phosphorus (PP) vary directly with river flow (Figure 1c, d), and typically peak during major seasonal flood events (Mitchell et al. 1995), reflecting the transport of organic matter and soil particles from the watershed. Higher concentrations of particulate-associated N and P typically occur during the rising limb of flood hydrographs (Mitchell et al. 1995). The strong relationship between flow rate and particulate nutrient concentrations illustrates the importance of intensive sampling during flood events to construct accurate estimates of particulate material fluxes from rivers. Elevated concentrations may also occur during first-flush events, though the significance of this phenomenon in terms of overall transport may be as a relatively minor contribution.

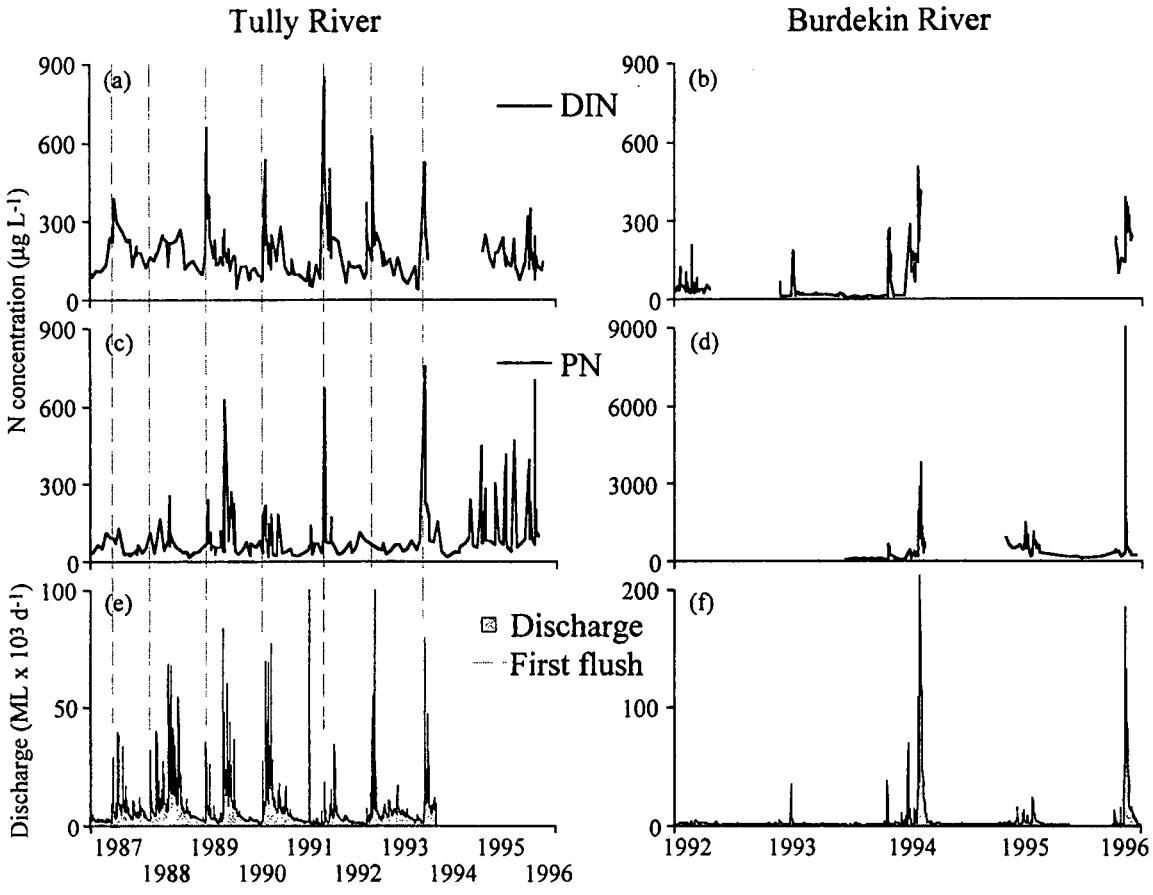
Table 1: Statistics of major river systems draining into the Great Barrier Reef region. After Lough (1992) and Furnas et al. (1996b).

River	Period	Gauged catchment area (km^2)	Mean annual discharge (ML x 10^6)	Minimum annual discharge (ML x 10^6)	Maximum annual discharge (ML x 10^6)	C.V. (%)
Normanby	1968-92	2,460	0.911	0.054	2.615	33.8
Daintree	1968-92	830	1.011	0.351	2.252	54.1
Barron	1958-92	1,940	0.807	0.144	2.617	77.6
Mulgrave	1966-92	365	0.567	0.187	1.045	40.7
Russell	1966-92	231	0.851	0.488	1.344	26.6
N. Johnstone	1967-92	930	1.840	0.651	3.761	39.0
S. Johnstone	1958-92	390	0.813	0.291	1.384	33.8
Tully	1972-92	1,475	3.039	1.660	4.704	29.7
Herbert	1958-92	8,805	3.370	0.407	10.418	70.4
Burdekin	1958-92	129.660	9.272	0.540	50.927	116.7
Fitzroy	1964-92	135,895	5.574	0.172	22.126	99.9
Burnett	1958-92	2,455	1.050	0.117	6.237	114.7

Particle-associated N and P occur in a variety of forms. Particulate nitrogen occurs as ionic ammonium adsorbed to soil particles, organic compounds in detritus and N which is bound within clay mineral lattices (Bremner 1965; Rosenfeld 1979), though the bulk of particle-associated N is generally considered to be biologically accessible. Particle-associated phosphorus also occurs in a variety of forms, ranging from adsorbed phosphate ions to P which is directly incorporated into mineral lattices. In contrast to PN, considerable uncertainty remains regarding the proportion of total P which is biologically available, and over what time frames (e.g. Froelich 1988; Pailles and Moody 1992; Eyre 1993). It is unlikely that P held within mineral lattices, and not extractable by 'mild' digestion procedures (eg. acid/persulfate) would be readily available for biological uptake. Some of the P attached to particles is desorbed under conditions of increasing ionic strength as particulate material is transported through estuarine or river plume salinity gradients (e.g. Brodie and Mitchell 1992). As a consequence, the proportion of the total river P flux which is biologically relevant to the receiving marine environment is still unresolved.

Temporal Dynamics of Nutrient and Sediment Fluxes during Flood Events

Temporal changes in concentrations of riverine particulate matter are typically more dynamic than those for soluble material (Mitchell and Furnas 1994). Even when sampling frequency is targetted to episodic stormflows, there is a high likelihood that peak concentrations will be missed. The contribution of particulate nutrients to overall nutrient fluxes are not as well resolved as those for dissolved components. In order to acquire comprehensive data during stormflows, we have recently developed instruments ('river loggers') which record suspended sediment concentrations at frequent (30 minute) intervals over extended periods (2-4 months). These instruments were designed with a self-cleaning function to ensure consistent data quality and to operate over the wide range of suspended sediment concentrations (5-10,000 mg L^{-1}) observed among NQ rivers.


Tully River
Burdekin River
(a)
(b)
(c)
(d)
(e)
(f)
DIN
PN
Discharge
First flush
N concentration (µg L-1)
Discharge (ML x 10³ d-1)
900
600
300
0
9000
6000
3000
200
100
50
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996

large flow events, when reduced concentrations suggested the influence of dilution. For the period 8 Jan 1996 to 21 May 1996 (Figure 2c), we estimate that 61 x 10^3 tons suspended sediment was transported from the Tully catchment. Most of this export (75%) occurred during the two largest discharge events.

Burdekin River

Only one significant discharge event occurred in the Burdekin River (Figure 3a), during the summer of 1995-96. Aside from a very small discharge in late December, the first significant flow event of the year occurred on 9 January 1996 (peak, 3166 $m^3 s^{-1}$), followed three days later by a secondary peak (1523 $m^3 s^{-1}$) when the Burdekin dam overflowed. Derived suspended sediment concentrations were much higher than found for the Tully River, reaching a peak of 7.3 g L^{-1}.

Few surface suspended sediment samples were collected through this period. PN measurements during the initial peak track relative changes in the instrument-derived suspended sediment concentrations (Figure 3a). However, during the secondary peak, concentrations of suspended sediment (and PN) determined from surface samples were much lower than the suspended sediment concentrations derived from our underwater instrument. We surmise that suspended sediments were vertically mixed through the river water column during the initial high-level discharge, but poorly mixed during the lower discharge velocities of the second peak. Peaks in surface DIN concentrations on either side of the flow maxima (Figure 3b) suggest dilution during high discharge, similar to the trend observed in the Tully River (Figure 2b).

Given our uncertainty about the vertical mixing of suspended sediment during the secondary peak, two suspended sediment flux curves were determined (Figure 3c). The lower limit assumes that surface sample sediment concentrations prevailed through the entire water column during the secondary flow, while the upper limit assumes that the near-bottom sediment concentrations predominated. On this basis, we estimate that between 2.6 and 4.8 x 10^6 tons of suspended sediment was transported in the Burdekin River, between 20 December 1995 and 12 February 1996. More than half of this export (2.5 x 10^6 tons) occurred over a four day period during the initial large flow event.

Comparison between wet and dry-catchment rivers

The temporal pattern of multiple flow events observed in the Tully River is typical for this river. In contrast, the main discharge event in the Burdekin River was relatively small, even for this highly variable river. The water level rose just 3 m above our instrument, resulting in a total discharge of 1.7 x 10^6 ML over the 2-month flood period considered here (Figure 3). During the 5 month deployment period in the Tully River (Figure 2), the discharge was approximately 1.7 x 10^6 ML. Annual discharge in the Burdekin River for the 1995-96 hydrological year (Oct. - Sept.) is estimated to be < 2 x 10^6 ML, much less than this river's average discharge (9.3 x 10^6 ML, Table 1) and less than the long-term average for the Tully River (3.0 x 10^6 ML). The sediment yield from one small flood in the Burdekin River was 40-80 times that from a number of significant flood events in the Tully River.

Differences between the profiles of suspended sediment concentration for each river account for this huge difference in sediment yield. Peak suspended sediment concentrations varied 17-fold between the Burdekin and Tully Rivers (Figures 2,3). Furthermore, suspended sediment concentrations declined very rapidly in the falling stages of each flow event in the Tully River, resulting in minimal flux after the peak flows. In the Burdekin River, high concentrations of suspended sediment were sustained for some time beyond the secondary flow event, at least through part of the water column. Different sub-catchment source water entering the river system, probably above the Burdekin Dam, may have been responsible for the delayed concentration peak during the secondary flow.

Nitrogen exports during the logger deployment period may be estimated from surface sampling, though with less confidence than for suspended sediment due to the smaller number of samples. An interpolation procedure was applied to DIN concentrations (Figures 2b, 3b), while average concentrations from previous summer sampling periods were used for DON, since the current samples had yet to be analysed. Interpolation was considered inappropriate for PN flux estimation, due to the sharp nature of these peaks. Instead,

average weight percentages of the PN content in suspended sediment, determined for each river (Table 3), were applied to the suspended sediment flux estimations.

Fluxes of N estimated during the 5-month logger deployment periods are presented in Table 2. Dissolved forms of nitrogen (DIN + DON) constituted 53% of total N export from

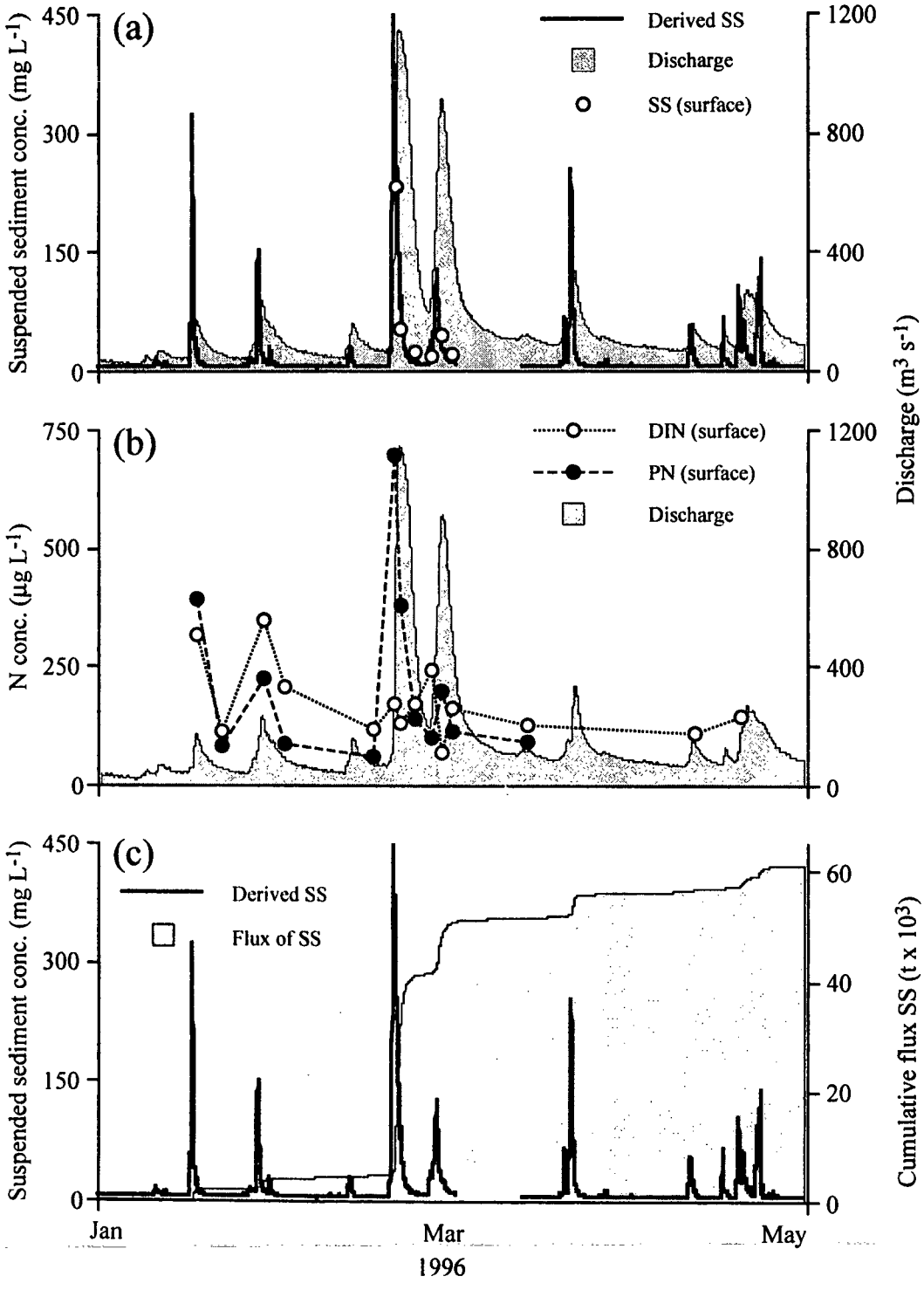


Figure 2: (a) Suspended sediment concentration in the Tully River derived from a moored transmissometer at Euramo, 8 January 1996 to 21 May 1996. Open circles represent suspended sediment concentrations determined in surface water samples. Gray area graph represents discharge from nearby guaging station (113006A), operated by D.N.R. Qld.; (b) DIN (open circles) and PN (closed circles) concentrations in surface samples; (c) Estimated cumulative flux of suspended sediment

the Tully River. Dissolved N was a much less important component in the Burdekin River (7-13% of total exports), where PN exports dominated (87-93%). The low concentration of PN in suspended sediment from the Burdekin River (0.15%, Table 3) compared with the Tully River (0.53% - 1996 flood only) considerably reduces the importance of the huge differences in sediment yield between the two rivers, at least for N export (Burdekin PN, 12-22 times that in the Tully).

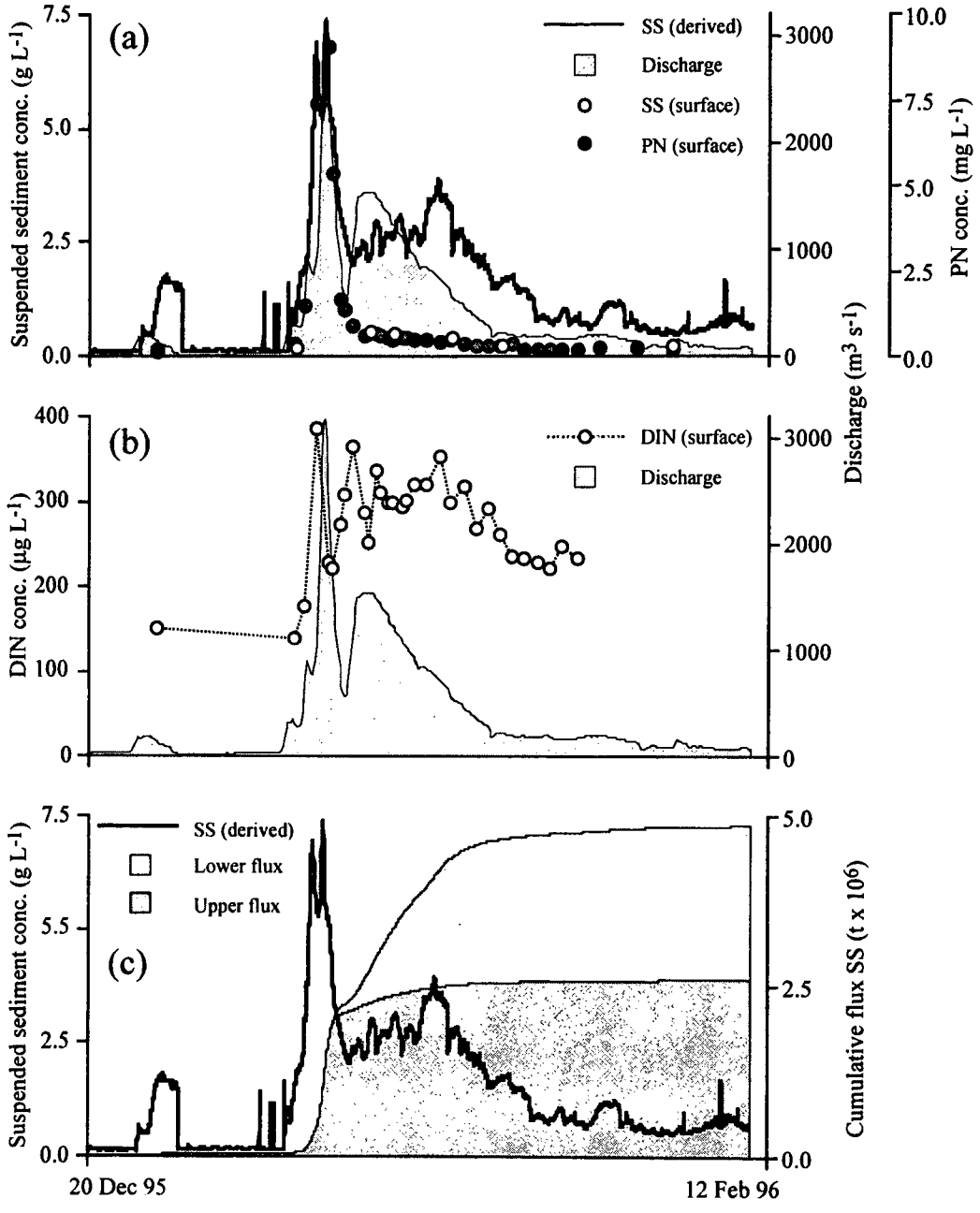


Figure 3: (a) Suspended sediment concentration in the Burdekin River derived from a moored transmissometer at Home Hill, between 20 December 1995 and 12 February 1996. Open circles represent suspended sediment concentrations, closed circles denote PN concentrations, determined in surface water samples. Gray area graph represents discharge from Clare guaging station (120006), operated by D.N.R., Qld.; (b) DIN (open circles) concentrations in surface samples; (c) Estimated cumulative flux (upper and lower limit) of suspended sediment

In most of the nutrient flux estimates made (Table 4), insufficient account has been taken of the differences in the proportions of nutrient forms among rivers draining to the GBR shelf.

In particular, the large differences in sediment yield, as demonstrated by our river logger results, have not been recognised. An exception is the climate-driven model of Neil and Yu (1995), which emphasises the importance of rainfall variability on catchment sediment yield due to its influence on groundcover. Their estimate of total sediment flux was similar to that of Belperio (1983). However, they proposed a considerably different distribution of sediment inputs, with a much higher proportion from the Burdekin and the Fitzroy Rivers (ca. 2/3) and a much lower contribution from the wet tropical coast. Our river logger findings clearly support this redistribution.

As a comparative exercise, the suspended sediment yield determined using our river logger for the small Burdekin River flood of 1996 (2.6-4.8 million t for 1.7 x 10^6 ML discharge) can be used as a crude estimator of sediment yield in other years. First, it is assumed that the sediment yield in the Fitzroy River is similar to that in the Burdekin. If this yield is extrapolated to the average annual discharges for these rivers (Table 1), then the average annual flux of suspended sediment for the Burdekin and Fitzroy Rivers combined is estimated at 23-42 million t. This range covers and exceeds the estimates of Belperio (1983) and Neil and Yu (1995) in Table 4. Further extrapolating this yield to a recent year of high discharge in the Burdekin River (1974, Table 1), it is estimated that 100-185 million t of suspended sediment was transported that year by the combined discharge of the Burdekin and Fitzroy Rivers. This estimate may be conservative, since increasingly higher levels of soil erosion are associated with very intense rainfall (Yu, 1995).

Table 2: Estimated transport (t) of different nitrogen forms from the Tully and Burdekin Rivers during 1996 logger deployment periods. Period for Tully River - 8 January to 21 May 1996; Burdekin River - 20 December 1995 to 12 February 1996.

River	PN%	DIN (t)	DON (t)	PN (t)	Total N (t)
Tully	0.53	274	86	323	681
Burdekin - upper limit	0.15	468	129	3900	4497
- lower limit				7200	7797

Estimates of river nutrient exports to GBR

Furnas et al. (1996a, b) recently employed three approaches to re-estimate river nutrient exports to the GBR (Table 4). The first approach used discharge-weighted mean annual concentrations of N and P derived from three years of intensive sampling in the South Johnstone River. The assumption was made that volume-weighted concentrations established for this single river were broadly applicable to the diverse catchments draining to the GBR. This estimate is regarded as highly conservative. The second approach utilized monthly mean concentration-discharge relationships derived for individual wet and dry catchments and mean monthly discharges for those catchments to integrate total annual exports to the GBR. This approach, while applying some weighting to the data, is also regarded as conservative. The third approach used estimates of annual sediment inputs to the GBR from Belperio (1983), Moss *et al.* (1992) and Neil and Yu (1995), and assumptions about the N and P composition of sediment discharged from rivers and relationships between the proportions of dissolved to particulate forms of N and P exported.

The sediment-based estimates of N and P inputs to the GBR are considerably larger (1.5 to 3-fold for N; 8 to 16-fold for P) than the estimates calculated from water sampling alone. There is considerable uncertainty surrounding each approach. The sediment-based approach is limited by the tenuous assumptions of constant suspended sediment composition across all catchments and constant proportions between dissolved and particulate nutrient forms exported. The water sampling based estimates are based on sparse

datasets and lack nutrient and sediment data from the two largest catchments (Burdekin and Fitzroy) during major flood events. Continued sampling in these two rivers remains a high priority, given that large flood events in these dry catchments appear to heavily influence discrepancies between the sediment-based and water-based estimate.

Table 3: Nitrogen and phosphorus composition of suspended sediment in NQ rivers, sampled during flood periods.

River	Sampling conditions	N (% w/w)	P (% w/w)
North Johnstone	cyclone Sadie flood, sampled by DPI (from Mitchell *et al.*, 1996b)	0.44	#1 0.215
South Johnstone	cyclone Sadie flood, sampled by DPI (from Mitchell *et al.*, 1996b)	0.45	#1 0.166
Tully	flood periods during Jan/Feb 1995 and Mar 1996, sampled by BSES and AIMS	0.55	0.098
Herbert	cyclone Sadie flood, sampled by AIMS and CSIRO (from Mitchell *et al.*, 1996a)	0.35	0.059
Burdekin	small discharge event in January 1996, sampled by B. Leahy for AIMS	0.15	0.049

Notes: #1 - Kjeldahl digestion method used for PP determinations.

Inputs of freshwater, sediments and nutrients of this magnitude are likely to have significant impacts on the receiving shelf system, though such flood events in the large dry catchments are highy episodic. In contrast, relatively constant loads of nitrogen are delivered to the central GBR shelf from year to year by rivers draining the wet tropics. However, the contribution by the combined wet tropics rivers is likely to be a minimal proportion of the total nitrogen flux during those years in which the dry catchment rivers flood.

The impact of medium or longer-term rainfall cycles on material fluxes to the GBR shelf has been acknowledged (e.g. Neil, 1995), though not tested. Apart from highly variable year-to-year discharge, the Burdekin and Fitzroy catchments are subject to extended periods of consecutive wet or dry years. A 6-year 'wet' period can be discerned from the Burdekin gauging record at Clare between 1953-1958, when annual discharge averaged 19.4 x 10^6 ML (Figure 4). In contrast, the last 5 years (1992-1996) represent the longest, sustained dry period over this 46-year record (average annual discharge 1.3 x 10^6 ML). Much of the Fitzroy catchment is in a similar near-drought position. Given the importance of high levels of groundcover in limiting erosion (Gardner et al. 1988; Pressland et al. 1991; Finlayson et al. 1995; Neil and Yu, 1995), it is expected that abnormally high soil losses will occur in these catchments during the next large flood event (Mitchell et al. 1995).

Table 4: Estimates of riverine inputs of nitrogen, phosphorus and suspended sediment to the Great Barrier Reef using different methods (from Furnas et al., 1996b).

Method	Total sediment ($t \times 10^6$)	Sediment N ($t \times 10^3$)	Sediment P ($t \times 10^3$)	Total N ($t \times 10^3$)	Total P ($t \times 10^3$)
Water-based approach: Volume-weighted mean annual concentration in South Johnstone River, 1990-91.				15.4	1.5
Weighted monthly flow rates and monthly mean nutrient concentrations.				21.2	2.0
Sediment-based approach: Belperio (1983) (from Moss *et al.*, 1992)	25.4	41.9	29.2	97.5	38.0
Moss *et al.* (1992)	14.0	23.0	16.1	77.0	11.0
Neil and Yu (1995)	23.0	38.0	26.5	88.3	34.4

Implications for Management

1. River runoff is the largest external source of N and P to the GBR lagoon which has been quantified to date.
2. River runoff is the largest nutrient and sediment source directly influenced by human activity, principally through land use practices in catchments (land clearing, farming, grazing).
3. Because of the large intra- and inter-annual variability in discharge, nutrient concentrations and sediment loads in all types of rivers, estimates of exports cannot be reliably extrapolated from short-term data sets.
4. All discharges from rivers initally enter the nearshore zone and for small floods and low-flow conditions, remain near the coast. Under conditions of strong flooding or onshore-free wind stress, flood plumes can extend offshore to the reef tract and directly influence 100's to 1000's of km^2 of the shelf.
5. There are considerable differences between the flow dynamics, nutrient speciation and exports and sediment yields of wet- and dry-catchment rivers. These differences must be respected in order to make accurate and reliable estimates of nutrient and sediment inputs to the GBR lagoon.
6. The bulk of sediment and nutrient inputs to the GBR occur during flood events, particularly the very large floods following cyclones and monsoonal rain depressions.
7. In terms of water, sediment and nutrient exports, the two very large dry-catchment rivers (Fitzroy, Burdekin) exert the largest impact upon the shelf system. Such impacts, however, are highly episodic.
8. The wet-tropical catchments between the Daintree and Herbert Rivers supply a large proportion of total runoff to the GBR (ca. 40%), but volume-specific nutrient and sediment yields are lower than those of dry-tropical catchments.

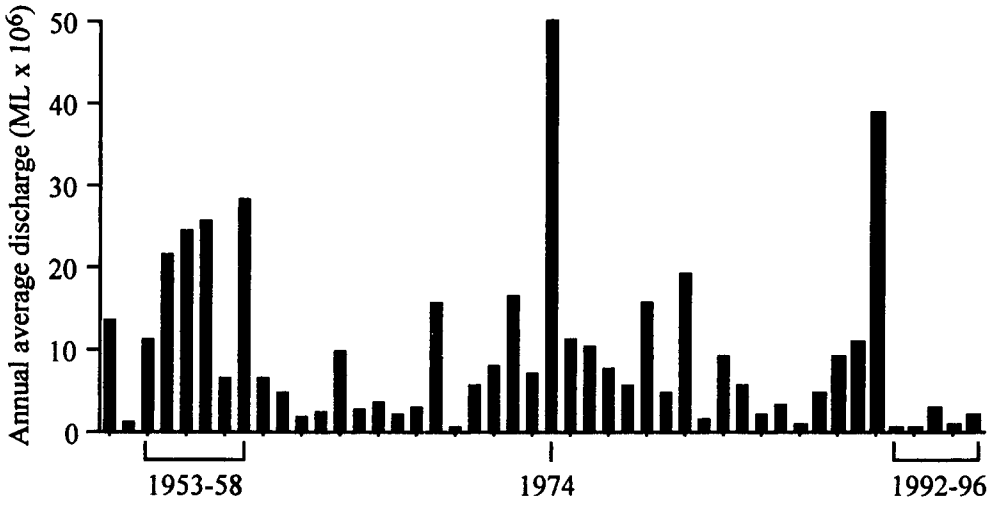


Figure 4: Annual discharges (ML x 10^6) in Burdekin River, 1951-1996. Discharge at Clare gauging station (120006E); data courtesy of DPI, Water Resources office, Ayr

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Marine plants as bioindicators to infer source, transport and fate of nutrients on the Great Barrier Reef

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ABSTRACT

The Great Barrier Reef (GBR) is characterised by low ambient nutrients, high productivity and diversity of marine plants, such as mangroves, seagrasses and corals. Qualitative evidence of ecosystem level alterations in the GBR as a result of increased nutrient inputs include a) changes in some reef flat communities assessed with historical photographs; b) increased seagrass coverage at Green Island (near Cairns); and c) increased mangrove coverage at Low Isles. Yet, standard water quality monitoring over the past several decades has not detected appreciable trends, largely due to the pulsed nature of the GBR nutrient inputs and to the rapid biological incorporation of nutrients by organisms. Thus the causal agents (anthropogenic or natural variation) for these changes remain elusive, and the biotic community responses provide the least ambiguous evidence of changes. The use of marine plants as nutrient bioindicators that integrate nutrient pulses and provide information as to the source and fate of nutrients therefore has particular relevance in the GBR system. Examples of nutrient bioindicators include phytoplankton bioassays, macroalgal metabolic profiling, seagrass depth range and stable isotope analyses. These bioindicators have been employed at various sites on the GBR, including inshore (Airlie Beach, Green Island), offshore (Heron Island), and an offshore site with experimental nutrient enrichments (One Tree Island). The following general conclusions can be drawn from these bioindicator studies: a) both dissolved nitrogen and phosphorus are rapidly incorporated into the biota; b) nitrogen appears to be the primary limiting nutrient for marine plant growth; c) while the responses of marine plants to dissolved nutrient inputs are species-specific and site-specific, they can be used to assess the source, transport and fate of nutrients in the GBR.

SESSION 2

Pressures and effects on the Great Barrier Reef lagoon

Chair: Terry Done

Rapporteur: Chris Crossland

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Keynote Paper: Biological oceanography of the Great Barrier Reef
M Furnas* and A Mitchell

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Soft-bottom benthic communities and processes in the Great Barrier Reef lagoon
D Alongi
(Paper not presented)

•

Impacts on and responses of seagrasses in the Great Barrier Reef - issues for management
W Lee Long* and R Coles

•

The effects of prawn trawl fisheries on Great Barrier Reef seabed habitats
R Pitcher*, C Burridge, T Wassenberg and I Poiner

•

Endangered and charismatic megafauna
H Marsh*, P Arnold, C Limpus, A Birtles, B Breen, J Robins and R Williams

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Biological Oceanography of the Great Barrier Reef

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ABSTRACT

Biological oceanographic characteristics of the Great Barrier Reef (GBR) ecosystem relevant to management are reviewed. Reefs *per se* only make up a small fraction (<9 percent) of total continental shelf area in the GBR ecosystem. The GBR shelf sea is normally characterised by low nutrient concentrations and plankton biomass. Abrupt and short-lived shifts in water quality, plankton biomass and ecosystem productivity occur after major disturbance events (floods, cyclones). Despite low nutrient levels, plankton in GBR waters are highly productive. Overall primary production in the GBR is on the order of 1 metric ton of carbon per km^2 per day with most (ca. 70%) due to phytoplankton. Nutrients supporting this production are primarily supplied by recycling within the ecosystem. River runoff is the largest external nutrient source quantified to date, though N inputs from atmospheric fixation by *Trichodesmium* may be very large. An examination of historical chlorophyll data from the central GBR lagoon fails to show evidence for large-scale eutrophication.

INTRODUCTION

The Great Barrier Reef (GBR), Australia's pre-eminent tropical marine ecosystem, extends over 14.8 degrees of latitude between the NE Torres Strait (9°30'S) and Lady Elliott Island (24° 20'S). Virtually all of the GBR south of Cape York (Figure 1) lies within the Great Barrier Reef Marine Park. In part because of historical precedents, the GBRMP is managed as a multi-use (fishing, tourism, conservation, transportation) regional system; however, the prime management goal remains the preservation of the declared World Heritage conservation values of the region.

The GBR Shelf Sea Ecosystem

The continental shelf ecosystems of the GBRMP contain approximately 2,900 identified reefs and 918 islands. Overall, reefs occupy < 9 percent of the total continental shelf area (224,000 km^2) within the GBRMP (Hopley *et al.*, 1989). The GBR may therefore be considered a shallow coastal sea, bounded by and encompassing to varying degrees a porous matrix of coral reefs. Reef area as a proportion of shelf area is highest in the far northern GBR (36.7 percent between 12°S and 13°S) where the continental shelf is also narrowest (22 km at 14°S) and lowest (1.1 percent) in the southern GBR (22-23°S) where the outermost reefs lie >250 km offshore. The major proportion of total shelf area and water volume lie seaward of the 30 m isobath. The shallow nearshore band (depth <20 m) occupies only a small proportion of total shelf area and total shelf water volume.

From Cape Tribulation (16°) southward, most reefs are located on the outer half of the continental shelf. The reef matrix, to varying degree, isolates the GBR shelf sea from the adjacent Coral Sea. The linear density of reefs along the shelfbreak varies with latitude, from between 90 percent in the northern GBR (9-16°S) and Pompey Reef complex (19-21°S) to ca. 10 percent in the central (16-19°S) and southern GBR (Pickard et al, 1977). Between the reef matrix and the coastline lies a contiguous north-south body of open water which is commonly referred to as the "GBR lagoon". This open water exchanges freely with water in the reef matrix along the outer shelf. The width of open water in the lagoon increases from ca. 18 km near Cape Tribulation (16°S) to 150 km at the entrance to the Capricorn Passage (23°S). North of Cape Tribulation, reefs occur across much of the width of the shelf and the "lagoon" is often narrow (< 10 km) or ill defined. Importantly, the GBR lagoon is the primary receptacle of river runoff and associated terrestrial materials which enter the GBR system. Physical, geological, chemical and biological oceanographic processes occurring within the lagoon (eg. Wolanski and van Senden, 1983) tend to distribute terrestrial materials along the coastline (eg. Gagan et al., 1987) and the degree and form of terrestrial materials which reach and influence outer-shelf reefs. As a result, coastal and inner lagoonal reef and benthic ecosystems experience conditions considerably different to and more variable than those confronting outer-shelf reefs.

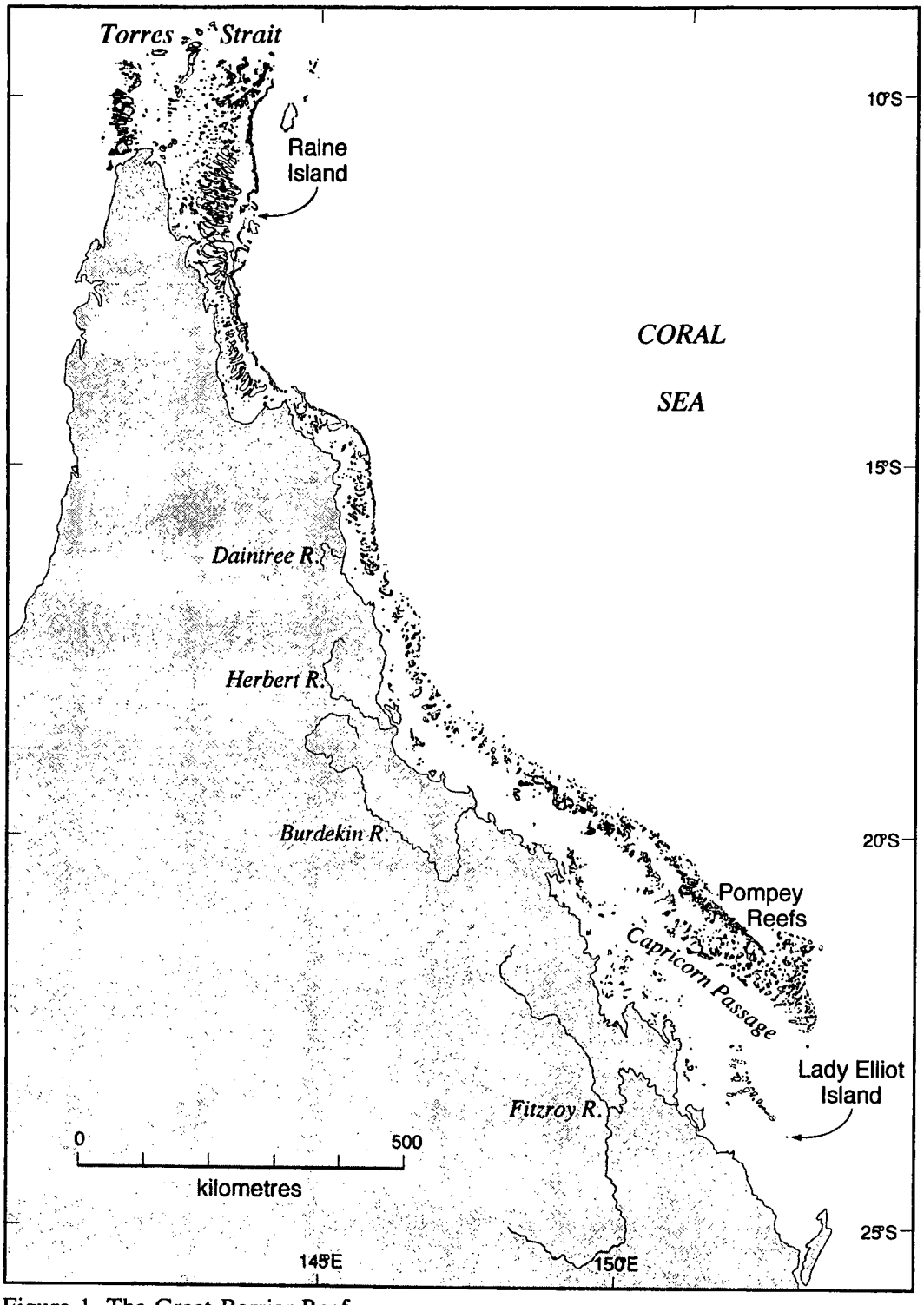


Figure 1 The Great Barrier Reef.

Thirty-three river basins with an aggregate area of 411,000 km^2 drain into the GBRMP (Tarte et al., 1995). The long-term average discharge from these river basins is close to 40 km^3 of freshwater per year, with aggregate flows in individual years ranging from ca. 12 km^3 to >120 km^3. Approximately 76 percent of this catchment area is grazing land (Tarte *et al.*, 1995). Cropping, dominated by cultivation of sugar cane (3 percent of total catchment area) occurs in the coastal plain, generating an export crop valued in excess of $1billion. A significant proportion 37 percent (15 km^3) of the long-term averaged freshwater discharge to the shelf is derived from two dry catchment river systems, the Burdekin and Fitzroy, though the flow can vary by orders of magnitude between years (Mitchell and Furnas, this volume).

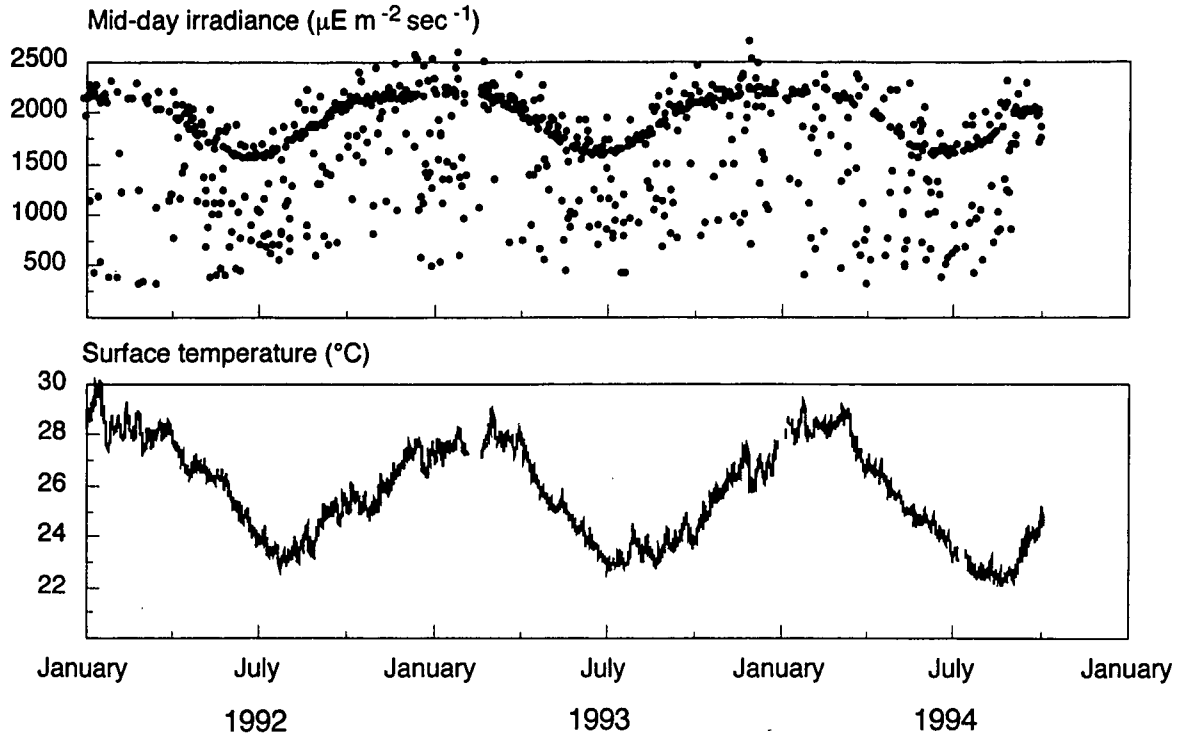


Figure 2. Annual cycles of mid-day solar irradiance (Top) and near-surface water temperature (Bottom) measured at Davies Reef (19°S). Source - AIMS

Based upon long-term discharge rates, approximately 30 percent of the total river runoff onto the shelf (12 km^3) comes from the small wet tropical catchments between the Daintree and Herbert Rivers (aggregate catchment area = 22 x 10^4 km^2). Direct rainfall upon the shelf (Pickard *et al.*, 1977) ranges between 0.8 and 2 m (170-440 km^3 p.a.).

Water movements within the reef matrix and GBR lagoon are related to geostrophic pressure gradients in the adjacent East Australian Current (EAC: Church, 1987), shelf waves (Wolanski and Bennett, 1983), tidal currents (Church *et al.*, 1985) and wind stress (Wolanski and Pickard, 1985). In most cases, mixing induced by wind stress and the reef matrix is sufficient to keep the water column well mixed vertically. From 16° southward, wind stress from the SE trade winds tends to force surface and coastal waters northward in opposition to the southward geostrophic flow driven by the EAC. As a result, waters in the outer portion of the GBR lagoon and outer-shelf reef matrix are separated from the coastal zone by a dynamic front in the GBR lagoon (King, 1995). This front also traps terrestrial material near the coast. A variety of geological and geochemical evidence (eg. Gagan *et al.*, 1987) clearly indicates that most sediments and other particulate-associated materials derived from the land are constrained to a narrow (10-15 km) band near the coast.

Water temperatures and insolation undergo well-defined seasonal cycles (Figure 2). Although the annual temperature range (20-30°C) is small, virtually all biological processes related to biological productivity and nutrient cycling are temperature dependent and increase exponentially with temperature. Significant, but short lived, stratification of the water column occurs as a result of upwelling along the shelfbreak and the extension of flood plumes along and across the shelf (Figure 3).

Shelf waters of the GBR are, for the most part, characterized by low to very low levels of suspended matter, dissolved nutrients and plankton biomass (Furnas and Brodie, 1995). When carefully measured, concentrations of DIN species (NH_4, NO_2, NO_3) are close to or below the "normal" limits of detection (ca. 0.01 μM) in lagoon and reef waters. Organic N (DON ≈ 5 μM, PN ≈ 1 μM) species are the dominant forms of nitrogen in reef waters. Concentrations of phosphorus species (PO_4, DOP, PP) are low and roughly similar in

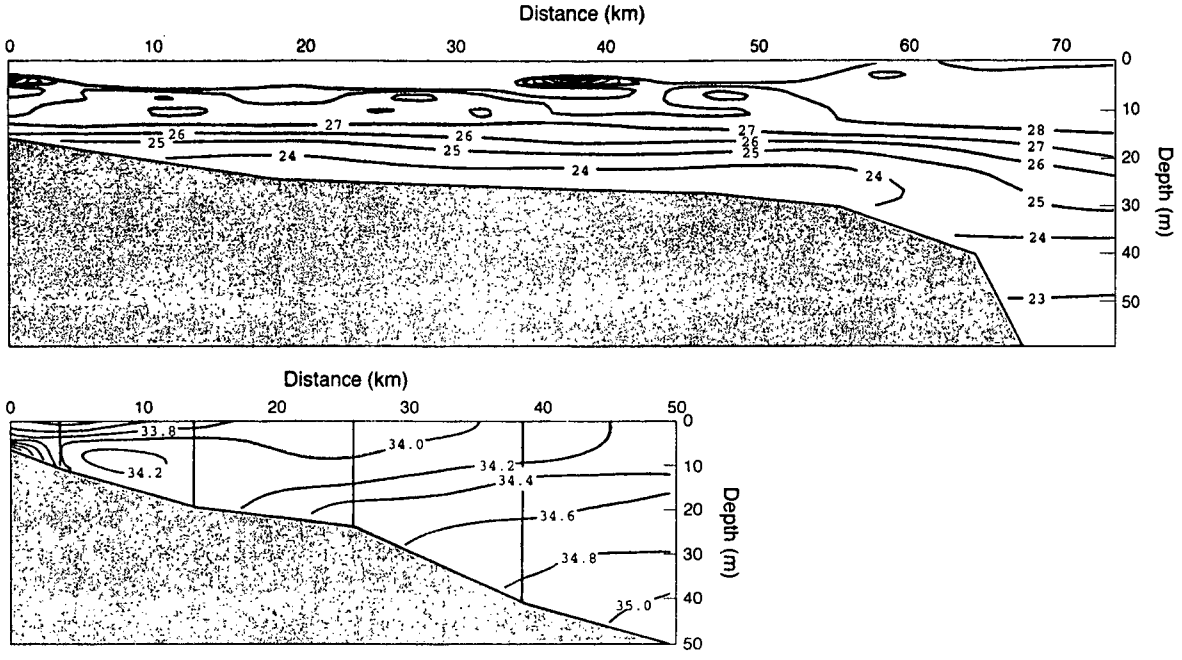


Figure 3 Top: Cross-shelf temperature section (°C) through an intrusion of Coral Sea water in Palm Passage (18° 30'S) during October, 1987. Bottom: Cross-shelf salinity section through river plumes seaward of Innisfail (17° 30'S) following cyclone Winifred in February, 1986. Source - Furnas, unpubl.

magnitude (ca. 0.05-0.2 μM), but are consistently detectable. While absolute differences between mean concentrations of nutrients at regional scales are generally small, persistent differences in nutrient and plankton biomass levels do exist (Figure 4). At most times of the year, there is relatively little latitudinal variations in chlorophyll and nutrient concentrations within the GBR lagoon proper (Figure 5), but broad-scale "quantum" changes in water quality status associated with cyclonically generated resuspension of shelf sediments (post-cyclone Winifred, 1986) and very large runoff or monsoonal rainfall (post- cyclone Joy, 1991) events occur episodically. The nutrients (particularly N and P) introduced to shelf waters as a result of these floods are rapidly taken up by phytoplankton in the lagoon, resulting in significant phytoplankton blooms (2 to 5-fold increase) over broad areas (10^3-10^4 km^2).

Cross-shelf gradients in salinity, nutrient concentrations, phytoplankton biomass and zooplankton biomass , while persistent or recurrent, are relatively small. Elevated nutrient concentrations and plankton standing crop levels are generally found within a few kilometres of the coast (Liston, 1990), but the highest chlorophyll concentrations are not infrequently measured near the shelfbreak or in the reef matrix. These elevated chlorophyll levels are indicative of both enhanced nutrient inputs from the Coral Sea via shelfbreak upwelling (Furnas and Mitchell, 1996) and active mixing around reef topography (Wolanski et al., 1996).

Plankton communities in GBR shelf waters are comprised of oceanic, coastal and benthic elements. Phytoplankton biomass is overwhelmingly dominated by very small phototrophic picoplankters (< 2 μm: *Prochlorococcus*, *Synechococcus*) which comprise between 50 and 80 percent of measured chlorophyll stocks. Prochlorophytes predominate in oceanic and outer-shelf waters, giving way to cyanobacteria in the coastal zone. Causes for this difference are currently unresolved, but are likely related to cross-shelf changes in water quality or light quality in the more turbid nearshore waters. Co-existing with this ubiquitous community of picoplankters is a diverse, but numerically sparse assemblage of oceanic dinoflagellates and coccolithophorids (Hallegraeff, 1984) and a cosmopolitan assemblage of diatoms (Revelante et. al., 1982; Hallegraeff and Jeffrey, 1984). Members of this diatom assemblage are distributed worldwide in temperate coastal and tropical upwelling zones which are subject to frequent disturbances and enhanced nutrient inputs.

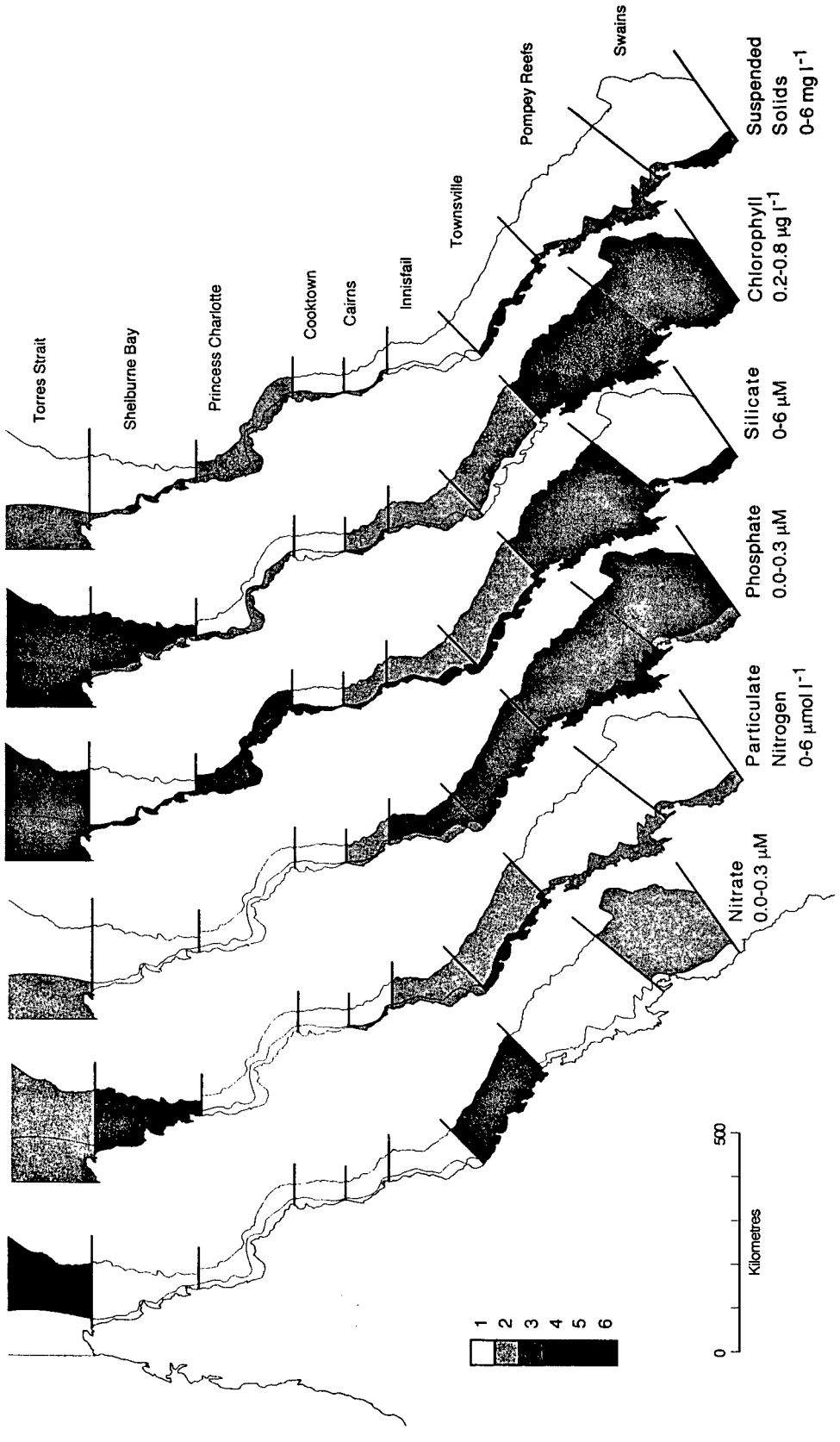


Figure 4. Representative latitudinal and cross-shelf distributions of mean concentrations of water quality parameters in the GBR. Data from nine latitudinal sectors is divided into nearshore (<20 m depth) and outer-shelf (>20 m depth) bins. Regional mean concentrations are shown by degrees of shading. The ranges given for each parameters were divided into six equal parts. Data replotted from Furnas and Brodie, 1995.

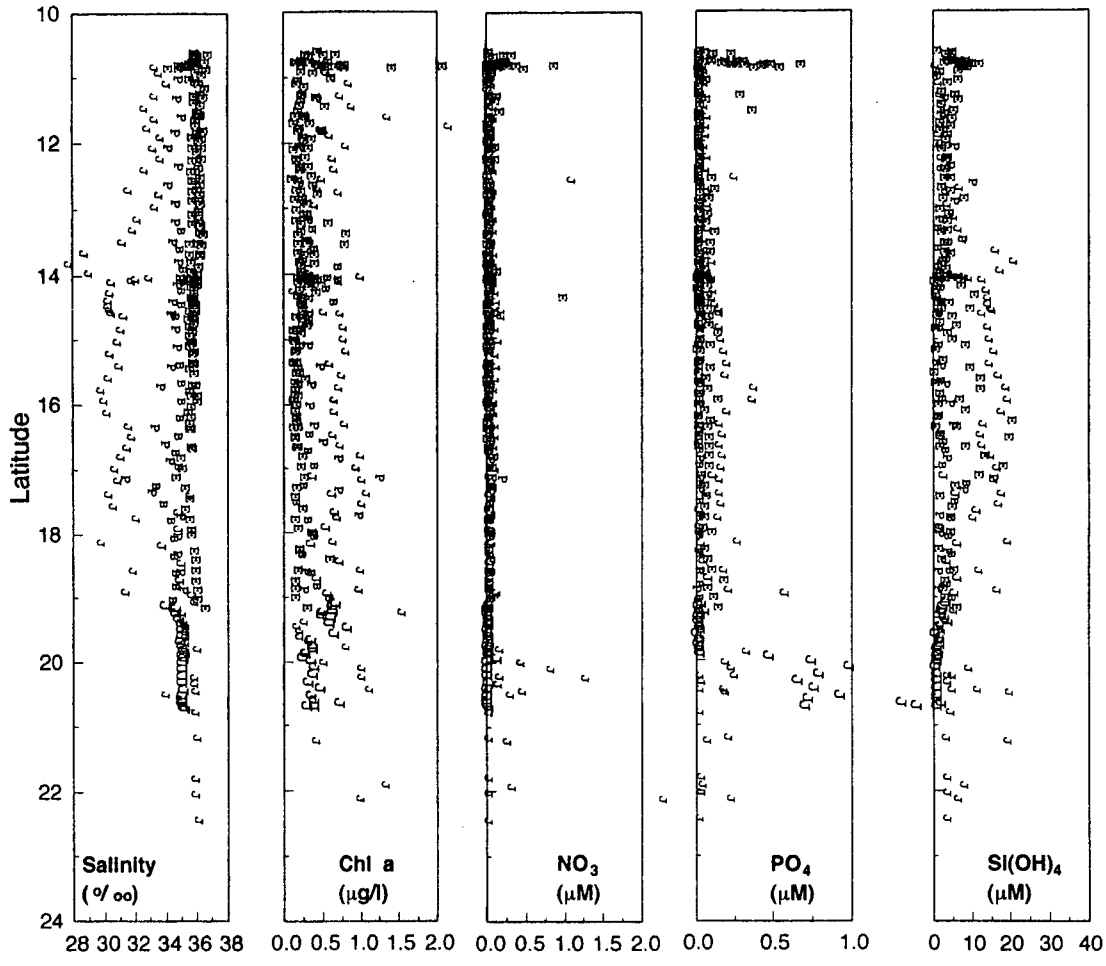


Figure 5 Latitudinal and seasonal variations in salinity, chlorophyll a, nitrate, phosphate and silicate in surface water samples collected on steaming passages in the GBR lagoon between March 1991 and February 1996. Summer samples are identified by closed symbols and winter-spring samples by open symbols. Summer transects between 10° and 19°S were sampled in March 1991 (J) and February 1996 (HB). Source - Furnas unpubl.

Equivalent mixtures of coastal, reef-associated and oceanic zooplankton also occur in GBR shelf waters (Sale et al., 1976; Sammarco and Crenshaw, 1984; Williams *et al.*, 1988; Liston, 1990; McKinnon and Thorrold, 1993). Reef-associated zooplankton are primarily epibenthic in habitat (Sale et al., 1976), either feeding on the reef substratum or migrating into the water column above the substratum during the night to feed. Although frequently found away from reefs, these forms are generally not abundant in open shelf waters. While most zooplankton taxa are widely distributed throughout the GBR (Liston, 1992), assemblages characteristic of "coastal" and offshore or oceanic conditions can be discerned on the basis of relative abundance of taxa (eg. McKinnon and Thorrold, 1993). Within the GBR lagoon, the seaward extension of coastal assemblages are typically related by the dynamic front between coastal and shelf waters (King, 1995) and seasonal discharge dynamics of regional rivers (Sammarco and Crenshaw, 1984; McKinnon and Thorrold, 1993). Where upwelling or regional conditions in outer-shelf waters favor the production of larger phytoplankton (eg. Pompey Reefs), regionally enhanced populations of "coastal" copepods may occur (Williams et al., 1988; Liston, 1990).

The nitrogen fixing colonial cyanobacterium *Trichodesmium* is a conspicuous component of GBR phytoplankton communities (Furnas, 1991b). Large, dense blooms of *Trichodesmium* were first reported by Cook as he sailed northward up the GBR lagoon (Beaglehole, 1955). Under calm conditions, dense patches of *Trichodesmium* form on the surface in coastal, outer shelf and oceanic water, though the bulk of the population is usually distributed through the upper part of the water column. *Trichodesmium* population numbers at individual sites vary radically between and within years. Atmospheric nitrogen

fixation rates measured in GBR waters (10-30 pg N trichome per hour; a trichome is a chain of individual cells within a colony which is comprised of several to many 100's of trichomes) are amongst the highest measured worldwide (O'Neil, 1995).

In spite of the prevailing low concentrations of dissolved nutrients in GBR shelf and lagoon waters, regional phytoplankton populations frequently exhibit high in situ growth rates (Figure 6). Maximum growth rates differ considerably between species, but the phytoplankton community (as chlorophyll *a*) and all important species or groups (except *Trichodesmium*) have the potential to grow at rates exceeding 1 doubling per day. Small diatoms, in particular, are capable of very high in situ multiplication rates (> 3 doublings per

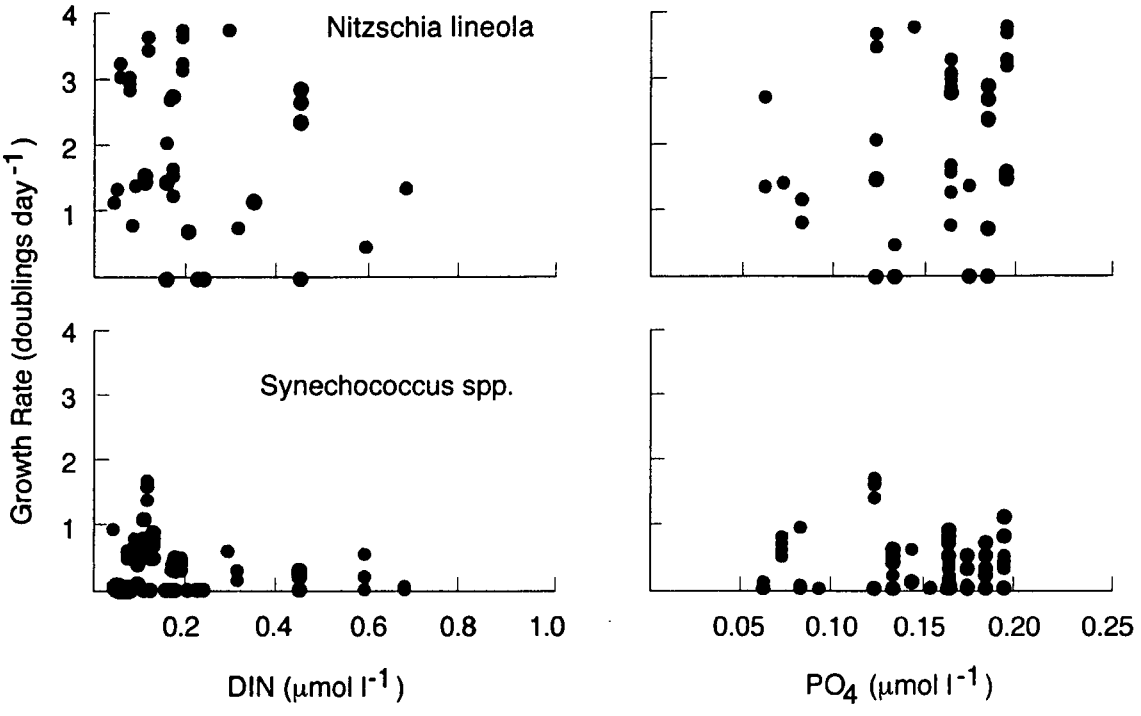


Figure 6 Measured in situ growth rates of acommon diatom species (*Nitzschia lineola*) and the pelagic cyanobacterium, *Synechococcus* sp. in GBR waters in relation to in situ concentrations of dissolved inorganic nitrogen (DIN = NH_4+NO_2+NO_3) and phosphate (PO_4). Source - Furnas, 1991a

day; Furnas, 1991a). All of the abundant or prominent bloom-forming diatoms and picoplankters appear capable of achieving near-maximal growth rates at DIN and PO_4 concentrations only slightly above the very low ambient levels normally found in GBR waters. Under normal conditions, however, total DIN stocks are only sufficient for approximately one doubling of phytoplankton biomass. In contrast, sufficient P and Si are usually present for several to many biomass doublings. High in situ growth rates can only be sustained by equally rapid grazing of the phytoplankton produced and continual mineralisation of particulate organic matter. Where significant amounts of nutrients, particularly N, are introduced to shelf waters by floods, upwelling or disturbance events, resident phytoplankton populations have the capacity to develop significant blooms within 1-2 days (Figure 7). These blooms are characteristically dominated by diatoms (> 10 µm size raction; Revelante and Gilmartin, 1982; Furnas and Mitchell, 1986) which are a preferred ood for herbivorous copepods and pelagic larvae. Event-associated enhancements of phytoplankton and zooplankton production may therefore be an important factor in the growth and survival of pelagic larvae of reef fish and other organisms.

As a consequence of the high ambient water temperatures, high insolation and rapid specific growth rates of resident phytoplankton, the GBR shelf ecosystem is very productive (Figure 8). We estimate the GBR has a daily primary production rate (weighted for season, latitude and reef cover) close to 1 g C m^{-2} (2.22 x 10^5 metric tons daily for the full shelf). This

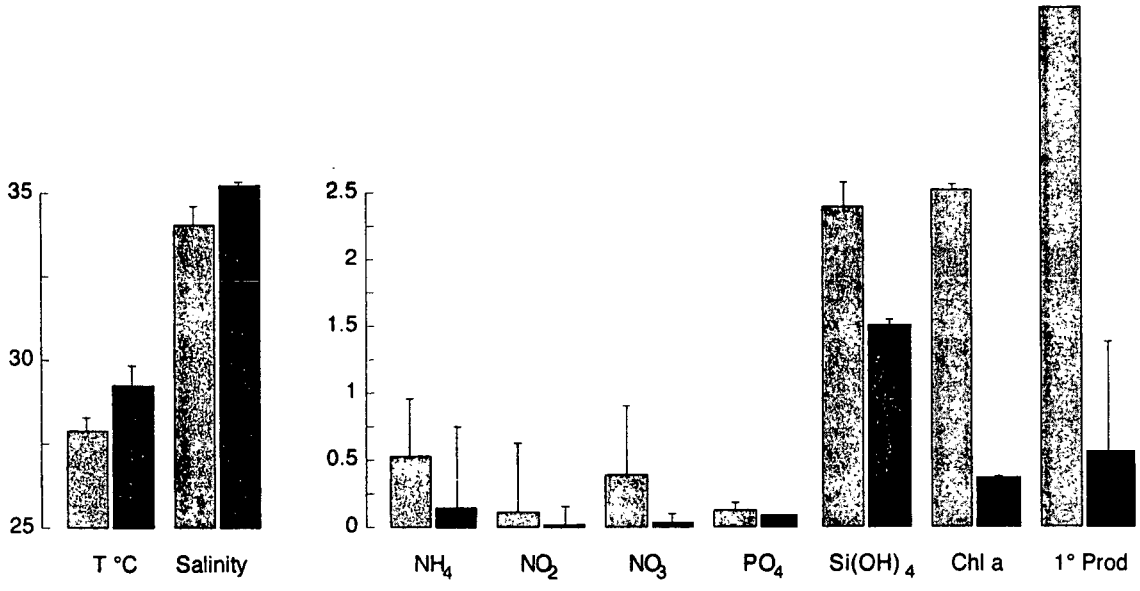


Figure 7 Mean values of water temperature (°C), salinity (ppt), dissolved inorganic nutrients (μM), chlorophyll a (μg l^{-1}) and water column primary production (gC m^{-2} day^{-1}) measured in central GBR lagoon and outer-shelf waters immediately following cyclone Winifred (shaded bars) and under normal summer conditions (February 1987: solid bars). Error bars indicate 1 standard deviation about the mean. Source - Furnas *unpubl.*

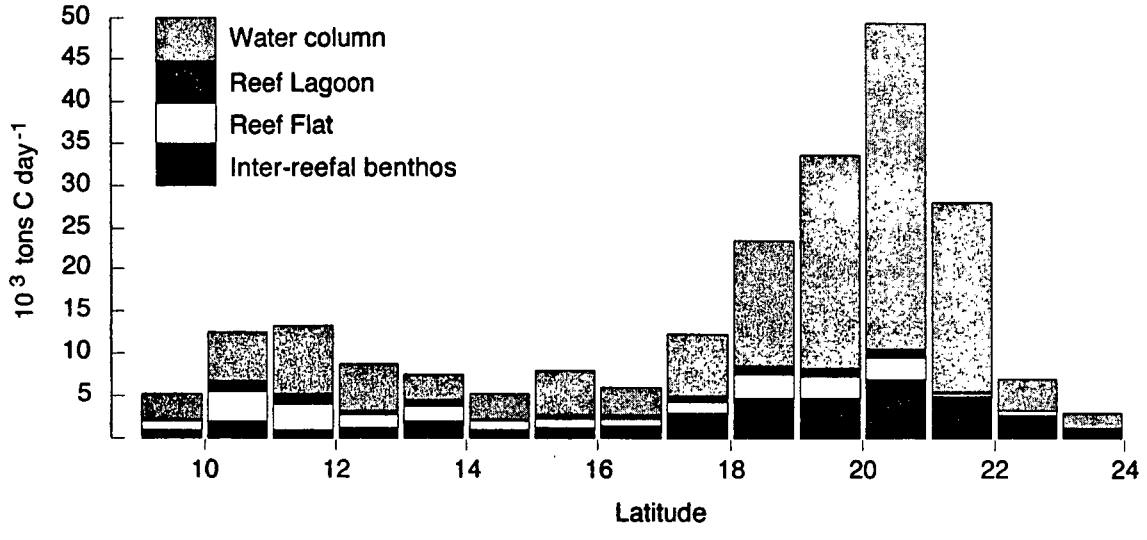


Figure 8 Average daily primary production of the GBR shelf ecosystem within 1° latitude bands. Estimates are areally and seasonally weighted. Source - Furnas, unpubl.

translates to an average annual primary production of ca. 360 g C m^{-2}, similar to rates measured in other "productive" temperate shelf and estuarine ecosystems (eg. Nixon, 1986). We estimate that approximately 72 percent of total shelf production is attributable to phytoplankton (ca. 0.67 g C m^{-2} day^{-1} for open waters), 11 percent to benthic algae on reef surfaces or sediments and provisionally, 17 percent to algal and seagrass populations on the inter-reefal benthos (91 percent of total shelf area). Picoplankton (< 2 μm size fraction) contribute approximately 2/3 of the total phytoplankton production. Shelf production varies considerably with latitude, both as a consequence of shelf area and productivity per unit area. The highest normal areal rates of phytoplankton production (≥ 1 g C m^{-2} day^{-1}) are typically measured in the far northern and southern GBR. Very high water column primary production rates (>3 g C m^{-2} day^{-1}) have been measured in coastal and mid-shelf waters following cyclonic disturbances and near Raine Island as a result of episodic

shelfbreak upwelling (Furnas, unpubl.). Largely because of a general lack of data on in situ production by benthic algae (macro and micro) and seagrasses on the inter-reefal benthos, considerable uncertainty remains about the estimate of primary production in benthic habitats. Means of daily production/biomass (P/B) ratios for GBR phytoplankton vary with latitude and range from 23 to 135 g C g chl a^{-1} day^{-1} (shelf mean = 53, shelf median = 40). For healthy phytoplankton which normally have C/Chl ratios on the order of 50 g/g, this range of P/B ratios again implies that the biomass of resident phytoplankton populations is doubling and must be consumed on a daily basis. Phytoplankton biomass thus appears to be constrained by grazing pressure and low ambient concentrations of nitrogenous nutrients in shelf waters. In the event of significant nutrient additions, for example from a resuspension event or flood, biomass can increase rapidly (2-fold per day).

What is the fate of this primary production? Organic matter produced by phytoplankton enters a variety of benthic and pelagic food webs. Benthic filter feeding assemblages on reefs have the capacity to capture a wide range of algae, including picoplankters from waters flowing over them (Ayukai, 1995; Fabricius et al., 1995); however, only a small fraction of total shelf water volume directly impinges upon reef surfaces. Most must be consumed within the water column.

Copepods are the dominant metazoan grazers in GBR waters (Liston, 1990; McKinnon, 1991) and feed primarily upon algae and detritus particles > 10 µm in size. As a result, the bulk of primary production which is derived from very small phytoplankters (< 2 µm) is not directly available to copepods. These small algae are largely consumed by protozoan grazers or fall prey to viruses. As a result, a significant proportion of picoplankton primary production and associated nutrients cycle within a "microbial loop" (eg. Fuhrman, 1992). Many of the protozoan grazers feeding upon the picoplankters are suitable prey for larger filter feeders, but such multi-step food webs are not ecologically efficient. Copepod-based food webs are most productive in estuaries and zones of the GBR where local conditions favor the production of larger phytoplankton (eg. diatoms). In open shelf waters, higher abundances of copepods typically occur in association with (diatom-dominated) phytoplankton blooms (e.g. Williams et al., 1988; McKinnon and Thorrold, 1993) At ambient temperatures, the dominant small copepods have potential generation times on the order of 1 week. However, for much of the time, secondary production by copepods in the GBR lagoon is food limited (McKinnon and Thorrold, 1993).

Direct flux measurements with sediment traps (Furnas et al., 1995) indicates that organic matter with N and P contents ranging between 25 to 100 percent of particulate stocks within the water column fall to the bottom each day. Higher sedimentation fluxes (>100 percent of water column stocks) are episodically measured in the nearshore zone following resuspension events. Much of this organic matter is detritus resuspended from the bottom. At present, relationships between regional productivity, organic sedimentation and water column mixing are not well established. Direct measurements of nutrient fluxes from the benthos (Alongi, 1989) indicate that benthic communities recycle 10 to 20 percent of the nutrients needed to sustain average daily primary production rates in the central GBR.

What are the sources of nutrients which affect water quality and sustain pelagic food webs in the GBR? Most of the nutrients supporting plant communities are derived from mineralisation of organic matter, either in the water column (Furnas *et al.*, 1995) or by soft-bottom communities (Alongi, 1989). Nutrient materials come into the GBR from a variety of external sources, including: river runoff (see Mitchell and Furnas, this volume), shelfbreak upwelling (Furnas and Mitchell, 1996), rainfall (Furnas et al., 1995), sewage (Brodie, 1991) and fixation of atmospheric nitrogen (Larkum et al., 1988; O'Neil, 1995).

At present, a comprehensive effort to identify and quantify all significant nutrient fluxes within a shelf-scale budget has only been attempted in the central GBR (16-19°S: Furnas et al., 1995). While significant gaps remain in our understanding of nutrient fluxes, the relative magnitude of known fluxes and their relation to shelf nutrient stocks can be assessed (Figure 9). All of the major external sources of nutrients which sustain shelf production are either episodic, seasonally variable or are initially delivered to one boundary of the shelf system. River runoff and most of the sewage enters the shelf system via the shallow nearshore band while upwelling occurs along the seaward margin of the reef. Inputs of N from biological fixation and rainfall are widely distributed, but variable in time. Of the external sources which have been quantified to date, rivers are the major external source of

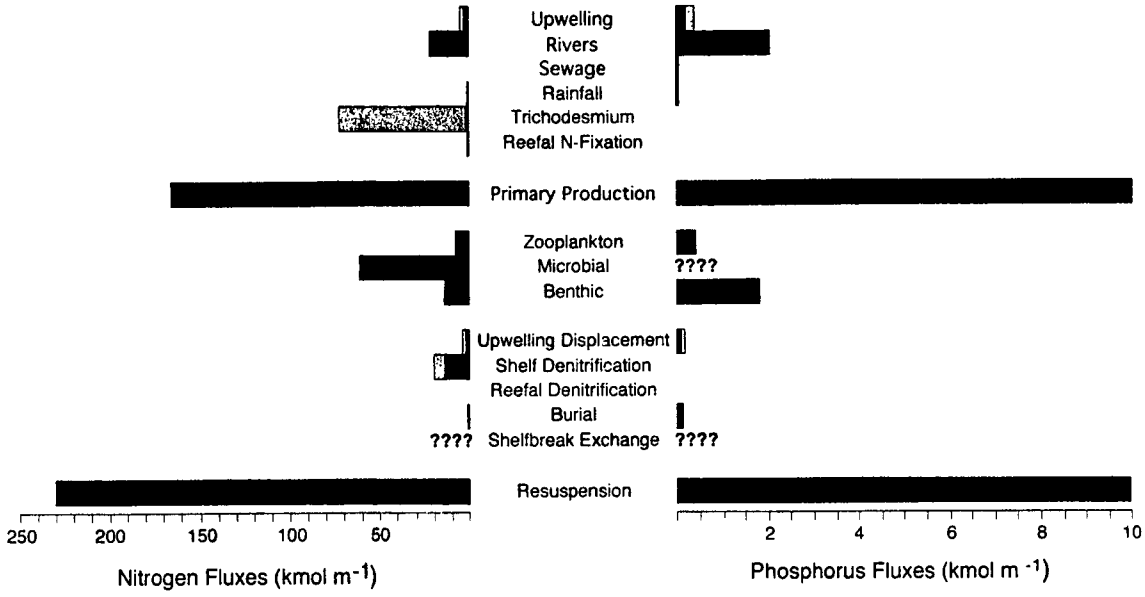


Figure 9 Estimated annual fluxes (kmoles per longshore metre) of nitrogen (Left) and phosphorus (Right) on the central GBR shelf (16°-18°S). Shaded bars indicate known inter-annual variability or uncertainty related to variability in key flux parameters. Fluxes are normalized for area and season. Replotted from Furnas et al., 1995.

N and P entering shelf waters. Most of this input occurs during brief flood events (Mitchell and Furnas, this volume). For the central GBR (16-19°C) where the most comprehensive

measurements of river nutrient fluxes have been made, we estimate that annual river N and P fluxes are on the order of 3.8 and 2.3 times existing water column N and P stocks within the GBR lagoon (depths <30 m). Runoff from large monsoonal rainfall events can lead to 2-4 fold increases in water column chlorophyll concentrations which are roughly indicative of changes in nitrogen stocks. At the lagoon scale, annual sewage inputs are negligible (< 3 percent of lagoonal N and P stocks), but can be significant within local settings or embayments (Anon, 1991). Upwelling events result in the import of NO_3 and PO_4 stocks 1.5-6 times the amounts normally present in outer shelf waters, but concurrent displacement exports of organic N and P (particulate and dissolved) to the Coral Sea reduce the net effect of these events on shelf nutrient stocks considerably (< 2-fold).

Has water quality in the GBR lagoon been changing? A variety of evidence (Moss *et al.*, 1992) suggests that sediment and associated nutrient runoff to the GBR lagoon has increased several-fold over the last century as a result of grazing and farming activities. Likewise, increasing amounts of fertilizer are being applied to fields and pastures in catchments draining into the GBRMP (Pulsford, 1996). This has led some workers to suggest that the GBR lagoon has become eutrophied (Bell and Gabric, 1990, 1991). Examination of the longest (22 years) and most consistent data set available (Brodie *et al.*, *in press*) for the central GBR lagoon (17-20°S) fails to show evidence for chronic eutrophication (**Figure 10**). Overall, no change in mean chlorophyll concentrations appears to have occurred. However, episodic 2- to 3-fold changes in mean water column chlorophyll concentrations were observed. The large scale of these changes (10^3 km^2) strongly suggest natural causes are responsible. These abrupt shifts suggest that comparisons between relatively short-term data sets may not be reliable.

Implications for Management

- The GBR "lagoon" and adjacent inter-reefal waters are a large, hydrodynamically open system. Dissolved and particulate nutrient concentrations in outer-shelf and lagoon waters are generally very low. Abrupt, large-scale changes in water quality may

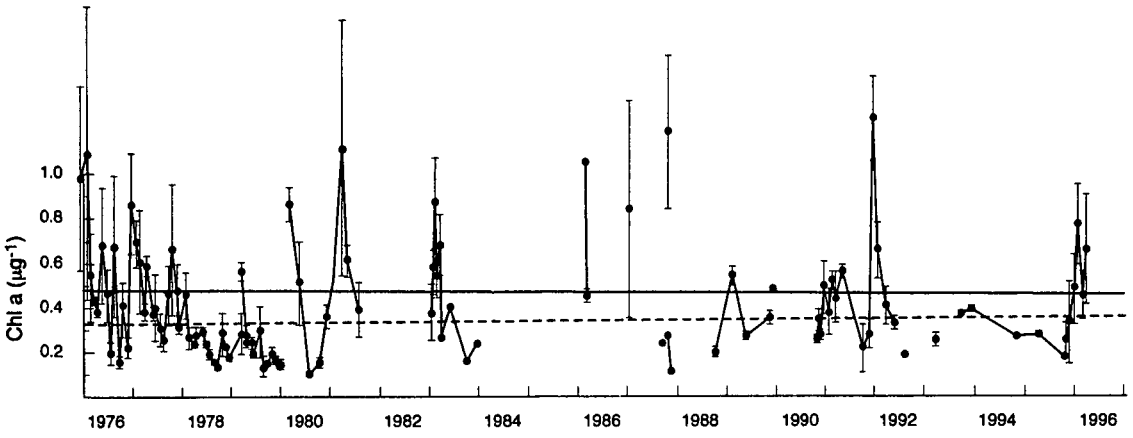


Figure 10 Mean (± 1 standard deviation) water column chlorophyll concentrations measured in the central GBR lagoon over a 22-year period by AIMS oceanographers. Individual data points are averages for all stations occupied on individual cruises. Solid line - mean of summer (October-April) stations. Dashed line - mean of winter (May-September) stations. From Brodie et al., (in press).

occur as a result of floods or cyclones, but such changes are temporary. On the broad scale, deteriorations of water quality will be slow to develop (decades) but are likely to be equally slow to improve due to storage of nutrients in sediments and biomass.

- Because of hydrodynamic factors, shelf waters in the nearshore zone may be intermittently isolated from shelf waters and remain trapped against the coast. As a consequence, coastal reefs and ecosystems experience water quality conditions considerably different from offshore reef ecosystems.
- Natural ecosystem recycling processes are the major source of nutrients to GBR shelf ecosystems.
- Both the absolute amount of nutrients added to shelf waters and their relative contribution to shelf stocks vary with latitude, season or events. Rivers are the major external source of nutrients (N and P) entering the GBR lagoon for which estimates are quantified to date. Annual runoff fluxes are typically several times stocks normally present in nearshore and lagoonal waters.
- N_2 fixation by *Trichodesmium* may be a major natural source of nitrogen for shelf waters, but estimates are constrained by the lack of knowledge about abundances in GBR waters.
- Despite normally low nutrient concentrations in shelf waters, the GBR shelf is moderately to highly productive due to rapid growth of resident phytoplankton. Only a small fraction of this production is immediately available, however, for transfer to higher trophic levels (eg. zooplankton, fish). This small proportion, however, may be critical for the support of planktonic larvae of fish and benthic fauna during pelagic dispersal.

ACKNOWLEDGMENTS

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Soft-bottom benthic communities and processes in the Great Barrier Reef lagoon

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ABSTRACT

Despite their importance as food for many lagoonal organisms, and as consumers and regenerators of matter and nutrients derived from marine and terrestrial sources, the structure and function of soft-sediment communities within the Great Barrier Reef lagoon is poorly understood. Most data is derived from work conducted in inshore embayments in the central section of the lagoon. The available data suggest across-shelf changes in abundance, community composition and diversity, and low nutrient concentrations but rapid recycling. In inshore areas receiving large inputs of detritus from adjacent rivers and mangrove forests, a low-diversity benthic regime persists, dominated by bacteria and small-sized, surface-dwelling polychaetes and amphipods; sediment remixing occurs mainly as a result of physical processes as bioturbation is restricted to surface sediment layers. A preliminary carbon budget for one such embayment off Hinchinbrook Island indicates that nearly 80% of the organic carbon settling to the bottom is mineralised immediately by bacteria; biomass equivalent to < 3% of bacterial productivity is directly consumed by larger organisms. The size spectrum of the benthic community suggests that these assemblages are perpetuated by a variety of disturbances and by variable food quality. Whether or not the mid-shelf or inter-reef benthic communities and nutrient recycling processes are similarly affected by disturbances awaits a coordinated, multidisciplinary approach. Being able to distinguish between natural and human-induced disturbances is crucial to being able to manage potentially damaging impacts on the marine park.

Introduction

The uniqueness of the Great Barrier Reef lagoon is evident when viewed on a global scale. The distribution of unconsolidated carbonates on the world's continental shelves shows that they are not restricted to subtropical and tropical latitudes, but comparatively few examples of fully-developed, open or rimmed carbonate shelf settings exist. Open carbonate shelves inclined seawards with no physical barriers are found off sections of western Florida, the eastern Gulf of Mexico, Yucatan, the western North Atlantic, northern Australia and the Persian Gulf, whereas rimmed (or 'protected') carbonate shelves are found in the Bahamas, Florida, Cuba, Belize and the Great Barrier Reef. The Great Barrier Reef and Belize shelves, however, are the only two examples of clastic-influenced, rimmed shelves (Sellwood 1986).

The Great Barrier Reef shelf runs nearly 2000 km along the Queensland coast, with the shallow (most 40 m depth) lagoon between the shore and reef proper widening southwards. Water circulation varies greatly seasonally and spatially, being topographically influenced within the reef proper and within the lagoon (Wolanski 1994). Subsurface intrusions occur at the shelf break, upwelling cool, nutrient-rich Coral Sea water into the shelf which episodically intrudes into the lagoon (Andrews and Furnas 1986, Furnas and Mitchell 1996). Inshore, variations in river flow are directly related to rainfall, most of which falls from monsoonal rain depressions in summer. The mixing of riverine, estuarine and shelf waters is complex. In the dry season, high evaporation results in a salinity maximum zone in estuaries, particularly in mangrove-lined systems of the northern and central sections (Wolanski 1992). The movement of tidal water is slowed in these estuaries partially as a result of friction induced by the presence of mangrove vegetation; this time lag results in significant trapping of water and to the formation of a coastal boundary layer in which there is limited mixing between inshore and shelf water (Wolanski et al. 1990). In summer, this boundary layer breaks down, but coastal and shelf waters become stratified, with river plumes staying close to the coast and moving northwards (Hamilton 1994). The transport of estuarine water and terrestrial material is limited mainly to inshore, except during cyclones

when clastic material can be transported to the mid- and outer-shelf regions and offshore carbonates can be transported shorewards (Gagan et al. 1990).

Nearly 30% of the ~ 270 000 km^2 comprising the Great Barrier Reef shelf is dominated by terrigenous (50% CaCO3) sediments (Belperio and Searle 1988). The remainder of the shelf floor is composed of mixed terrigenous and carbonate deposits across the lagoon, carbonates within and between reefs, and a small percentage of hard-bottom areas. The shift from terrigenous to carbonate sedimentary facies seawards across the lagoon is not gradual (Flood and Orme 1988) due to dominant northwards transport of water and sediment. Fluvial input is the dominant form of sedimentation, averaging 10 tonnes per meter of coastline (Belperio and Searle 1988), but *in situ* production of carbonate by various organisms may be diagenetically significant given that carbonate sediments in the lagoon are biogenic, with little carbonate debris derived from the reef proper. Analysis of the carbonates within the central section of the lagoon shows that the major producers of calcium carbonate are benthic foraminiferans (mainly *Operculina, Amphistegina, Marginopora, Alveolinella* and *Cycloclypeus*), the green alga *Halimeda*, molluscs, bryozoans, echinoids, and, to a much lesser extent, corals (Scoffin and Tudhope 1985). Toward the mainland, there are abrupt increases in concentration of terrestrially derived materials. Within the coastal zone, quartz sand and mud fractions dominate, with a variable fraction of carbonates derived from molluscs and echinoids; coarse and finer sands are most frequently deposited as bars off river mouths merging laterally with sandflats. Seagrass beds proliferate within the lagoon; most are ephemeral and vary greatly in space and time (Lee Long et al. 1993). Naturally, the most extensive and persistent beds are within sheltered lagoonal areas. These shallow subtidal environments give way onshore to extensive mangrove forests in sheltered estuaries and on the leeward side of high islands within the lagoon (Robertson and Alongi 1992). With the exception of large deltaic mangrove systems, such as in the Hinchinbrook Channel and in the Lockhart River, most sedimentary facies within Queensland mangrove forests are remnants of sandy beach ridges.

This overview of the physical settings within the lagoon illustrates the diversity of soft-bottom environments available for colonisation and inhabitation by microbes, meiofauna, macroinfauna and epifauna, including demersal fish and crustaceans. In this review, I will focus on the functional role of these communities, how they fit into the lagoonal ecosystem, and why it is important to consider them in the management plans for the marine park.

Patterns of faunal abundance, diversity and trophic structure

Except for a few anecdotal studies, most work on the structure and function of soft-bottom benthic communities in the Great Barrier Reef has focused on the central and northern sections of the lagoon, particularly from the Hinchinbrook Island region south to the Burdekin River. Extensive benthic studies have been conducted in lagoons of individual reefs, such as on Davies Reef and on One Tree Island (Riddle 1988; Alongi 1989a; Riddle et al. 1990; Hansen and Skilleter 1994).

Work on epibenthic community structure and diversity has dealt mainly with species patterns in relation to sediment type and location. The studies of Birtles and Arnold (1983, 1988) and their colleagues (Lemmens et al. 1995) show that a clear discontinuity exists between the inshore assemblages and the mid-shelf communities at about 20–25 meters depth across the shelf in the central section of the lagoon off Townsville. Inshore epifaunal echinoderm and mollusc assemblages are less abundant and less species-rich than those further offshore. An analysis of echinoderm feeding types indicates a greater proportion of carnivores, and to a lesser extent, of detritivores and browsers inshore, with a trophic shift across the shelf to a dominance of suspension-feeders. A similar analysis of molluscs shows that deposit-feeders dominate on the inner shelf; further offshore, the proportion of carnivores increases slightly.

Both total abundance and number of epifaunal species peak at mid-shelf, attributed to colonisation and settlement of solitary and clonal organisms on a wide variety of biogenic debris and mixtures of seagrasses, algae, rubble, gravel and sand deposits. Pockets of coarse biogenic rubble and coralline algae support a large number of hard-bottom dependent, suspension-feeders, such as crinoids, dendrochirote holothurians, siliquariid gastropods and some bivalve species. The predominance of suspension-feeders on the outer shelf was ascribed to increased bottom stability, lower turbidity and greater suspended food than at

the more turbid, frequently disturbed inner shelf (Birtles and Arnold 1988). This suggests a close trophic linkage between benthos and plankton at the mid- shelf and inter-reef areas of the lagoon. A detailed study of the inshore region's major epifaunal predators, the sea stars *Astropecten zebra* and *A. velitaris*, found that both species subsist mainly on bivalves and gastropods (Lemmens et al. 1995), with the latter species also feeding on crustaceans. There was little evidence of competition between both species, although they demonstrate limited spatial overlap. Neither species frequent areas 3 m depth due to very high turbidity and sediment instability.

Two studies conducted in the far northern section of the Great Barrier Reef (Pitcher et al. 1992; Blaber et al. 1993) similarly suggest a clear spatial distinction between epibenthos, demersal fish and crustacean communities inhabiting different sediment types and hard substrates. In the Torres Strait, an extensive survey found that epibenthic macrofauna and pearl oyster abundance varies greatly, with greatest numbers and diversity on hard substrates (Pitcher et al. 1992). Further south, an effects of prawn trawling study is underway (Blaber et al. 1993) in which preliminary results indicate clear differences in epifauna, demersal fish and prawn community structure between inshore and inter-reef areas; simulated trawling was found to affect different benthic groups differently. For instance, cephalopod abundance increased, but gastropod and echinoderm numbers decreased, in the disturbed areas compared to control sites.

Further south in the central lagoon, epibenthic communities are neither abundant, nor rich in species, in some inshore and estuarine areas. In the vicinity of Hinchinbrook Island, Daniel and Robertson (1990) found that the epibenthos of mangrove creeks and of open embayments 5 m depth are taxa poor (0–33 taxa per trawl) and low in numbers (2 animals m^{-2}). Lowest densities occurred during the wet season. This is attributed to the greater tidal amplitudes and flushing of creeks and rivers of detritus and associated epifauna, as well as resuspension of sediment in shallow subtidal embayments. Variation in the amounts of mangrove detritus recovered in nets explained a significant amount of the variance in animal densities, presumably reflecting the fact that some organisms such as penaeid shrimps use the detritus for food and refuge from predatory fish. However, the low densities and variety of epifaunal taxa in this inshore area are attributed mainly to the poor nutritional quality of river-and mangrove-derived organic matter, and frequent physical disturbance of the seabed.

Macroinfaunal and meiofaunal communities show similar across-shelf patterns in the central lagoon. In mangroves and in intertidal mudflats and sandflats, macroinfauna and meiofauna numbers and diversity are usually low; exceptions are sheltered areas with high rates of seagrass and benthic microalgal production (Robertson and Alongi 1992). As potential food items are abundant in these intertidal areas, the sparseness of such assemblages has been attributed to factors such as intense sediment disturbance, physiological stress of high temperatures, desiccation and variable salinity, and chemical defenses of plants. Further offshore, densities recover somewhat, but are still low compared to benthic communities on other continental shelves. A study across the central shelf revealed that the macroinfauna attain peak abundance (5406 individuals m^{-2}) and biomass (3.37 g AFDW m^{-2}) at mid-shelf (Alongi 1989b). The communities are dominated by small, tubiculous deposit- and suspension-feeding polychaetes and burrowing and tube-dwelling crustaceans. Meiofauna are also most abundant (3255 individuals m^{-2}) at mid-shelf; biomass exhibits a similar pattern, peaking at 3130 g DW 10 cm^{-2}. Nematodes dominate the meiobenthos. Further study of their community structure (Tietjen 1991) reveals that species diversity (Shannon information function, H = 3.35–4.08) is higher on the shelf proper than nematode communities on adjacent reefs, mangroves (Alongi 1989a) and on other continental shelves (Heip et al. 1985), approximating diversity and species richness characteristic of the deep sea. Such extraordinarily high diversity and richness was attributed to high habitat heterogeneity, a rich bacterial flora, warm climate and intermediate levels of disturbance. Trophically, these assemblages are dominated by deposit-feeders and epistrate feeders, with no clear change in trophic composition across the shelf.

A carbon inventory and budget: relative impacts of outwelling and physical disturbance

Functional aspects of benthic communities in the Great Barrier Reef lagoon have rarely been studied. The most complete analysis of benthic processes and carbon flow is the study

of the influence of outwelling of mangrove litter on the benthic regime off Hinchinbrook Island out to the inter-reef area between Otter and Britomart Reefs in the Central Section.

Long-term investigations of mangroves on Hinchinbrook Island indicate that net annual exchange of most dissolved materials between mangroves and adjacent coastal waters is a net import of DOC, inorganic nitrogen and phosphorus, but a substantial export (14,337 kg yr^{-1}) of silica (Boto and Wellington 1988; Alongi 1996). The import is driven by high rates of forest primary production and microbial activity; about 95% of the net annual import of total dissolved nitrogen and roughly 66% of the net annual import of total dissolved phosphorus is taken up by various forest components (Alongi 1996). Dissolved organic carbon is retained within mangrove sediments, with net import of DOC driven by very high rates of bacterial production (Boto et al. 1989). This indicates that mangrove forests in this region are a highly efficient sink of dissolved C, N and P, and a source of Si.

These forests import most dissolved materials, but export particulate matter on the order of 25 000 tonnes C yr^{-1} to adjacent bays and channels in the lagoon (Robertson et al. 1988). This material is composed mostly of refractory litter such as pieces of aged leaves, bark, twigs, shoots, propagules and flowering parts. This material has a mean C:N ratio of 52:1 (Alongi et al. 1989), so is of poor nutritional quality, but does contribute greatly to particulate nutrient concentrations in the inner shelf (Alongi 1990a). Litter accumulates and mixes into the sediments, most heavily in quiescent areas such as in the central subtidal region of Hinchinbrook Channel. The impact of outwelling on nutrient concentrations in the porewater is less clear, obscured by variations with sediment type and contributions from river run-off.. Nutrient regeneration rates do not correlate directly to litter accumulation, and additions of mangrove detritus to sediments free of litter do not affect rates of nutrient regeneration (Alongi 1990a).

Densities of protozoans, meiobenthos, macroinfauna and epibenthos are low across the entire inner shelf and do not correlate with standing amounts of outwelled material (Alongi 1990b; Daniel and Robertson 1990; Alongi and Christoffersen 1992). Ciliate and large (20 m) flagellate densities range from 23 to 511 cells cm^{-3} and from 40 to 806 cells cm^{-3}, respectively (Alongi 1990b). Densities of nanoprotozoans (mostly flagellates) range from below detection limits to 261 103 cells cm^{-3}. There is no discernible seasonality. Vertically, densities of protozoans decline with increasing sediment depth, but low-density, subsurface pockets of sarcodinids, amoeboflagellates, and yeasts and yeast-like cells exist in most inner shelf deposits. Variations in abundance can be attributed to sediment type rather than standing amounts of mangrove litter. Laboratory experiments indicate that litter is not a nutritious food for protozoans.

In contrast, macroinfaunal densities (mean: 1452; range: 308–3950 individuals m^{-2}) correlated negatively with standing amounts of detritus. Biomass (range: 0.17–6.31 g AFDW m^{-2}) did not relate to outwelling. There is no clear seasonality for either macroinfauna or meiofauna. As noted earlier, the macroinfauna is composed of small-sized, surface-dwelling organisms; there are no large, deep-dwelling equilibrium species in this or in other areas of the central lagoon (Lemmins et al. 1995). Meiofaunal abundance is highly variable, with total densities ranging from 295 to 1568 individuals 10 cm^{-2} and a grand mean of 715 individuals 10 cm^{-2} (Alongi and Christoffersen 1992). The total fauna correlated only with redox potential, suggesting a greater impact of sediment type than outwelling.

Nematodes comprise most (73%) of the total fauna. Species diversity (H, Shannon information function) ranges from 2.02 to 3.13, which is significantly lower than nematode diversity further offshore (Tietjen 1991). Both species diversity and evenness (J) correlate negatively with detritus standing stocks, implying that the presence of mangrove litter has a negative impact on the number of species. This negative effect may be due to physical smothering or to leaching of soluble tannins from the litter. The latter is most likely considering that tannin concentrations in the porewater correlated positively with the standing amounts of litter and constitute a large (~30%) of the sedimentary DOC pool (Alongi et al. 1989). Soluble tannins inhibit meiofaunal population growth (Tietjen and Alongi 1990).

Low food availability is only one possible cause for the low densities of benthic organisms on the inner shelf. Two other possible causes are (1) physical disturbance and (2) heavy predation pressure. The latter is less likely because of the low numbers of epifauna and bottom-dwelling fish in this area (Daniel and Robertson 1990). Indeed, trophic interactions among benthic size groups have not been experimentally verified, although presumably affect food chain dynamics.

Some evidence exists suggesting that physical disturbance plays a key role in regulating the structure and function of benthos on the inner shelf. X-radiographs consistently show that the sedimentary fabric in this region consists of shell-gravel bands and cross-bedding features attributable to erosional episodes (Snelgrove and Butman 1994). This area is shallow, above the shoaling depth for wind waves and tidal scouring. Summer cyclones, storms and wet season floods are capable of resuspending and transporting sediments in the lagoon as exemplified by the effects of Cyclone Winifred which resulted in clastic mud drapes out to 30 km from the coast (Gagan et al. 1990).

Tidal-induced erosion, resuspension and deposition cycles are more likely to be frequent than climatic disturbances. When spring tides (up to 3.8 m) coincide with low intervals of sea-level (which oscillates up to 35 cm), scouring, resuspension and transport of sediments, particularly at the very shallow, least sheltered sites (< 6 m depth), does occur. Such events can occur several times a year, as they may not be solely dependent on astronomical tides. Erosion may be magnified by lateral trapping of tidal water in the mangrove forests, leading to asymmetry of water exiting the creeks as water is entering with the incoming tide. The 210Pb study of Torgersen and Chivas (1985) in the same area also supports the idea of significant sediment disturbance. They calculated mixed-layer thicknesses of from 5 to 30 cm in these deposits. This agrees with the X-radiographic evidence which shows large pockets of buried litter to these sediment depths.

Unlike the protozoan and metazoan benthic communities, bacterial assemblages in these inner shelf deposits are abundant and metabolically active (Alongi et al. 1989; Alongi 1990b, 1992, 1995). Averaged over stations and seasons, bacterial densities in surface sediments range from 0.5 to 20.8 1010 cells g^{-1} sediment DW, declining with increasing sediment depth to 2.9 to 38.1 109 cells g^{-1} sediment DW. However, vertical profiles of tritiated thymidine uptake and specific growth rates show an actively growing bacterial flora to at least 20 cm depth. There are seasonal differences, with greater bacterial activity in warmer months. These rates of bacterial growth are rapid enough to sequester all available porewater carbon. Unless sediments are poisoned with mercury, there is no significant release of DOC despite a concentration gradient suggesting net release. Release rates from poisoned sediments average 375 mg C m^{-2} d^{-1} (Alongi et al. 1989). In agreement with the thymidine data, oxygen consumption rates relate positively with standing amounts of litter, ranging from 8.7 to 60.2 mmol O2 m^{-2} d^{-1} (Alongi 1990a).

Why are bacteria so abundant and productive in this region, but larger benthos are not? The answer lies in considering the consequences and effects of physical disturbance as well as the outwelling of mangrove detritus and other available foods. First, an inventory of the biomass and estimates of production of the different size groups (table 1) highlights the clear

Table 1. Carbon biomass and production estimates of benthic size groups inhabiting Missionary Bay sediments to a depth of 20 cm. Data compiled from Daniel and Robertson (1990), Alongi et al. (1989), Alongi and Christoffersen (1992), Alongi 1990b, 1992, and using maximum P:B ratios in Alongi and Robertson (1995).

Group	Biomass (g C m^{-2})	Production (g C $m^{-2}yr^{-1}$)
Bacteria	8.2	350
Microalgae	0.1	11
Protazoa	0.05	1
Meiofauna	0.5	7.5
Macroinfauna	0.9	2.7
Epifauna	0.2	0.4

dominance of heterotrophic bacteria in these sediments. Bacteria account for ~82% of total benthic biomass. Moreover, they account for about 94% of total benthic production. Of course, most of these estimates are crude, but nevertheless underscore the relative importance of bacteria to benthic processes. Second, unlike metazoans, bacterial growth is rapid and generation times are short, so they are much better adapted to resist or recover from sediment disturbances. Third, bacteria possess a suite of extracellular enzymes that can solubilise a great range of substrates; over the long-term, many bacterial types can eventually mineralise substrates that are considered refractory, such as some humic compounds (Susic and Alongi 1996).

Physical disturbances may play an important role in determining the major bacterial pathways of organic matter decomposition and sediment chemistry. Unlike other organic-rich sediments of identical grain size, these lagoon deposits often lack measurable quantities of hydrogen sulfide and iron monosulfides to a depth of 20 cm. This is supported by visual observations in that these sediments are usually brown to olive in colour, rather than black which is imparted by the presence of iron monosulfides formed as a by-product of sulfate reduction. Rates of sulfate reduction in these sediments can be equivalent to those measured in temperate deposits of identical grain size and organic content (Alongi 1995).

If this is so, why are there no iron monosulfides or free hydrogen sulphides in these surface deposits as there are in similar temperate sediments? The most likely answer is that episodic, physical disturbance of sediments inhibits the buildup of reduced end-products of anaerobic decomposition. Such by-products are likely to be either oxidised and bound to solid-phase elements, or released to the overlying water column when sediments are resuspended, or both. Support for this idea comes from a seasonal study of sulfate reduction in this area (Alongi 1995). In the dry season, sulfate reduction rates range from 24 to 31 mmol S m^{-2} d^{-1}. In the wet season, there is a two- to three-fold decline in rates of sulfate reduction (range: 10 to 13 mmol S m^{-2} d^{-1}). These summer wet season measurements were made during a period of heavy monsoonal rains, squalls and wind-wave action. Such climatic events disturb the sediments leading to less anoxic conditions, as reflected in a large shift in redox conditions. Moreover, the percentage of reduced radiolabeled 35S recovered as acid volatile sulfide (H2S, FeS) ranged from 16–45% in the dry season, but only 15 to 32 % in the wet season. Unlike the pattern of sulfate reduction activity in temperate coastal deposits, there were no clear patterns in the proportion of radiolabel incorporated into the acid-volatile sulfide and chromium-reducible sulfur (elemental sulfur, pyrite) pools. This pattern implies either that most of the reduced volatile end-products are re-oxidised at or near the sediment surface to either sulfate or thiosulfate, or precipitated as a more stable mineral phase, such as pyrite. The latter is more likely considering the high proportion of radiolabel shunted into the chromium-reducible fraction. Such a pattern is more reminiscent of those found in vegetated sediments such as in salt marshes and mangroves, where oxidation by roots and low pH favor rapid formation of pyrite, than in coastal subtidal deposits. This scenario is further supported by porewater and solid-phase distributions and sediment-water solute exchange rates of iron and manganese (Alongi et al. 1993). Vertical profiles of these two metals indicate very low solute concentrations and moderately slow rates of sediment release, compared to solid-phase concentrations. Moreover, the lack of vertical patterns with increasing sediment depth lends further support to the idea that these deposits are physically disrupted.

A preliminary budget of benthic carbon flow (figure 1) in Missionary Bay off the northern end of Hinchinbrook Island illustrates some of the important sources of organic matter fuelling benthic decomposition, and the relative importance of the various aerobic, post-oxic and anoxic bacterial diagenetic pathways. The major organic carbon sources are mangrove litter, phytodetritus and seagrass litter, detritus advected from offshore, and net benthic microalgal production. Macrophyte litter and phytodetritus are by far the large sources, although the relative contribution may change seasonally and, undoubtedly, spatially in the lagoon. Riverine organic matter probably contributes to this pool but data are lacking.

Even assuming that all protozoan and metazoan production is fuelled by detritus rather than the more likely mixture of bacteria and detritus, the secondary production of these groups only equates to net benthic primary production; the vast bulk of organic carbon is consumed by bacteria, and the remainder buried in deeper sediment layers. Of the organic carbon that is shunted through bacterial pathways, 64.5 % is decomposed by sulfate reducers, 29% by aerobic bacteria, and roughly 3% is mineralised by denitrifiers and iron

and manganese reducers, respectively. These are crude estimates, but the budget is not greatly different from the proportion of organic carbon mineralised by such pathways in other coastal sediments (Canfield 1993).

These results from the Hinchinbrook Island region imply that mangrove outwelling and physical disturbances play important roles in perpetuating a benthic regime dominated by bacteria and comprised of small-sized, surface-dwelling metazoans. The lack of large, bioturbating organisms that mix sediments suggests that these deposits exclude all but the most tolerant species to disturbance. This scenario may also be true for the benthos of nearby reef lagoons. Riddle (1988) found that macrobenthos in the lagoons of Rib, Potter, Otter, Noggin, Feather and Gibley Reefs recovered rapidly from the disturbance effects of

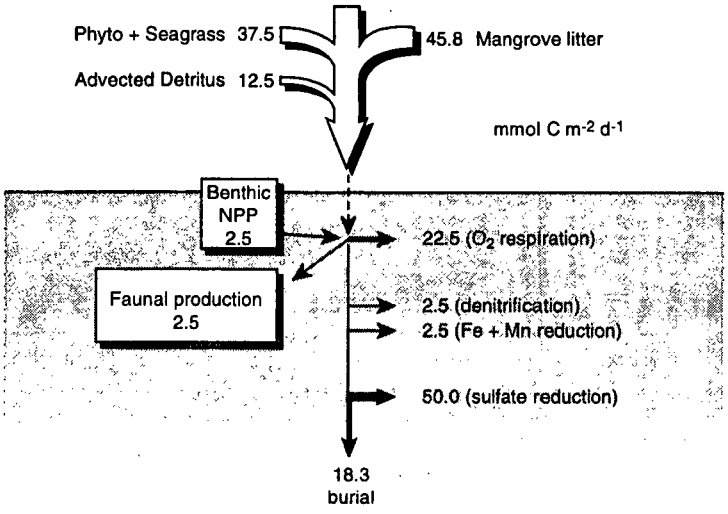


Figure 1. A preliminary budget of benthic carbon flow (mmol C m^{-2} d^{-1}) in Missionary Bay. Compiled from data in Torgersen and Chivas (1985), Furnas et al. (1995), Alongi (1990a, 1995), Alongi et al. (1993) and Robertson et al. (1988). Rates of denitrification and metal reduction were estimated from porewater profiles using diagenetic models in Berner (1980).

Cyclone Winifred. Recent reviews of the soft-bottom benthic literature indicate that physical disturbances from a variety of localised and regional causes, are more common than previously believed in temperate and tropical sedimentary environments (Hall 1994; Snelgrove and Butman 1994).

Knowledge of benthic processes in the Hinchinbrook Island region is not necessarily applicable to other inshore areas of the lagoon. A good example of differences between inner shelf areas is a comparison of the benthos and nutrient standing stocks of Missionary Bay with those of Bowling Green Bay, which is approximately 130 km south of Hinchinbrook Island (table 2). Hansen and Alongi (1991) found that the benthos and nutrients in sediments of Missionary Bay are more abundant than in Bowling Green Bay. They suggested that Missionary Bay not only receives substantial quantities of outwelled mangrove litter, but has greater rates of water-column primary productivity than Bowling Green Bay. This data implies that the enrichment of soft-bottom benthic communities in the Great Barrier Reef lagoon is closely linked to food input, especially from the overlying water column.

Benthic processes across-shelf

A variety of evidence indicates that, excluding the effect of cyclones, terrestrial (including mangrove) influence in the lagoon is restricted to a coastal zone which normally extends

only a few kilometres offshore. This is best reflected in the abrupt changes in sedimentary facies across the shelf (Belperio and Searle 1988). This shift from terrestrial to mainly carbonate facies is also reflected in dissolved and particulate nutrient concentrations, and in specific organic compounds. For instance, Susic and Alongi (1996) found that lignin degradation products

Table 2. Comparison of benthic faunal standing stocks and nutrient concentrations between Bowling Green Bay and Missionary Bay. Values are means; ranges in parentheses. Data from Hansen and Alongi (1991), Alongi et al. 1989, Alongi and Christoffersen (1992) and Alongi (unpublished data).

	Bowling Green Bay	Missionary Bay
Bacteria abundance (No. g^{-1}DW)	2.3 (0.4–7.0 x 108)	5.9 (0.5–20.8 x 1010)
Bacterial production (mg C $m^{-2}d^{-1}$)	273 (32–1115)	612 (23–1854)
Specific growth rates (d^{-1})	0.5 (0.02–3.6)	0.1 (0.004–0.8)
Ciliates (cells cm^{-3})	63 (0–393)	157 (23–511)
Flagellates (cells cm^{-3})	56 (0–371)	185 (40–806)
Meiofauna (No. 10 cm^{-2})	232 (60–608)	715 (295–1568)
Macroinfauna (No. m^{-2})	1052 (179–3120)	1452 (308–3950)
TOC (% DW)	0.7 (0.12–1.1)	1.2 (0.22–2.6)
Total N (% DW)	0.06 (0.02–0.10)	0.009 (0.004–0.12)

vanillic and syringic acids and often p-hydroxybenzoic acid specifically derived from terrestrial plants (including mangroves but not marine macroalgae and phytoplankton) exhibit a rapid decline in concentrations in surface sediments from the coastal zone to the inter-reef area in the central lagoon. This is in agreement with the decline in organic carbon concentrations across the shelf. Stoichiometric ratios reveal that C:N ratios are lower in the offshore sediments than inshore, probably reflecting less deposition of refractory carbon from land and vascular plants, as well as deposition of higher quality detritus. An across-shelf decrease in the C:P ratio reflects preferential retention of total P to increasing concentrations of carbonate.

Nutrient fluxes across the sediment-water interface are dominated by silicate release, followed by nitrogen and phosphate release (Alongi 1989b). Low stoichiometric ratios of N:P and O:N release imply loss of nitrogen via denitrification, and that the processes involved in the short-term (respiration, bacterial productivity) and longer-term (dissolved inorganic nutrient fluxes) decomposition of organic matter are not closely linked. Indeed, rates of surface respiration and bacterial productivity do not correlate with nutrient concentrations or rates of release. There are no clear across-shelf patterns in aerobic respiration or bacterial activity, although these rates are generally higher than those measured on other shelves. A preliminary nitrogen cycling budget for mid-shelf sediments (figure 2) illustrates that the low concentrations of dissolved and particulate nitrogen are rapidly turned over by bacterial ammonification, nitrification and denitrification processes. These are crude estimates, but clearly imply that highly abundant and active bacteria in surface deposits are responsible for rapid turnover and release of nitrogen. Nutrient release contributes, on average, 13 and 24% of the annual N and P requirements of the lagoon phytoplankton (Alongi 1989b). This contribution is greater than from inshore benthos which account for 6 and 9% of the respective nitrogen and phosphorus demand of coastal phytoplankton, implying that other nutrient sources such as land run-off and/or higher rates of pelagic recycling, contribute to inshore primary production (Alongi 1990a).

Benthic carbon decomposition pathways have not been measured on the mid- and outer-shelf regions of the lagoon, so it is impossible to judge the relative importance of aerobic and anaerobic processes, and potential regulatory factors, on the fate of organic matter and associated materials (e.g. trace metals) within the lagoon. Of equal consequence is the fate of organic and inorganic carbon that is closely tied to the diagenesis of carbonates in unconsolidated sediments. This is a poorly understood topic particularly on tropical carbonate shelves containing various mixtures of clastic and carbonate material.

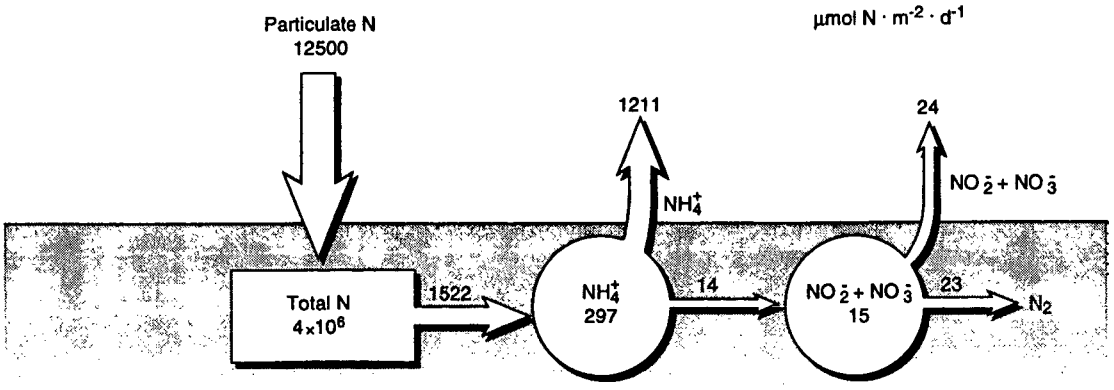


Figure 2. A preliminary nitrogen budget (mol N m^{-2} d^{-1}) in surface (0–20 cm) sediments at mid-shelf in the central Great Barrier Reef lagoon. Complied from data in Alongi (1989b; unpublished data) and Furnas et al. (1995). Denitrification and nitrification rates were estimated from porewater nitrate and nitrite profiles using diagenetic models in Berner (1980).

Rates of organic matter oxidation greatly affect the precipitation/ dissolution kinetics of carbonates in sediments which has important consequences for the flux of inorganic carbon (CO2) and interstitial alkalinity. In carbonate-rich sediments, carbonates normally dissolve because of the production of carbonic acid generated by aerobic respiration (Walter et al.1993). Carbonate sediments are ordinarily iron-poor, so iron sulfide precipitation is limited resulting in accumulation of H2S and an interstitial pH slightly 7. This in turn results in the dissolution of carbonate minerals and release of dissolved inorganic carbon. This is in contrast to coastal sediments which are iron-rich and where carbonate dissolution is usually restricted to surface layers, because in deeper sediments, iron sulfide precipitates, increasing pH and causing carbonate supersaturation.

In the Great Barrier Reef lagoon, however, vast expanses of the shelf floor are composed of mixtures of clastic and carbonate minerals, so it is unclear under what conditions carbonates will precipitate or dissolve in deposits of mixed origin. Recent data from Ningaloo Reef lagoon in Western Australia (Alongi et al. 1996) suggest that carbonate kinetics in mixed terrigenous-carbonate deposits is more similar to that in clastic sediments. This means that carbonates may precipitate rather than dissolve in sediments over large areas of the Great Barrier Reef lagoon consisting of similarly mixed unconsolidated deposits. The key is whether or not reactive iron concentrations and rates of sulfate reduction are sufficient to accumulate iron sulphides, increasing pH to levels promoting carbonate precipitation. This may be happening with the lagoon, as several workers (Birtles and Arnold 1983, 1988; Scoffin and Tudhope 1985; Alongi 1989b) have observed large patches of cemented carbonates. If true, it may be safe to say that the behaviour of carbonates in sediments can have a significant ecological impact.

Implications for management

The structure and function of soft-bottom benthic communities have substantial impacts on the ecology of the Great Barrier Reef lagoon, responding not only to inputs (and impacts) derived from various sources, but in turn, affecting ecosystem productivity. Benthic organisms, especially bacteria, are responsible for decomposing organic matter that settles to the lagoon floor and returning dissolved nutrients to be reused to sustain pelagic life, including many commercially important species.

The trophic dominance of sediment bacteria and the regulatory role of physical disturbance for soft-bottom benthic communities in the Great Barrier Reef lagoon are unique compared to other shelf benthos and have important consequences for management, particularly of inshore areas. First, even if benthic metazoans consume only bacteria, metazoan productivity is low compared to bacterial productivity implying that only a small proportion of bacterial biomass is consumed. The remainder presumably dies naturally and is recycled within microbial food chains. Second, if physical disturbance is an important factor regulating the trophic structure and function of soft-sediment benthic communities, how can these effects

be distinguished from anthropogenic disturbances such as prawn trawling? It is clear from this review that distribution, abundance and diversity data for benthic communities and their functional role over time and space is lacking, and is inadequate for making informed management decisions regarding the sustainability of species dependent on benthic food chains. A concerted research effort is urgently needed to better understand:

- the spatial and temporal variability of lagoonal soft-sediment benthos and their food sources;
- the trophic connections between infaunal food chains and demersal fisheries;
- the impact of changes in community species and size structure on community function;
- relative impacts of natural physical disturbance (e.g. cyclones) versus human-induced disturbance (e.g. trawling, contaminants);
- the importance of episodic events (i.e. cyclones);
- the interaction between benthic organisms and sediment biogeochemistry;
- nutrient cycling processes, such as denitrification and sulfate reduction;
- the fate of river-borne material, including contaminants;
- how benthic processes differ with changes in carbonate concentration;
- export/ import of dissolved and particulate nutrients from mangroves, seagrass beds and reefs to the lagoon proper;
- how benthic community structure and function are affected by hydrography.

These are only some of the major information gaps needed to be filled in order to properly manage the sustainability of life and nutrient cycling processes within the lagoon, in line with the 25 year strategic plan for the Great Barrier Reef (GBRMPA 1994).The benthos on this shelf are in many respects unique to those on other shelves, so it is not proper to implement management plans designed for other biogeographic regions, such as the Baltic. The current study of the effects of prawn trawling in the far northern section suggests some impacts on demersal fish and megabenthic communities, but are these changes severe enough to alter benthic nutrient recycling processes sufficiently to eventually affect the entire ecosystem? As suggested by Kensington and Crawford (1993), only a coordinated multidisciplinary approach can answer these questions which are of fundamental importance to sustainably develop, yet conserve, the Great Barrier Reef and its lagoon.

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Impacts on and responses of seagrasses in the Great Barrier Reef – issues for management

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ABSTRACT

An estimated 3000 km^2 of coastal seagrass habitat and at least 2000 km^2 of deepwater seagrass habitat has been mapped in the Great Barrier Reef region from broad-scale coastal surveys in the 1980s and ongoing inter-reef surveys. Seagrasses have been found in estuaries, shallow coastal bays and inlets, on fringing and barrier reef platforms, and in inter-reef areas to depths greater than 60 m. Most of the fourteen known species are common to the Indo-West Pacific region, but some reach the latitudinal limits of their distribution in Queensland and at least two *Halophila* species may be endemic to the Great Barrier Reef region or north-eastern Australia.

All seagrasses are important in primary production and therefore in supporting complex marine food webs. Estuarine and shallow coastal seagrass meadows appear to be more important than deeper meadows as nursery habitat for juvenile prawns and fish. Dugong and green sea turtles – species listed as endangered or threatened – depend on seagrasses for survival. Large populations of dugong have also indicated the existence of large areas of seagrass at depths between 10 and 30 metres. The ecological role of seagrasses in deep water (>10 m) is not well understood and requires study. Large areas of macro-green algae communities in deep water, mostly on the outer shelf, are little studied and receive no special protection measures.

Natural cyclone and flood events can cause widespread loss of seagrasses in shallow and deep water. Agricultural land-use practices may exacerbate the effects of these natural events or reduce the resilience and recovery of seagrasses from natural impacts. The most immediate threats from urban and agricultural run-off, or coastal and Barrier Reef development appear in southern, populated regions. Localities which provide shelter and water conditions ideal for productive seagrass habitat are often targets for port development, and at the downstream end of heavily impacted catchments. Reducing the threats to seagrasses and dependant fauna from oil-spills requires improved management of shipping traffic and oil-spill responses. Current fisheries legislation for marine plant protection, policies for protection and sustainable use of seagrass habitat areas, marine parks and area closures to trawl fishing help protect valuable inshore seagrass prawn nursery and dugong feeding habitat, but seagrasses in deep water do not yet receive formal protection measures.

Natural year-to-year change in Queensland seagrasses has not been recorded in any detail and the causes, scale and ecological consequences of long-term changes are poorly understood. Seagrass monitoring programs need long-term support and methods for hindcasting seagrasses in the tropics require development. Impacts on seagrasses in the Great Barrier Reef currently appear low to moderate, but incremental increases in the total impact must be managed. Land-use practices and coastal management need careful attention to minimise adverse impacts of increasing population and development. Research must help describe the responses of seagrass to natural and human impacts and attempt to determine acceptable levels of changes in seagrass meadows and water quality conditions which may cause those changes. Catchment management programs and heightened community awareness of the alternatives for reducing run-off impacts are considered essential for maintenance of Great Barrier Reef seagrasses.

Status of seagrasses in the Great Barrier Reef

At the time of the first Great Barrier Reef Conference (1983) we knew close to nothing about the extent of seagrasses in the Great Barrier Reef region. Collections for taxonomic classifications (den Hartog 1970; Greenway 1979) and studies of succession in intertidal seagrasses at Townsville (Birch and Birch 1984) formed the strength of our knowledge then. Broad-scale seagrass surveys along the Queensland coastline were initiated by the Queensland Department of Primary Industries (Coles et al. 1985a,b, 1987a,b, 1992; Lee Long et al. 1992, 1993) following recognition of the importance of seagrasses as nursery habitat for juvenile prawns of commercially valuable tiger prawn fisheries (Coles and Lee Long 1985). The dietary dependence of dugongs and green sea turtles on seagrasses was also established at about this time (e.g. Lanyon et al. 1989). Dugong and green sea turtle conservation became an additional impetus for subsequent seagrass research, mapping and monitoring. Conservation management priorities for these endangered or threatened species strongly influences the direction of Great Barrier Reef seagrass studies today.

Broad-scale surveys of separate regions from 1984 to 1989 (Coles et al. 1985; Coles et al. 1987a,b; Coles et al. 1992; Lee Long et al. 1992) indicated where seagrasses occurred in estuaries, shallow coastal bays and inlets, on some fringing reefs, barrier reef platforms and limited sites in deep water. Coastal waters were broadly mapped for all of Queensland, but surveys of deeper water (>10 m), inter-reef, inshore-reef and barrier-reef platform areas have only recently begun. Seagrasses have been found to depths of 58 m in the Cairns and Far Northern Sections (Lee Long, McKenzie and Coles 1996).

Approximately 3000 km^2 of coastal (<15 m depths) seagrass habitat was mapped during initial broadscale surveys in the Great Barrier Reef region (Lee Long, Mellors and Coles 1993), and at least a further 2000 km^2 of deepwater seagrass habitat has been estimated so far (Lee Long et al. 1996). Fourteen known seagrass species were recorded from surveys of Queensland coastal, island and reef waters between 1984 and 1989 (Lee Long, Mellors and Coles 1993). Most of these species are common to the Indo-West Pacific region, but some reach the latitudinal limits of their distribution in Queensland (Lee Long, Mellors and Coles 1993) and at least two species (*Halophila tricostata* and *Halophila* sp.) may be endemic to the Great Barrier Reef region. One recently described species (*Halophila capricorni*, Larkum 1996) has since been described and taxonomic studies of additional undescribed plants in the Genus *Halophila* may lead to further increases in the species list for the Great Barrier Reef (Kuo, pers. comm.).

There are few records of seasonal variability in Queensland seagrasses. Mellors et al. (1993) recorded a two-fold increase from winter to summer biomass in a *Halodule uninervis/Cymodocea serrulata* meadow at Green Island, but McKenzie (1994) measured up to six-fold change in above-ground biomass of a coastal *Zostera capricorni* meadow from winter to summer, at Cairns nearby. Information on year-to-year variability in tropical seagrasses remains limited because of few opportunities for long-term studies. Long-term variation in seagrasses has potentially large consequences on prawn fisheries, dugongs and sea turtle populations, and successful management of these populations requires much better information on seasonal and long-term variation in seagrass distribution and abundance. Attempts at formalising seagrass monitoring programs are just beginning.

Seagrasses represent important components of coastal primary production and support complex marine food webs. They are often valuable nursery grounds for commercially and recreationally important species of prawns and fish. Estuarine and shallow coastal seagrass meadows appear to be much more important as nursery habitat for juvenile prawns and fish (Derbyshire et al. 1995). Seagrasses in the Great Barrier Reef are also major sources of food to dugong and green sea turtles – species listed as threatened or endangered. Meadows dominated by *Halophila* and *Halodule* species are preferred dugong feeding areas. Seagrasses in coastal regions play important roles in maintaining sediment stability and water clarity. Their physical role in deep water (>10 m) is less understood.

Impacts on, and responses of, seagrasses in the Great Barrier Reef

Research on the responses of seagrass to nutrients is very limited, but current work indicates seagrass growth at coastal and reef localities is nutrient limited (Mellors, Udy pers. comm.). Excessive nutrient inputs from agricultural and urban run-off however, have led to

widespread loss of seagrasses at locations in Australia and overseas (Shepherd et al. 1989). The loss of over 1000 km^2 of seagrasses in Hervey Bay in 1992 followed two cyclones and prolonged flooding (Preen et al. 1995) and the influence of suspended sediments and nutrient loads on seagrass mortality was probably exacerbated by coastal land-clearing and agriculture. The responses of seagrasses to increased light attenuation (caused by high concentrations of phytoplankton and suspended sediments) has been used to develop models where seagrass growth and distribution are used as broad indicators of water quality and environmental health (Dennison et al. 1993). Simple models of the responses of Great Barrier Reef seagrasses to light and nutrient concentrations will be useful when assessing the status and impacts on Great Barrier Reef water quality.

Current land-use practices and continued urban and agricultural expansions present a chronic threat and may exacerbate the effects of natural events through increased soil erosion and nutrient run-off. Land run-off impacts may also affect the recovery of seagrasses after loss. Integrated Catchment Management (ICM) programs seek to address these issues and are seen as an important part of good management for continued survival of seagrasses in the Great Barrier Reef.

Seagrasses are common in sheltered areas where coastal developments are concentrated and bring increased threats of urban and industrial run-off, dredging or burial. Impacts which increase water column sediments and nutrients, or phytoplankton or epiphyte density can lead to greater attenuation of light and reduced seagrass survival at depth (Dennison et al. 1993). Introduction of exotic marine species to Queensland ports, via ships' hulls or ballast water, present potential threats to local seagrass communities. Sea-urchins or other seagrass grazers could denude seagrass areas, and other introduced invertebrates or plants could compete against native species. The abovementioned threats are greatest in semi-enclosed bays and ports where water exchange rates are low. Far Northern Section seagrasses do not yet face the same immediate threats from urban and agricultural run-off, or coastal and Barrier Reef development that occur in southern populated regions.

Accidental and non-accidental impacts of trawling may impact on seagrasses – including chronic, low level disruption within meadows (causing patchiness and erosion) or incremental impacts on the edges of meadows. Most seagrasses in shallow, coastal bays and inlets are in water too shallow for trawlers to operate and damage to inshore seagrass meadows by trawling activity should be minimal under the fishery management policy of strip closures. Dense meadows in deep water are usually avoided by trawlers when possible. Low density seagrass meadows in deep water may receive greater fishing pressure. Many of these areas are dugong feeding habitat, but receive no special zoning or protection from trawling and may be at risk of damage.

Increases in shipping traffic along eastern Queensland will lead to the increased likelihood of oil spills. Oil spills may cause severe and immediate damage to intertidal seagrass meadows but subtidal seagrasses may be at lesser risk (Jackson et al. 1989; Kenworthy et al. 1993). Impacts on the invertebrate and fish communities which seagrasses support can be severe, but may respond positively to subsequent regeneration of seagrasses.

Management issues

Widespread loss of seagrasses in shallow and deep water in Hervey Bay had devastating effects on dugong populations (Preen et al. 1995; Preen and Marsh 1995). There have been few opportunities for documenting seagrass losses in the Great Barrier Reef and associated impacts on associated fisheries and fauna have been less studied. Management plans and management responses to impacts on Great Barrier Reef region seagrasses are designed primarily around the maintenance of seagrasses for commercial prawn fisheries and for dugong and turtle populations. The Great Barrier Reef Marine Park Authority and port authorities at Cairns, Mourilyan, Gladstone, and other areas, support seagrass management measures which also consider the broader ecological importance of seagrasses in maintaining coastal water quality, sediment stability, and as the basis for other marine fisheries and food-webs.

Management policies and options

In 1990, the Queensland Fisheries Management Authority (QFMA), in consultation with fishing industry, acknowledged the value of seagrasses to tiger and endeavour prawn stocks, and added to the seasonal prawn closures with a coastal strip closure system to protect juvenile prawns and their seagrass habitat. Most shallow, coastal seagrass habitat in the Far Northern and Cairns Sections north of Cape Tribulation, is thus currently in areas zoned as free from trawling activity, either within the QFMA policy of coastal strip closures or within Great Barrier Reef Marine Park Authority zoning. An extension of this reasonably effective strip closure system to protect coastal seagrasses south of Cape Tribulation is also being considered for evaluation in Queensland trawl fisheries management.

Important dugong feeding areas inshore between the Starcke River and Barrow Point receive special protection through scientific and preservation zones. In this area, seagrasses offshore in deep water (>10m) are important dugong feeding habitat (e.g. Lee Long et al. 1989), but are not afforded complete protection through zoning. There may be other unsurveyed areas of deep water seagrasses in the Great Barrier Reef important to dugongs and green sea turtles, but which receive no special protection. Seagrasses are listed as protected marine plants under section 51 of the *Queensland Fisheries Act 1994*. This Act also includes Chief Executive powers to enable prosecutions for wilful and unlawful damage to seagrass habitat, or for unlawfully causing damage to seagrass habitat.

Integrated catchment management programs have wide acceptance across Queensland and should be encouraged from a seagrass conservation perspective, since seagrasses are at the 'downstream end' of catchment run-off. This may be one of the best management measures for successful seagrass conservation. Point-source discharges are also being addressed and effluent controls are being slowly introduced at reef locations to help minimise impacts on seagrasses and corals. Gradual, incremental increases in all of the above impacts, associated with an expanding population, presents a serious threat to long-term survival of seagrasses in the Great Barrier Reef region. Planning for and management of these increasing pressures must be acknowledged by the whole community. We strongly recommend greater community education, awareness and involvement in land-use practices and programs which minimise downstream impacts on seagrasses. Programs to monitor the status of seagrass systems need to be formalised to evaluate the effectiveness of seagrass management in the Great Barrier Reef.

Seagrass research priorities

Mechanisms or structures for directing research and management of seagrasses in the Great Barrier Reef region include the interchange of information at annual Great Barrier Reef and CRC researcher conferences, and through ad hoc workshops and discussions. The Great Barrier Reef Marine Park Authority, the Queensland Fisheries Management Authority (QFMA), the Queensland Department of Environment (QDoE), and the Queensland Department of Primary Industries (QDPI) are the major organisations responsible for seagrass management in marine park and fisheries areas. The Cooperative Research Centre for Ecologically Sustainable Development of the Great Barrier Reef supports new initiatives in seagrass studies to obtain information of direct use toward management of the Great Barrier Reef. Research on Great Barrier Reef region seagrasses is conducted primarily by the QDPI, the James Cook University's Tropical Environment Studies and Geography group and the University of Queensland's Marine Botany group. Requests from the above organisations, and initiatives from scientists, are currently the major avenue for generation of research and monitoring, and information gained on seagrass habitat distribution and ecology is distributed to these organisations and extended for public use.

The Great Barrier Reef Marine Park Authority holds an archival GIS database using Arc-Info to store QDPI data on survey sites and seagrass distribution for research and management use. The Queensland Department of Primary Industries' MapInfo GIS databases include full sets of the raw data generated from a series of fine- and broad-scale mapping and monitoring programs.

Initial QDPI surveys conducted in the 1980s and 1990s provided information on seagrass distribution and abundance for large parts, but not all, of the Great Barrier Reef region. This information is now very dated and should be used with some caution in zone planning.

Large areas of deep-water and reef-platform habitat remain unsurveyed for seagrasses, and the immediate priority is to collect at least preliminary information on seagrass habitats for the remainder of the Great Barrier Reef.

There is a paucity of information on year-to-year change in seagrass distribution and abundance for most seagrass species and community types. There is no formal strategy or program in place for monitoring seasonal or long term change in seagrass distribution and abundance for any part of the Great Barrier Reef region. Limited studies of year-to-year change at specific coastal and deep water sites in the Cairns Section are currently supported by some port authorities and by the CRC Reef Research Centre. An effective monitoring program would include a range of localities – coastal, reef, deep-water, near population centres and remote. Seagrass growth rate (or productivity) is at least as important as standing crop to the populations which depend on seagrasses, and information on temporal variation in seagrass production rates, for a range of species and localities, would enable much better interpretations of how seagrasses support marine animal populations, fish and prawn production.

The CRC Reef Research Centre is now conducting studies on a) growth responses to natural and human impacts (e.g. nutrients and light), and b) mechanisms of seagrass recovery after loss. These will provide for inclusion within management plans: guidelines on ecologically acceptable water quality standards and a better understanding of the requirements and potential for recovery of seagrasses after loss.

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The effects of prawn trawl fisheries on GBR seabed habitats

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ABSTRACT

The non-reefal seabed area of the Great Barrier Reef (GBR) accounts for about 95% of the Marine Park region and comprises many different types of habitats. These seabed habitats support a great diversity of seagrasses, algae, seabed animals and fishes, some of which are commercially important while others are rare and/or endangered. The GBR also supports a valuable prawn trawl fishery of about 900 vessels that land catches worth about $150 million annually. However, despite of the extent and importance of the non-reefal area, there have been few studies of the non-reefal seabed habitat.

The few large-scale studies of GBR seabed benthos have consistently showed that the habitats and their flora and fauna are related closely to sediment type. Muddier areas tend to be the least diverse, whereas sandier and harder substrata are more diverse and support a more abundant fauna. Large epibenthos, which form living structural habitats on the seabed, usually are restricted to rubbly or rocky patches. Because of the habitat requirements of the fauna, there are distinct cross-shelf zones related to the change from the terrigenous muddy sediments of the inshore lagoon to the coarse calcareous sediments of the offshore inter-reef.

Most of the management issues for GBR seabed habitats are related to the effects of prawn trawling. These effects have been documented most comprehensively by a 5 year CSIRO/QDPI study in, and adjacent to, the Cross-Shelf Closure in the Far Northern Section of the GBR. The seabed and associated communities in the study area were described, then sampling was conducted to compare areas open and closed to trawling. There were few significant differences between the benthic communities in open and closed areas — but this should not be interpreted as a direct comparison of trawled vs untrawled areas because the inshore area of the closure was trawled before the closure, and some trawling has continued in this area. Also, given that fishing effort is highly aggregated, much of the area open to trawling has not been trawled. A Before-After-Control-Impact experiment was then conducted, in which twelve 2.7 × 1.2 km treatment plots were trawled entirely, once-over, and compared with control plots. Between 1-7 t of benthic material was removed from each treatment plot. Despite this obvious impact, there were few significant differences between the benthic communities in trawled plots and control plots. The impact of intensive repeated-trawling on seabed benthos was then determined by conducting a repeated-trawl depletion experiment. Preliminary analyses indicated that each trawl removed roughly 5-20% of the available biomass of sessile benthos and that 13 trawls removed roughly 70-90% of the apparent initial biomass. These results show that the impacts of prawn trawling may not be detectable in areas that are trawled sparsely or infrequently; however, the cumulative effect of frequent prawn trawls over the same grounds may be substantial.

Extension of these trawl impact results to the remainder of the GBR will require information on the distribution and dynamics of benthos communities, as well as the distribution and intensity of prawn trawler effort at fine spatial scales (GPS

resolution). This information will be essential for developing management strategies that ensure ecologically sustainability of the fishery and of the rich and diverse lagoon seabed fauna.

INTRODUCTION

Most research in the Great Barrier Reef (GBR) has concentrated on coral reefs because of their visual appeal and accessibility in shallow water. However, the coral reefs themselves account for only about 5% of the region. The deeper water seabed areas between the reefs have been neglected (Hutchings 1990). This may be because they have been perceived as less 'charismatic' than the coral reefs and certainly less obvious than the reefs, and because of the difficulties of working in the deeper seabed areas. As a consequence, little is known about the non-reefal seabed habitats and their faunal communities (Hutchings 1990). This meagre knowledge contrasts distinctly with the size and extent of the major user of these deeper seabed areas, ie. the prawn trawl fishery; as well as with the strong public perception that trawling damages the seabed environment; and with the magnitude of difficulties that managers face in addressing these issues in the absence of scientific knowledge (Zann 1995). It is commonly believed that the fauna living on the seabed are delicate in their structures and, in many areas of the GBR, they are exposed to trawling (Hutchings 1990).

In this paper, we define the non-reefal seabed habitats and describe briefly the prawn trawl fishery as the main user of the seabed. We also identify the management issues related to these habitats and summarise the available information on non-reefal habitats. Recent research on the impacts of trawling on these habitats in the GBR is described. Finally, the implications of the scientific knowledge for addressing the management issues are discussed, and we identify the information needs.

What are the GBR seabed habitats ?

The non-reefal seabed habitats of the GBR encompass the relatively protected area between the outer barrier reefs and the Queensland coast. The entire area in the lee of the barrier reefs can be described as a lagoon (Mather and Bennett 1993); however, the inshore side of this area has relatively few coral reefs and is often referred to as the '*main lagoon*', whereas the offshore side has many coral reefs and the non-reef part is often referred to as the '*inter-reef*' area (Fig. 1, inset b). Together, the main lagoon and the inter-reef areas comprise the 'GBR lagoon' and account for about 95% of the area of habitat of the GBR Marine Park region. In this paper, the term 'GBR lagoon' will refer to the entire non-reefal area, unless the italicised terms defined above are specifically used.

The GBR lagoon includes many different types of physical habitats, ranging from nearshore terrigenous muds, silts and sands through to offshore carbonate sands of various grades — all variably interspersed with rubbly and rocky cracks and patches, deep reefs and shoals with hard corals, and exposed areas of bedrock. These habitats support a great diversity of seabed (benthic) fauna: from the microscopic to macroscopic; meiofauna within the sediments to the large epibenthic structural organisms; sessile and mobile invertebrates; seagrasses and algae; and many species of fishes (Hutchings 1990). Some of these seabed organisms (benthos) are commercially important, particularly those targeted by prawn trawlers. These habitats are also used by rare and endangered vertebrate species (eg. turtles and dugongs). Despite the extent and importance of the lagoon seabed, however, our knowledge of the benthos is limited to only 4-5 descriptive studies (see below) and there is no information on long term trends, which may indicate any alteration in the state of these habitats .

What is the nature of the trawl fishery ?

The GBR Lagoon supports a valuable otter-trawl fishery, with about 900 boats and annual landings with a value of about $150 million (Queensland Fisheries Management Authority data). The boats are licensed to trawl from Cape York to the NSW border, but within this region, most effort is concentrated in Princess Charlotte Bay, the Townsville region, and Moreton Bay. In the cross-shelf axis, effort is concentrated in the main lagoon, but also extends into the offshore inter-reef at some latitudes (Hutchings 1990). Penaeid prawns are the primary target species group (with ~7,000 t landed per annum). Scallops (~1,000 t), sand crabs, scyllarid lobsters, squid, and a few fin-fish species are also landed (QFMA data). All vessels are required to complete a daily logsheet of catch and effort, using a 30 minute grid reference.

The target species are caught by dragging otter trawl nets (typically 'quad-gear', comprising 4 nets with a combined foot-rope length of ~44 m) across the seabed. In the process, many other seabed organisms, both mobile and sessile are caught and/or damaged — these are called bycatch (Zann 1995). There have been many anecdotal reports and a few scientific studies that have demonstrated that prawn trawl nets remove benthos. However, the overall ecological significance of this impact is not yet clear.

What are the management issues ?

The management issues for lagoon seabed habitats are driven primarily by the need to manage their sustainable multiple use (by prawn trawlers, tourism, line fishery, shipping, and conservation interests). There is also an obligation to report on their status and World Heritage Values, and a requirement for feedback on the goals and objectives of the GBR 25-year Strategic Plan (GBRMPA 1994). Questions that arise about management of the seabed include: What are the pressures and impacts on these habitats? What are the ongoing impacts? Is biodiversity being lost? Do impacts differ in different seabed habitats? What is the distribution and intensity of habitat use? How should the lagoonal and inter-reefal areas be classified for representative marine protected areas? How should the zoning system be reviewed to manage seabed areas to maintain biodiversity? — currently the lagoon seabed is not well represented in protected areas of the GBR. Should some currently unprotected areas be set aside in reserves? If so, how should they be selected? For impacted areas, what kind of recovery can be expected, and over what time period? The underlying problem is that there is insufficient scientific knowledge available to answer these questions and manage the related issues.

The activity most likely to have significant impacts on GBR seabed benthos is prawn trawling (Hutchings 1990). This is because there is an extensive prawn trawl fishery operating in the lagoon, and the available evidence suggests that there have been, and continue to be, direct impacts on the lagoon seabed habitat due to prawn trawling, as well as indirect changes to other components of the ecosystem (eg. trophic structures). Consequently, most of the management issues for lagoon benthos are related to the effects of prawn trawling on the seabed (Zann 1995). Confounding the issue is that very little is known about the distribution, composition and status of the lagoon habitats.

The impacts of prawn trawling on seabed habitats and the benthic communities they support is an important issue (Zann 1995). This is because of the indirect effects on target species (eg. through impacts on predator or prey species, or habitat) and indirect effects on other valuable species (eg. commercial or recreational finfish species), and direct but more general environmental effects and conservation issues (eg. destruction of structural habitat, loss of biodiversity, loss of rare and/or endangered species).

What is known about the GBR seabed habitats ?

The fauna of the seabed are classified broadly by their relationships with the substratum and their size (Gray 1981, Longhurst and Pauly 1987). Animals living on the seabed are known as epifauna (or epibenthos) and animals living in the sediment are known as infauna. Animals washed through a 1 mm sieve from a grab sample are meiofauna, whereas those retained are macrofauna (or macrobenthos). Animals too large to be properly sampled by a 0.1 m^2 grab are megafauna (or megabenthos) and those firmly attached to the substratum are sessile.

Previous studies of GBR seabed benthos, with significant spatial coverage, include the following:

- Birtles and Arnold (1983 and 1988) used a 1.6 m epibenthic dredge to sample inter-reefal epibenthos during a series of integrated studies at up to ~90 sites, on a roughly 8 n. mile grid off Townsville, at various intensities between 1977 and 1983. Most sites were in the main lagoon area, between the coast and the reef-matrix, a few sites were sampled on the outer half of the shelf, in the offshore inter-reefal area.

- Cannon, Goeden and Campbell (1987) conducted classification and ordination analyses of prawn trawl bycatch (including macro- and mega-benthos and fishes) from two of a series of seven exploratory prawn trawl surveys in three main areas of the GBR. Samples were collected primarily with 2 m prawn try-shot nets at about 230 sites between 1979 and 1982. Although providing significant latitudinal coverage, most sampling was unstructured, with the objective of identifying new commercial prawning grounds.

- Jones and Derbyshire (1987), Watson and Goeden (1989), and Watson et al. (1990) used commercial prawn trawl gear to sample fauna at monthly intervals in up to 24 sites distributed from the inshore, across the main lagoon, into the offshore inter-reef matrix, over a ~1°x1° region off Townsville in 1985 and 1986.

- Coles et al. (1996) conducted a video survey over ~4° of latitude north of Cairns, primarily for broad-scale mapping of seagrass. Sediment, algae and epibenthic megafauna were recorded also. The sampling strategy for the survey was to divide the region into 15-minute-of-latitude blocks and select a cross-shelf transect at random from each block. Each transect was divided into 1 n. mile segments and a randomly placed video transect ~100-300 long was conducted in each segment.

These studies of GBR seabed benthos consistently showed that the physical habitats, and the flora and fauna associated with them, are strongly influenced by sediment type (ie. the continuum through mud, sand, rubble and rock). These patterns were similar to the typical patterns previously described for the ecology of the seabed (see reviews by Gray 1981 for soft seabed; also Longhurst and Pauly 1987). The GBR studies focussed on the larger animals living on the seabed, ie. the macrobenthos, and in many cases just the subset of species sampled as bycatch in prawn trawls. This epifauna has high species richness — typically 700+ species would be found in a representative set of samples from the GBR. The infauna was not included in these GBR studies, but similar work in adjacent regions (eg. Gulf of Carpentaria, Long and Poiner 1994) showed that tropical infauna also has high species richness — again, typically 700+ species larger than ~1 mm, and at least as many < 1 mm. It is likely that the infauna would have similar richness in a representative series of samples from the lagoon in any section of the GBR.

The GBR studies showed that the least diverse areas had muddier sediments, where the dominant animals were deposit feeders. Sandier and harder areas tended to be more diverse, at least partly because of the greater range of physical habitats. The fauna of harder areas were also more abundant, and the dominant animals were filter feeders, scavengers or carnivores. The megabenthic epifauna, which form living structural habitat attached to the seabed, generally were restricted to rubbly or rocky patches, or areas where the bedrock or coarse substrata were exposed by fast currents. Such patterns are also typical of other regions (eg. Torres Strait: Pitcher et al. 1992; Gulf of Carpentaria: Long and Poiner 1994, Long et al. 1995).

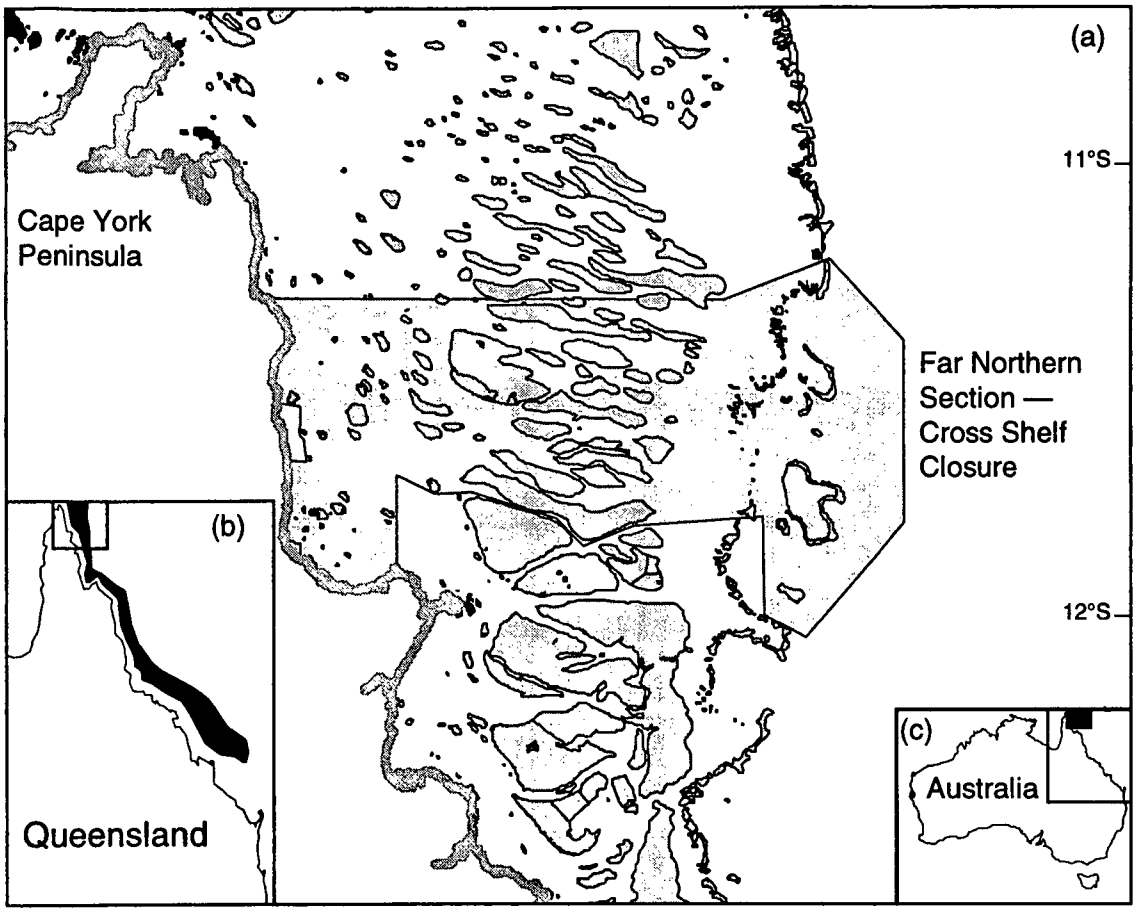


Figure 1. Map of the cross-shelf closure and adjacent areas open to trawling in the Far Northern Section of the Great Barrier Reef (a). The entire area between the coast and the ribbon of outer barrier reefs is the lagoon, although the outer shelf area among the reef matix is often termed the inter-reefal area (shaded in inset b) and the inshore area with few reefs is often termed the main lagoon (not shaded in inset b). Insets (b) and (c) show the location of the study area relative to Queensland and Australia.

The physical habitat requirements of inter-reefal benthos are responsible for the distinct cross-shelf zonation of benthic fauna in the GBR, related to the change from terrigenous muddy sediments of the inshore lagoon through to coarse calcareous sediments of the offshore inter-reef. Typically, multivariate analyses separated the fauna into three main groups: inshore lagoon, offshore inter-reef, and a mid-shelf lagoon transition area. This zonation was apparent in all the GBR studies, although the composition of the species groups among the different studies has not been examined for consistency. Only one of the studies (Cannon et al. 1987) compared samples from a range of latitudes (~12°S to ~18°S) and showed an overlapping continuum rather than discrete groupings of (prawn trawl bycatch) faunal variation. However, the authors treated this result with caution due to their unstructured sampling strategy.

In 1992-93, CSIRO and QDPI used commercial fish and prawn trawls, a 3 m epibenthic dredge, a video sled and a grab, to sample fish, prawns and benthos at >150 stations in the Far Northern Section of the Great Barrier Reef. The stations were distributed representatively, from the coast to the outer barrier, throughout the ~1°×1° area of the cross-shelf closure and adjacent open zones (Fig. 1; Blaber et al. 1993 and 1994). Note that stations were restricted to trawlable, or semi-trawlable ground. The patterns documented for epibenthic dredge fauna were similar to those of previous studies, with cluster analyses of sites by taxa showing three main cross-shelf groupings. These patterns are shown more informatively by a two-dimensional plot of the ordination of sites by taxa (Fig. 2a), which shows relatively close grouping of inshore sites, clearly separated from offshore sites, and with midshelf sites scattered mostly in between. Offshore sites were much more heterogeneous in composition than inshore sites. Ordination of high-level taxa by sites (Fig. 2b), clearly showed different cross-shelf distributions. The echinoids and bivalves were much more abundant inshore, whereas the ophiuroids, crinoids and zoanthids were much more abundant offshore. Other groups of taxa showed a range of patterns in between. Different species within each high-level group of taxa sometimes had quite different cross-shelf patterns of abundance to the group as a whole and these details are currently being analysed. As with the other GBR studies, these patterns were correlated with depth, sediment and carbonate content.

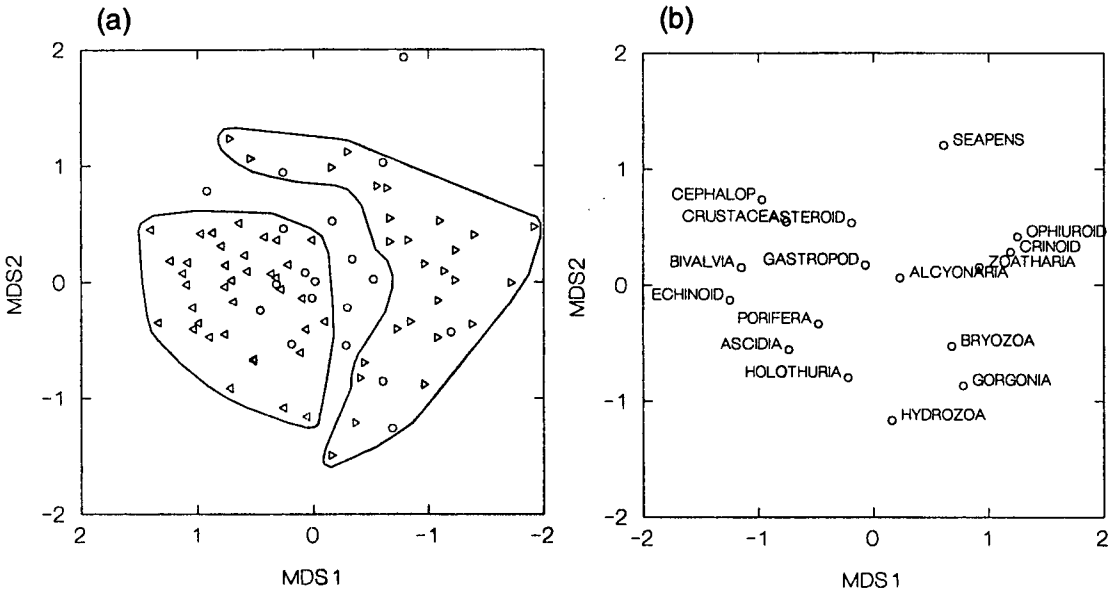


Figure 2. Multidimensional scaling plots of (a) dissimilarities of sites, by taxa, inshore sites (3), midshelf sites (η) offshore sites (4), and (b) dissimilarities of high-level taxa, by stations. Note, the MDS1 axis corresponds primarily with inshore to offshore orientation, left to right.

Part of the CSIRO/QDPI study focussed on the large (mega) benthic epifauna (ie. sponges, gorgonians, seawhips, soft corals, hard corals), because of their contribution to biodiversity, importance as structural habitat for other organisms, and vulnerability to trawl impact. These megabenthos were very patchily distributed at several scales and tended to have many other organisms associated with them (eg. fishes, holothurians, crinoids, echinoids, asteroids, molluscs etc), in addition to the sessile fauna themselves. The megabenthic patches represented islands of high diversity surrounded by extensive areas of sand and silt almost devoid of megabenthos. Where megabenthos did occur, they generally were confined to slightly raised harder substrata in offshore areas, and the occurrence of such substrata was often <5% in video transects. Typically, these patches were 1-10 m across and were separated by 10-100 m (Fig. 3), but were highly variable.

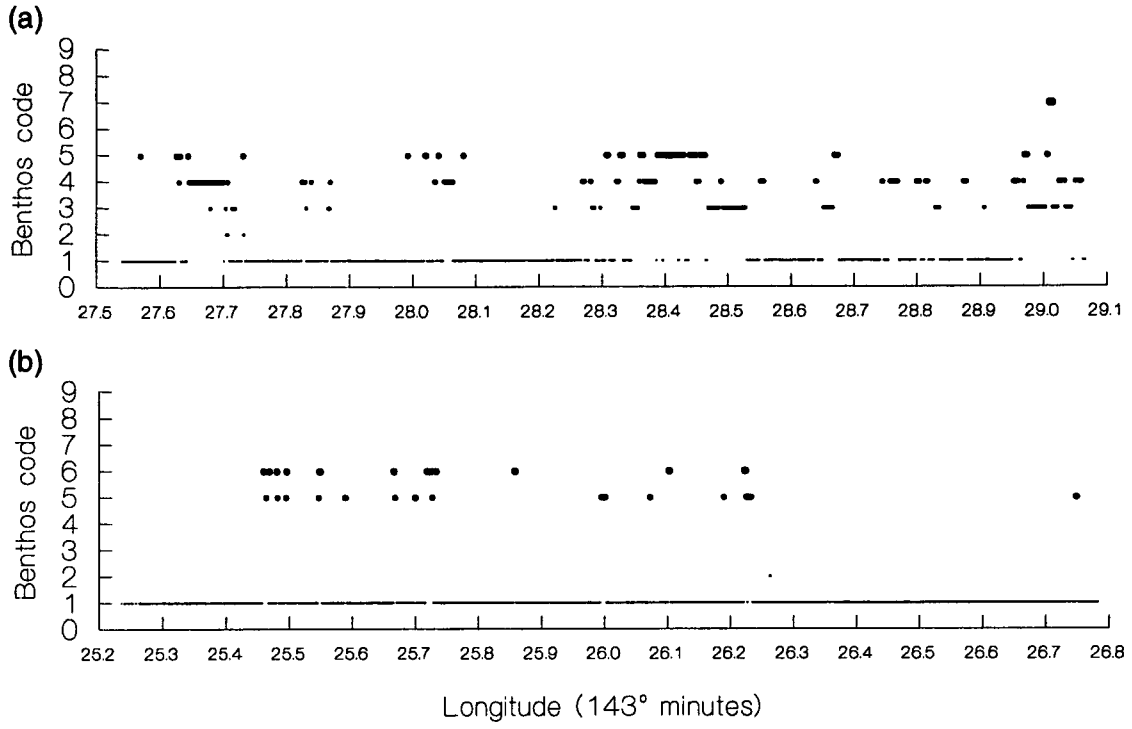


Figure 3. Distribution of major types in~2.8 km long coded video transects along (a) shallow (~20 m) shoaling seabed and (b) deeper (~35 m) seabed in the midsehelf of the Cross Shelf Closure. Codes: 1=silt/sand, 2=rubble, 3=algae, 4=shell beds, 5=patches of seawhips and gorgonians, 6=5+ sponges, 7=6+hard corals, 8=rocks, 9=reef. The multiple scales of patchiness of benthos are clearly apparent.

What are the documented effects of prawn trawling on seabed habitats ?

The effects of prawn trawling have been documented most comprehensively by a recent 5 year study conducted by CSIRO and QDPI in the Cross-Shelf Closure ('Green Zone') and adjacent open areas in the Far Northern Section of the GBR (Fig. 1). One aspect of this study was to measure the impact of prawn trawling on seabed communities. This was examined in three ways:

- by surveying the cross-shelf closure and comparing the species composition and abundance with that in adjacent areas north and south that were open to prawn trawling;
- by conducting a Before-After-Control-Impact experiment in the mid-shelf section of the area closed to prawn trawling, to determine the impact of a single trawl per unit area;
- by conducting a repeated trawl depletion experiment on selected tracks in the mid-shelf section of the area closed to prawn trawling.

The study area was initially sampled to describe the seabed and associated communities. This survey provided the distributional information described in the previous section (Fig. 2) and the statistical information needed for designing the subsequent studies.

Open vs Closed Comparisons

Sampling was conducted to compare the demersal communities of prawns, fishes, benthos, and bycatch species in the 'Green Zone' and adjacent areas open to prawn trawling (Blaber et al. 1994). Power analysis was used in designing a survey that could detect 10-fold differences between open and closed areas. Prawn trawls, fish trawls, epibenthic dredge and video sled

were used to sample 166 stations. However, the results presented here are only for the benthos communities sampled by ~15 minute tows of the 3 m epibenthic dredge at each station.

More than 700 benthic taxa, weighing 6-7 t, were collected. Many of these showed significant cross-shelf patterns of abundance due to differences in physical habitat, as summarised in Fig. 2. Analysis of variance indicated that only seven taxa differed significantly between the 'Green Zone' and adjacent areas open to trawling, and that only two of these were more abundant in the 'Green Zone' — this was less than expected by chance alone. Principal component analysis of stations by abundant species (those present at more than 60 stations, Fig. 4a) and by common species (those present at more than 20 stations, Fig. 4b) showed no clear separation of 'Green Zone' stations from open zone stations. The first principle component axis also shows the inshore–offshore separation identified in Fig. 2. The direction and magnitudes of differences between the closed and open areas are summarised most concisely by frequency distributions of the log of the ratio of species abundances in the closed and open zones (Fig. 5). A log-ratio value of +1 would indicate 10 times higher abundance in the 'Green Zone' and a value of -1 would indicate 10 times lower abundance in the open zone. Clearly, the abundance of most species differed little between the two zones, and the mean of the frequency distributions is close to zero — in fact, there were a few more species slightly more abundant in the open zone, but the means of the distributions were not significantly different from zero.

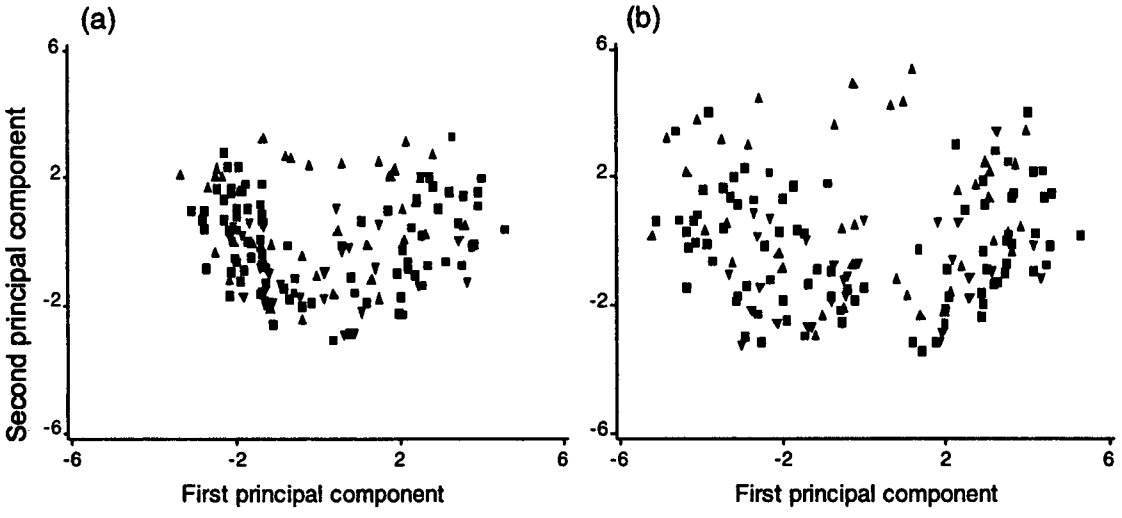


Figure 4. Principal component analyses of sites in open and closed areas for (a) very common species present at more than 60 stations, and (b) common species present at more than 20 stations. Symbols: ■=closed area, ▲=open area north, ▼=open area south.

The comparisons of the 'Green Zone' with adjacent areas open to trawling showed that, at this scale and resolution, there were few significant differences between the benthic communities of the closed and open areas. However, these results should not be interpreted as indicating that prawn trawling has no impact, because there was not a direct comparison of trawled vs untrawled areas. It is known that the inshore area of the closure was trawled before the declaration of the closure and some trawling has continued in this area. Further, in the area open to trawling much of the trawling is highly aggregated and some areas are rarely if ever trawled (Gribble and Robertson 1996).

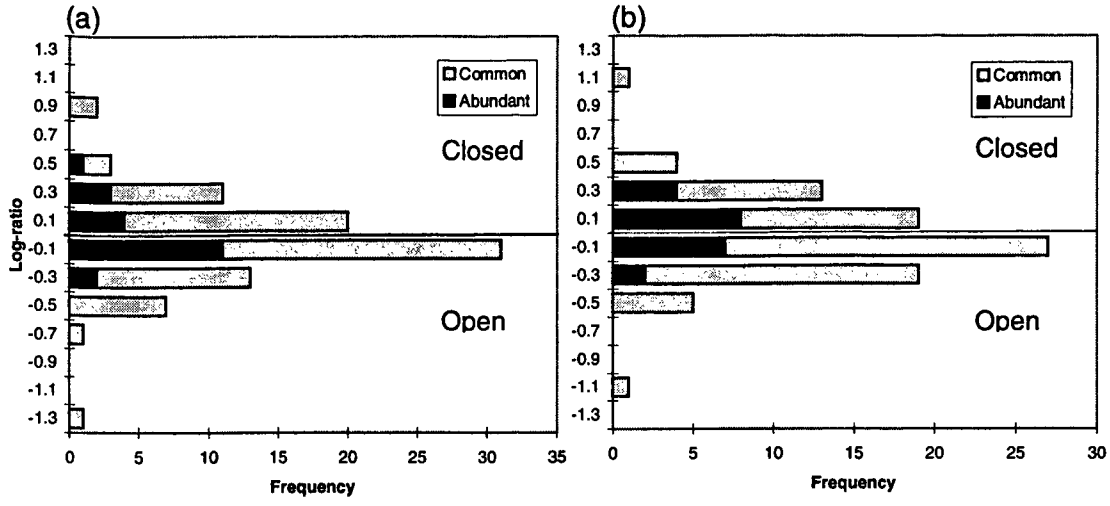


Figure 5. Frequency distributions of the log of the ratio of species abundances in the closed and open zones (a) by weights and (b) by numbers, showing the direction and magnitudes of differences.

Before-After-Control-Impact Experiment

The next phase of the study was to conduct a controlled trawling experiment where defined plots of seabed were sampled before half of them were trawled entirely, once-over, then all plots were sampled again after 6 months (Pitcher and Thomas 1992). This is known as a Before-After-Control-Impact (BACI) experiment. The experiment was intended to simulate prawn trawlers moving into new mid-shelf inter-reefal areas to target high-value red-spot prawns and the situation for grounds that are not trawled intensively (ie. the majority of the area of GBR trawl grounds). The size of the experimental plots had to be large to be relevant to the scale of commercial prawn trawling operations and the movement patterns of fishes, prawns and other non-sessile organisms, yet small enough to permit sufficient replicate plots to be established. Due to the need for 'before' sampling, the experiment could not be designed to answer questions about past impacts in previously trawled grounds. Also, due to the scale of plots required to assess impacts on mobile species, the experiment could not address the situation represented by the relatively small areas of very intensively trawled grounds. Power analysis was used to design the experiment to detect, with >80% power, order-of-magnitude decreases in the abundance of most benthic groups because this was at least the effect-size expected from previous research and anecdotal reports.

The final design was for 24 plots of seabed, each 2.7 x 1.2 km to accommodate replicate sampling trawl-shots. The optimum number of stations to sample within each plot was estimated by cost-benefit analysis, for both the before and after time periods, at ~3 stations per plot. The experiment was split into two phases started at different times of the year to counter seasonal differences in the biology of organisms and uncontrollable environmental risk factors (eg. cyclones, ENSO). There were two main types of trawlable ground in the area and trawling was simulated in both. They were deeper areas (35–50 m) where almost all ground within the plot could be trawled, and shallower areas (17-25 m) containing patches within the plot that were too rough to trawl. The factors and sampling hierarchy for this design were:

2 × Seasons (wet and dry)
2 × Habitats (shallow and deep)
2 × Impact (trawled and un-trawled)
2 × Time (before and after)
3 × Plots (replicates, a total of 24)
3 × stations, a total of 144 stations.

Establishing the BACI Experiment involved searching large areas with a video camera on a towed sled to locate appropriate plots of seabed for the experiment. The plots needed to include benthic structure because the experiment was intended to assess the impacts on benthic structure, of establishing new prawn trawl grounds. Once established, all plots were sampled before the impact by using fish trawls, prawn trawls, a benthic dredge and a video sled. The treatment phase involved two trawlers using heavy exploratory type gear. Approximately 45 hours of trawler effort was required to trawl each of the 12 impact plots entirely, once-over. All material retained in the nets was recorded. Differential GPS was used for accurate positioning of adjacent trawl tracks. All plots were sampled again 6 months after the impact, using the same methods. The design and timing of sampling for the experiment is shown in Fig. 6.

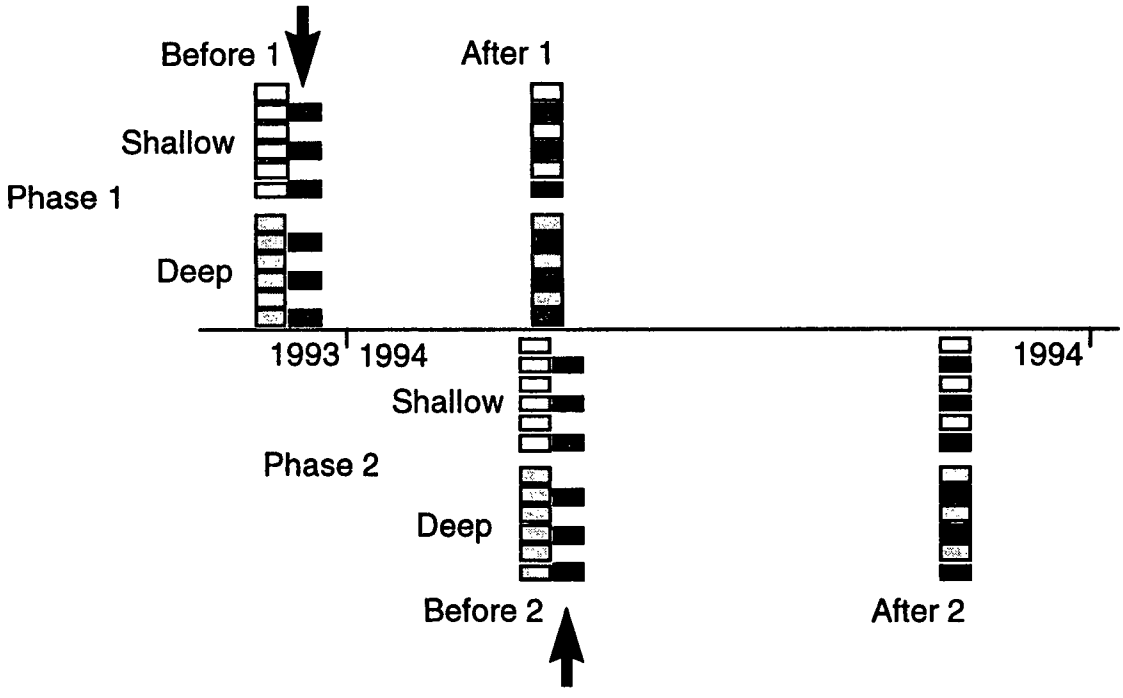


Figure 6. Design and timeline for the before and after sampling, and manipulation (arrows), of shallow and deep plots in phases 1 and 2 of the BACI experiment.

During the treatment phase, almost 40 t of benthos material was removed from all 12 trawled plots (Fig. 7). Of this, about 32 tonnes came from the 6 shallow plots (equivalent to ~13 kg/Ha) and the amount from each shallow plot varied between 2–7 t. About 6 tonnes came from the 6 deep plots (equivalent to ~2.5 kg/Ha) and the amount from each plot varied between ½–1½ t. Despite this obvious indication of some impact, and that the power of the experiment met the design criteria, few of the estimated impacts for benthos were significant (Table 1; Burridge et al. 1996). Direct observations of structural habitat also showed little change. Clearly, the impact of a single trawl per unit area was less than one order-of-magnitude.

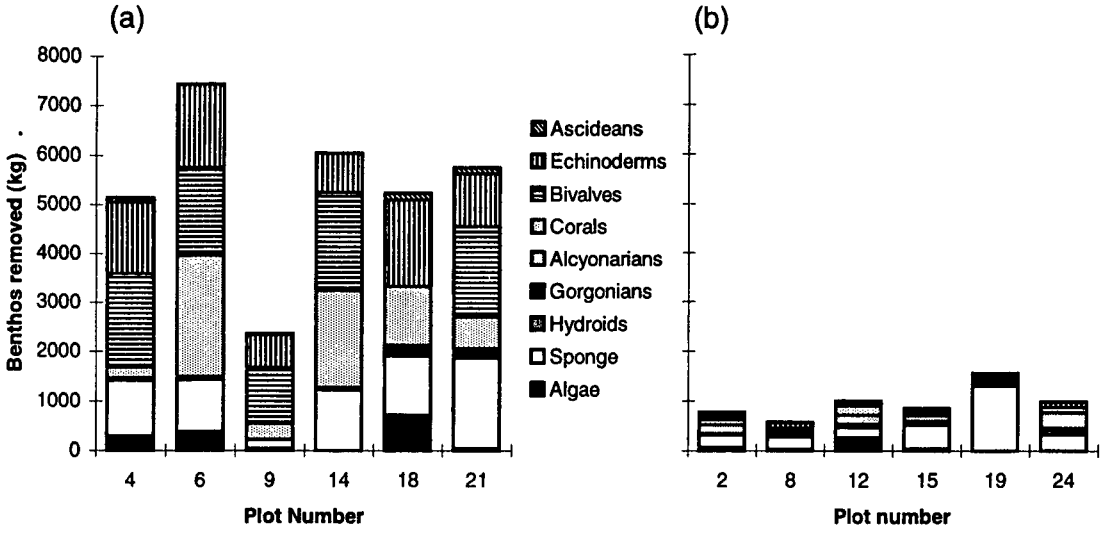


Figure 7. Amount of benthic material, by major benthic class, removed by trawl gear from each of the (a) shallow and (b) deep experimental plots, during the manipulation of the BACI experiment.

A further indication of the magnitude of the impact of a single prawn trawl in terms of removal of benthic organisms comes from comparisons of the relative 'efficiency' of the prawn trawl versus the dredge (Table 2). Comparisons of three information types (ie. the frequency of stations where each benthic class was observed, the composition of the benthos, and the estimated catch density per swept area) suggested that the dredge was more efficient at removing benthos than the prawn trawl (Burridge et al. 1996). Most benthic classes were caught more frequently in the dredge than in the prawn trawl; the composition of the benthos from the prawn trawl was biased towards larger benthic fauna (64%; sponges, crustaceans, zoantharians and octocorallians) compared with the dredge (14%); and the estimated density of most benthic classes from the prawn trawl was only ~5% of that from the dredge. Overall, the prawn trawl caught ~7 kg/Ha whereas the dredge caught ~340 kg/Ha, but the prawn trawl does not appear to have an equal impact on all classes of benthos — at least in terms of what it removes. Assuming the dredge catch was a reliable indicator of the actual density of benthos on the seabed, Table 2 gives an indication of the amount of each class that would be removed by a single pass of the trawl nets. For example, about 5% of the sponges would be removed.

It is arguable that the amount of material actually removed is irrelevant because the prawn trawl could damage much of the material that the ground-gear touches, without actually removing it. However, severely damaged organisms would have died and decayed in the time between the treatment and the after-sampling. If this effect was large, it should have been detected by the BACI experiment. The fact that it was not, suggests that only an unmeasureable fraction was severely damaged, and left in situ, during the manipulation.

Table 1. Estimates of impact (from log-weights) for benthic classes in benthic dredge and prawn trawl. Shaded cells highlight negative effects, ie. abundance of benthic class decreased in treatment plots relative to controls, but all estimates were not significant, except perhaps one borderline case (bolded cell — estimated impact effect with a probability level for a t-test $0.05<=p<0.01$).

CLASS	Dredge: Impact after 6 months		Prawn Trawl: Impact after 6 months		Combined: Impact after 6 months		Prawn Trawl: Impact after 12 months	
	Est.	S.E.	Est.	S.E.	Est.	S.E.	Est.	S.E.
Algae	-0.01	*0.22*	0.33	*0.21*	0.16	*0.15*	0.09	*0.21*
Ascidians	-0.02	*0.25*	0.04	*0.44*	0.01	*0.25*	0.41	*0.44*
Asteroids	0.15	*0.31*	0.24	*0.33*	0.20	*0.23*	0.27	*0.33*
Bivalves	-0.27	*0.33*	0.55	*0.36*	0.14	*0.24*	0.42	*0.36*
Bryozoans	-0.03	*0.21*	**0.56**	***0.31***	0.27	*0.19*	0.13	*0.31*
Cephalopods	0.28	*0.24*	0.19	*0.30*	0.24	*0.19*	-0.11	*0.30*
Crinoids	-0.18	*0.18*	-0.05	*0.27*	-0.12	*0.16*	-0.13	*0.27*
Crustaceans	-0.23	*0.16*	0.07	*0.21*	-0.08	*0.13*	0.19	*0.21*
Echinoids	-0.12	*0.30*	-0.01	*0.29*	-0.07	*0.21*	0.46	*0.29*
Gastropods	-0.35	*0.21*	0.21	*0.27*	-0.07	*0.17*	0.25	*0.27*
Holothurians	0.32	*0.33*	0.39	*0.34*	0.36	*0.24*	0.07	*0.34*
Hydrozoans	-0.06	*0.21*	0.26	*0.26*	0.10	*0.17*	0.11	*0.26*
Marine plants	-0.04	*0.24*	-0.26	*0.23*	-0.15	*0.17*	-0.28	*0.23*
Octocorallians	0.04	*0.30*	0.31	*0.29*	0.18	*0.21*	-0.46	*0.29*
Ophiuroids	-0.09	*0.16*	-0.24	*0.39*	-0.17	*0.21*	-0.23	*0.39*
Sponges	0.07	*0.31*	0.41	*0.46*	0.24	*0.28*	0.67	*0.46*
Zoantharians	0.16	*0.22*	-0.17	*0.41*	-0.01	*0.23*	0.37	*0.41*

Table 2. Comparisons of the sampling properties and benthos densities estimated by the epibenthic dredge and prawn trawl. Column headers: % presence = proportion of sites where benthic class was sampled by gear type; % weight = proportion of total weight of samples made up by each benthic class by gear type; kg/ha density = total catch of benthic class divided by estimated swept area (hectares). Sessile benthos are highlighted with shading.

CLASS	Dredge % presence	Trawl % presence	Dredge % weight	Trawl % weight	Dredge kg/ha density	Trawl kg/ha density	Trawls % of Dredge
Algae	99	94	14	1	42.16	0.09	<1
Ascidians	84	66	4	1	13.24	0.11	<1
Asteroids	92	48	5	4	14.85	0.26	2
Bivalves	84	73	52	12	159.69	0.89	<1
Bryozoans	85	65	2	1	7.13	0.04	<1
Cephalopods	29	90	<1	3	0.43	0.21	48
Crinoids	94	84	4	3	10.95	0.18	2
Crustaceans	98	99	1	18	3.19	1.28	40
Echinoids	74	30	<1	<1	1.30	0.03	3
Gastropods	83	52	<1	1	1.42	0.07	5
Holothurians	74	58	3	7	9.65	0.49	5
Hydrozoans	75	62	1	<1	2.92	0.01	<1
Marine plants	21	7	<1	<1	0.24	0.01	4
Octocorallians	87	94	3	14	8.90	1.02	11
Ophiuroids	96	80	1	2	1.85	0.17	9
Sponges	92	82	2	20	37.71	1.45	4
Zoantharians	97	63	8	12	24.07	0.83	3
TOTAL					339.70	7.14	2.10
SUB-Total Sessile Benthos					93.97	3.46	3.7%

Repeated-Trawl Depletion Experiment

A repeated-trawl depletion experiment was also conducted to determine the intensity of prawn trawling that would cause a substantial impact on the sessile benthos; to place the results of the BACI experiment in perspective and to document the rate of impact of intensive trawling on seabed benthos (CSIRO/QDPI unpubl.). The repeated trawls were conducted on six 2.7 km tracks from within the BACI plots, for which there was detailed information about their 'before' status. Each track was trawled 13 times over, with precise vessel navigation accomplished using differential GPS. The overall width of the trawled area in each track was ~35 m, compared with the width of the trawl gear at ~17 m. A central area of 10–15 m wide in all tracks was trawled at least 10 times (Fig. 8).

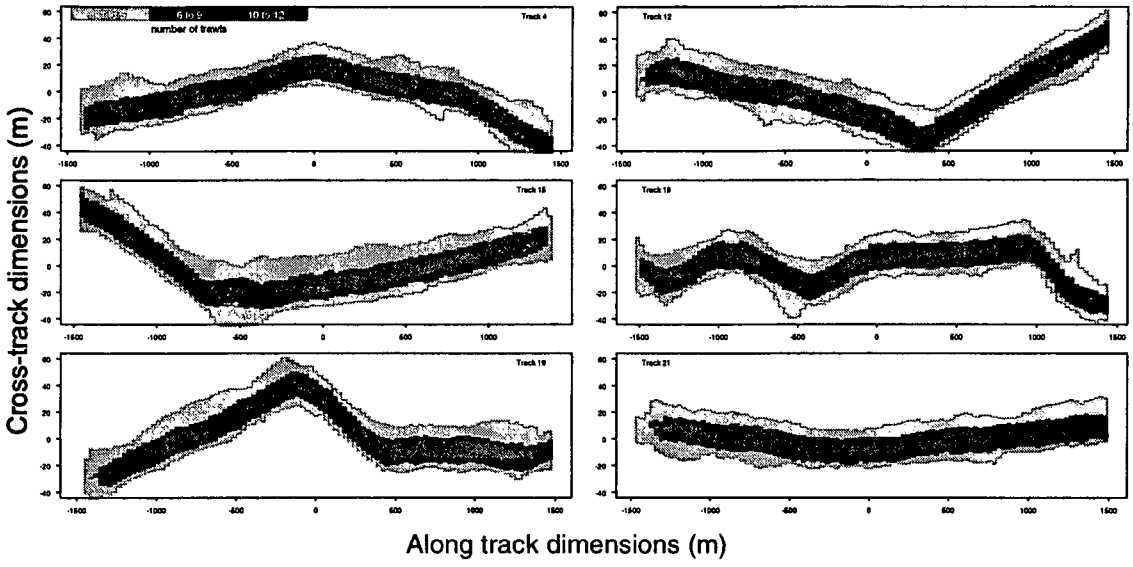


Figure 8. Spatial distribution and intensity of repeated trawls on the depletion tracks. Note different scales that exaggerate cross-track dimensions. Actual tracks were almost straight; bends indicate waypoints through which the trawler had to pass.

In the process of conducting the depletion experiment, about 2.25 t of sessile benthos was removed from the six tracks, corresponding to ~55 kg/Ha. Preliminary Leslie-Davis regression analyses of the biomass of sessile megabenthos removed by each repeated trawl and recorded on the trawler during the experiment (Fig. 9), indicated that the rate of removal of sessile benthos (= slope) by each trawl was roughly 5–20% of the estimated available biomass and that 13 trawls removed roughly 70–90% of the estimated initial trawlable biomass (= x-intercept). The biomass of benthos and depletion rate varied substantially among tracks (Fig. 9) and only one track (on Plot 18) did not shown a significant overall depletion trend during the experiment. Note that at the time of writing, these are oversimplified results based on incomplete data, and that more detailed analyses in progress are indicating that the results are much more complex, with depletion rates differing within and among different types of organisms (CSIRO Report in prep.).

Preliminary estimations, based on raw depletion data, indicated that initial sessile benthos biomass was in the range ~130 kg to ~710 kg per track, an average of ~470 kg, which corresponded to ~70 kg/Ha (depending on preliminary estimates of the effective area of the tracks). These biomass density estimates contrast with a biomass of ~95 kg/Ha from the dredge during the BACI experiment (Table 2). If the dredge biomass can be used as an approximation of the actual benthos biomass, this suggests that ~25 kg/Ha of benthos was more resistant to removal by prawn trawls. In this case, the ~55 kg/Ha of benthos removed by the depletion trawls, which was 70-90% of the apparent (x-intercept) biomass, may have been only ~60% of the actual benthos biomass on the seabed. This result concurs with remote video observations

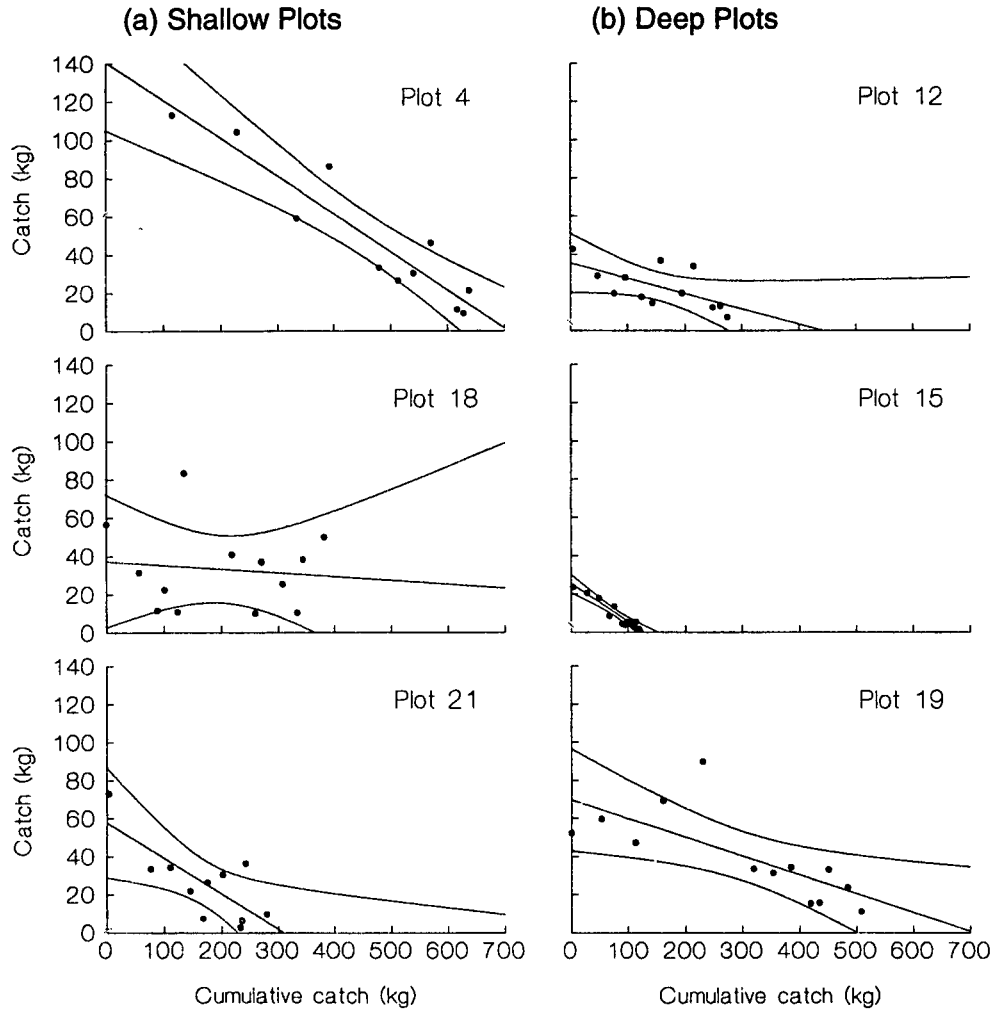


Figure 9. Leslie-Davis Plots of the depletion of sessile benthic classes (see shaded taxa in Table 2) on (a) three shallow tracks and (b) three deep tracks, all trawled repeatedly 12-13 times (● = catch data included in regression; ✱ = data excluded).

that suggest some fauna (eg. some gorgonians and seawhips) are very resilient to removal. The results from the more rigorous analyses in progress will differ in detail, although we anticipate that the overall implications will be similar.

Conclusions about the Effects of Prawn Trawling

Clearly, prawn trawling can degrade the state of the inter-reefal benthos and despite the absence of long-term data sets to confirm trends, anecdotal reports, circumstantial evidence and, extension of these research results, suggest that there have indeed been changes. The CSIRO/QDPI experiments showed that the cumulative effect of high intensity prawn trawling is likely to be substantial on epibenthos in species rich offshore areas, but the impacts may not

be detectable in areas that are trawled infrequently or sparsely. This result is important because the intensity of trawling is not uniform; some areas are trawled intensively, but large areas are trawled only occasionally or sparsely. The experiments could not be designed to answer questions about past impacts in previously trawled grounds on soft sediments of the main lagoon, especially smaller infauna. These lagoonal soft sediment fauna may, however, be less vulnerable to trawling. Because the intensity of trawling and impacts in soft sediments are poorly known, the overall significance of trawling effects on the GBR ecosystem is not yet fully clear. To determine whether the impacts of trawling on benthos are sustainable, more information is required on the distribution and dynamics of benthos communities, the spatial distribution and intensity of prawn trawl effort (at much finer scales than presently collected) in the GBR region, as well as information on the vulnerability of soft sediment fauna.

What is the significance of this knowledge to management ?

The scientific knowledge has affirmed the value of the lagoonal and inter-reefal seabed habitat, in terms of the high biodiversity of seabed benthos communities (with sponges in particular having a high level of endemism — Hooper and Lévi 1994), the support of significant representatives of marine biological evolutionary history, and provision of habitat for many other organisms, including fishes (Hutchings 1990). Some fauna are also valuable for the bio-prospecting industries.

Current zoning plans are focussed on and around the offshore reefs, but research has shown that inter-reefal communities have cross-shelf trends in composition that should be taken into account in strategic planning for conservation of representative communities. Latitudinal trends, though poorly known, are likely to exist (Hutchings 1990) and should also be taken into account. To meet strategic planning objectives, mapping and inventories of the GBR seabed benthos are required for regionalisation/zonation studies. These should target large scale latitudinal trends but must also account for cross-shelf patterns.

The documented information on the impacts of prawn trawling should be adopted by developing management strategies that ensure exploitation of prawn resources is conducted in a manner consistent with the principles of ecologically sustainable development. These impacts are not simple, as research has demonstrated that the impacts of trawling depend on the intensity of trawling and it is clear that trawl grounds are subjected to widely varying effort. The impacts of trawling also depend on the physical habitat and the question still remains '...what have been the impacts in previously and intensively trawled grounds in the main lagoon?' Particularly in softer sediments, as opposed to structured habitat patches. To properly address this question, information will be needed on fine-scale distribution of trawl effort (GPS resolution) so that sampling can be designed to cover a range of trawl-intensities and control for natural differences in habitat. Further, the impacts of trawling probably depend on the type of trawl gear used. There are many types of demersal trawl nets and their use depends on the target species and nature of the seabed. The gear used for trawling for demersal fishes is very different from that used for prawns, and the types of habitat targeted also differ, consequently the impacts of fish trawling are almost certainly different.

Documenting the direct impact of prawn trawling on the sessile seabed communities has been very important. But it is now perhaps even more important to determine the natural dynamics of benthos populations and the ecological processes structuring them, as well as their rates of recovery after trawling or other impacts. Such research would provide an assessment of the sensitivity of the fauna to a range of pressures and establish expected time frames for recovery. This knowledge is needed because large areas of the GBR have already been trawled, and for future management of the region, it is necessary to understand if and how these areas may recover if they were closed to trawling or if different strategies for trawling were implemented.

Strategies for managing prawn trawling will be required to ensure ecological sustainability, whilst allowing reasonable use. Certainly, seabed benthos can be impacted substantially and thus zoning plans should aim to preserve representative areas of such habitat and its biodiversity. Impacts on lagoonal soft-bottom benthos are suspected (Hutchings 1990), based on bycatch composition, but have not yet been formally documented. In the absence of rigorous information, the precautionary principle should initially be adopted and representative areas of this habitat and its biodiversity should also be preserved in zoning plans. Gaps in the biological and ecological information should be addressed and, in addition, systems to provide more reliable information on the fine-scale distribution and intensity of prawn trawling should be introduced. Such information could be obtained with the introduction of a vessel monitoring system and will be essential for assessing and managing the environmental impacts and ecological sustainability of prawn trawling.

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Endangered and charismatic megafauna

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ABSTRACT

The charismatic megafauna of the Great Barrier Reef includes 20 species of whales and dolphins, the dugong, and six species of sea turtles, several of which are listed as threatened. This fauna is highly valued by both Indigenous inhabitants and the wider community. The importance of the region to marine turtles and marine mammals was included in the World Heritage nomination. A questionnaire survey of 460 regular visitors to and workers in the Cairns Section of the Great Barrier Reef Marine Park identified the presence of megafauna as the second most important dimension in their perception of reef quality after ecological landscape. For some species, particularly loggerhead and green turtles and humpback and minke whales, tourism uses are increasingly important. Aborigines and Torres Strait Islanders wish to maintain their traditions of hunting green turtles and dugongs. Their interest in these species transcends hunting and they seek involvement in all aspects of their management. All the megafauna are long-lived, have low reproductive rates, and are difficult to monitor. Changes in population size must be large before they can be proved statistically. Declines have been detected in breeding female loggerhead turtles and in dugongs south of Cooktown. There are indications of declines in nesting green and hawksbill turtles in the Great Barrier Reef. Experimental work to separate the relative importance of impacts including habitat loss and degradation, incidental capture in fishing nets and traditional hunting (dugongs and green turtles only) is ethically unacceptable and will not provide results in a useful time frame. Consequently, it is important to minimise all these impacts.

INTRODUCTION

The charismatic megafauna of the Great Barrier Reef includes 20 species of whales and dolphins, the dugong, and six species of sea turtles, the whale shark, sharks and rays and large fish. The World Heritage Nomination specifically mentions sea turtles and marine mammals in the inventory of the Great Barrier Reef's natural heritage, stressing the importance of the Region as a feeding ground for dugongs and as a nesting ground for green and loggerhead turtles (GBRMPA 1981). This review will concentrate on sea turtles and marine mammals because it is these groups which include species which are both charismatic and threatened with extinction.

Species and their status

Sea turtles

Six of the world's seven species of sea turtle occur in the Great Barrier Reef region:

Family **DERMOCHELYIDAE**
Dermochelys coriacea, leatherback turtle

Family **CHELONIIDAE**

Caretta caretta, loggerhead turtle
Chelonia mydas, green turtle
Eretmochelys imbricata, hawksbill turtle
Lepidochelys olivacea, olive ridley turtle
Natator depressus, flatback turtle

Leatherback, loggerhead and olive ridley turtles are listed as `Endangered' in Queensland; green, hawksbill and flatback turtles are listed as `Vulnerable' (*Nature Conservation (Wildlife) Regulation 1994* Qld). In the Great Barrier Reef, most research has been carried out on green and loggerhead turtles. Studies on flatbacks and hawksbills are more recent but little is known about olive ridleys and leatherbacks.

Dugong

The dugong, *Dugong dugon*, is the only member of the Family Dugongidae and only one of four species in the mammalian Order Sirenia (sea cows). The coastal waters of northern Australia including the Great Barrier Reef are believed to support a significant proportion of the world's dugongs. The dugong is listed as `Vulnerable' (*Nature Conservation (Wildlife) Regulation 1994* Qld).

Cetaceans

Twenty-eight species of cetaceans have been recorded in Queensland waters, with about 20 species confirmed from the Great Barrier Reef Region. Most species are classified by the IUCN as insufficiently known, reflecting the paucity of knowledge of the order generally (Klinowska 1991).

Two species of baleen whale are often sighted in Reef waters: the humpback whale *Megaptera novaeangliae* which is listed as `Vulnerable' in Queensland (*Nature Conservation (Wildlife) Regulation 1994* Qld) and the minke whale *Balaenoptera acutorostrata sensu lato*. Two forms of minke whale occur in Great Barrier Reef waters (Arnold et al. 1987). Although their taxonomic status is unresolved, it is acknowledged that they need to be considered separately for management purposes (IWC 1991). Neither is listed under the *Nature Conservation (Wildlife) Regulation 1994* Qld. The `dwarf' or `diminutive' form is more commonly recorded in Great Barrier Reef waters than the `ordinary' or `dark-shoulder'. form. The Australian Cetacean Action Plan lists the `dwarf' minke as `No category assigned because of insufficient information' and the `dark shoulder' form as `Secure' (Bannister et al. 1996).

The IUCN Action Plan for Conservation of Cetaceans (Reeves and Leatherwood 1994) highlighted the vulnerability of coastal dolphins throughout much of their range. This assessment includes three of the species which are most often reported from the Great Barrier Reef region (the bottlenose dolphin, *Tursiops truncatus*; Indo-Pacific humpback dolphin, *Sousa chinensis*; and the Irrawaddy dolphin, *Orcaella brevirostris*). The last two are listed as rare under the *Nature Conservation (Wildlife) Regulation 1994* Qld, the bottlenose dolphin is not listed as rare and threatened.

Ecology

Sea turtles

Sea turtles share many common characteristics. They aggregate for breeding at a limited number of traditional nesting beaches, including some in the Great Barrier Reef. For example, Raine Island is an internationally significant green turtle nesting beach in the northern Great Barrier Reef; Wreck Island a major loggerhead nesting beach in the Capricorn Bunker Group. There is no parental care of eggs or hatchlings. Hatchling sex is determined by the temperature of the eggs during incubation with warm nests producing females and cool nests males (Limpus et al. 1983, 1985). Hatchlings are imprinted to the dip and strength of the earth's magnetic field and orient to light horizons and wave fronts as they disperse across the beach and out to sea (Salmon and Wyneken 1994; Lohmann and Lohmann 1996). Post-hatchlings are carried by ocean currents and spend the first years of their life in the surface open ocean waters following ocean gyres (Walker and Parmenter 1990). Flatback turtles are an exception to this pattern and remain within the waters of the

Australian continental shelf (Walker and Parmenter 1990).

Leatherback turtles continue to inhabit the open ocean throughout their lives, feeding principally on macroplankton. In contrast, the other species leave the carnivorous planktonic life phase at the size of a dinner plate or larger to enter shallow benthic feeding areas where green turtles eat algae and seagrasses (Lanyon et al. 1989); loggerheads molluscs and crabs (Moody 1979); and hawksbills sponges and algae (Meylan 1988). The Great Barrier Reef Region supports internationally significant feeding populations of green, loggerhead, hawksbill and flatback turtles.

Chelonid sea turtles are slow growing, taking decades to reach maturity (Chaloupka and Limpus in press) and remain associated with localised feeding areas for extended periods (Limpus et al. 1992, Limpus 1994a). Adult turtles migrate up to 2,600 km between these feeding areas and their rookeries displaying high fidelity to individual feeding areas and nesting beaches (Limpus et al. 1992). Thus widely separated clusters of rookeries support populations which are virtually genetically independent (Bowen et al. 1992; Norman et al. 1994).

Individual females do not breed annually and breeding frequency varies amongst species. For example, green turtles which nest in the southern Great Barrier Reef breed about every five to eight years (Limpus et al. 1984a, 1994) while flatbacks breed at two to three year intervals (Limpus et al. 1984b). The proportion of adult female green turtles that breeds in any one year is a function of regional climate (ENSO) two years before the breeding season (Limpus and Nicholls 1994). Except for the brief period of elevated mortality associated with the egg and hatchling dispersal phase (Gyuris 1994), sea turtles require high annual survivorship throughout their lives to meet the demands of their life history characteristics. Preliminary population modelling of eastern Australian loggerhead turtles suggests that the loss of only a few hundred adult and near adult turtles annually throughout the feeding range of the stock would be critical for the survival of the population (Heppell et al. 1996).

Dugong

The dugong is a seagrass specialist (Marsh et al. 1982; Lanyon et al. 1989) selecting lower seral or `pioneer' species. The genera *Halophila* and *Halodule* are favoured in the Great Barrier Reef Region (Lanyon 1991). Lee Long et al. (this volume) summarise the distribution and status of seagrasses in the Great Barrier Reef.

Dugongs may live for seventy years or more. A female does not have her first calf until she is at least 10 years old, and then only bears a single calf every three to five years (Marsh 1980, Marsh et al. 1984, Marsh 1995a). Adult survivorship must be very high (>95% p.a.) for population numbers to be maintained. Population simulations (Marsh 1995a) indicate that dugong numbers are unlikely to increase at more than about 5% per year, even if all the females in a population are breeding maximally. The maximum rate of increase must be lower in areas where there is mortality due to incidental drowning in mesh nets and Indigenous hunting. Sustainable losses from all anthropogenic impacts are likely to be in the order of only 1–2% of the female population per year (see Choquenot 1996).

More than 30 dugongs that have been tracked using VHF or satellite transmitters in northern Australia. Most movements have been local (Marsh and Rathbun 1990; Preen 1993). However, within the Great Barrier Reef, some individuals have undertaken long-distance movements of up to 400 km (Marsh and Rathbun 1990, Tony Preen personal communication 1996).

Cetaceans

Cetaceans typically bear one young at a time at intervals of several years (Perrin and Reilly 1984). The calves of some toothed whales and dolphins may suckle for up to several years (Perrin and Reilly 1984). Mean pre-reproductive periods ranges from three to four years for some dolphins to 20 years or more in male sperm whales (Best et al. 1984; Perrin and Reilly 1984).

The female reproductive cycle in baleen whales is usually two years, with a gestation period of about a year. Lactation lasts about half a year (Lockyer 1984). Normally one calf is born in warm temperate or sub-tropical waters. Most baleen whales undertake extensive

migrations for feeding and the reproductive cycle appears to be geared to this annual cycle of migration and feeding.

Humpback whales undertake an annual migration from summer Antarctic feeding grounds to winter tropical breeding grounds. Within the Great Barrier Reef Region, sightings peak in August. They are widely distributed but with few records north of 15°S. Most reports of calves from the east coast of Australia are from the Great Barrier Reef, especially about 20°–21°S. No discrete breeding grounds have been documented (Simmons and Marsh 1986, Paterson 1991, Kaufman et al. 1993, Paterson et al. 1994).

Life history and migration patterns of dwarf minke whales are incompletely known. They are recorded in the northern Great Barrier Reef (about 15°–17°S) between May–September, with maximum sightings in June and July. There are only a few records of cow – calf pairs (Arnold, unpublished data).

Life history and behavioural data are largely unavailable for two of the three species of coastal dolphins occurring in the Great Barrier Reef: *Sousa* (Ross et al. 1994) and *Orcaella* (Marsh et al. 1989). Better information exists for bottlenose dolphin *Tursiops* but the only 'local' data are from captive animals in Western Australia (Cheal and Gales 1992).

Trends in abundance

Sea turtles

Sea turtles are difficult to census because they are long-lived, highly migratory, do not follow fixed migratory paths and disperse in feeding areas up to 2,600 km from their breeding sites. Female loggerhead and green turtles have been censused at several nesting beaches in the Great Barrier Reef Region for more than 20 years. The number of loggerheads breeding in eastern Australia has declined by 50–80% since the late 1970s (Limpus and Reimer 1994, Heppell et al. 1996). In contrast, the high variance in annual nesting numbers in response to regional climatic cycles (ENSO; Limpus and Nicholls 1994) makes it difficult to interpret trends in the green turtles which nest in the Great Barrier Reef. However, monitoring of the northern Great Barrier Reef stock suggests that the mortality of adults in distant feeding areas is unsustainable. Early warning signals include an increased proportion of first time breeders in the population, decreasing average size of breeders and increased remigration interval (Limpus et al. 1996). Although there are only six years of hawksbill census data from the Great Barrier Reef Region (Milman Island), these data are consistent with a declining population (J. Miller and K. Loop personal communication). There are no clear indications that breeding populations of flatback turtles are in decline in the Great Barrier Reef (C.J. Parmenter personal communication).

Dugong

Aerial surveys are the only feasible method of determining the distribution and abundance of the dugong. For logistical reasons, the surveys in the Great Barrier Reef Region have been conducted in two series: one covering the remote coasts north of Cape Bedford near Cooktown, the other the urbanised coasts south of Cape Bedford. The remote coast was surveyed in 1984, 1985, 1990 and 1995 using the same techniques. In 1995, the survey resulted in a minimum population estimate of 8190 $\pm$ s.e. 1172 dugongs (Marsh and Corkeron 1996a). This region is the most important dugong habitat within the Great Barrier Reef and one of the most important in Australia (Marsh and Saalfeld 1989, Marsh et al. in press). There was no significant difference between dugong densities in 1985, 1990 and 1995 suggesting that dugong numbers are being maintained in the northern Great Barrier Reef. However, the survey techniques employed are appropriate for depicting only regional-scale trends and cannot accurately detect changes on a local spatial scale.

Aerial surveys were conducted between Cooktown and the southern boundary of the Great Barrier Reef Marine Park during 1986, 1987, 1992 and 1994. The number of dugongs sighted between Dunk Island and Cape Bedford was insufficient to estimate the population size in either 1986 or 1992 and was not attempted in 1994. The surveys indicate that the number of dugongs in the region has declined by over the past eight years from an estimated 3,479 $\pm$ s.e. 459 in 1986/87 to 1,857 $\pm$ s.e. 292 in 1992 and 1,682 $\pm$ s.e. 236 in 1994 (Marsh et al. 1996). The population estimate derived from the 1994 surveys was only 48.4% of the 1986/87 population estimate. Comparison of the results of the 1986/7, 1992

and 1994 surveys indicates that the decline in dugong numbers was spread throughout much of the region, but was most serious between Cape Cleveland and Broad Sound. Marsh et al. (in press) rate the status of the dugong in this region as `Critically Endangered' because dugong numbers have declined by approximately 50% over the past eight years. Over a large section of the region, this decline is over 80%. Other evidence (catches in shark nets, reports from Aboriginal hunters, comparisons with earlier reports by scientists) suggests that the decline has been occurring since the 1960s or even earlier.

Cetaceans

East Australian humpback whales belong to a stock which winters in the south-west Pacific and summers in that part of the Antarctic known as Area V. The stock size was estimated at 10,000 prior to whaling in 1949–1962; it declined to an estimated 200–500 animals when the whaling industry collapsed (Chittleborough 1965, Chapman 1974). Estimates for recovery are available only for the east Australian component of the stock. They range from 10% (95% CL: 6–13%; Paterson and Paterson 1989); 14.4% (no confidence limits; Bryden et al. 1990); 11.7% (95% CL: 9.6–13.8%, Paterson et al. 1994). Current estimates of the recovery of east Australian humpbacks approximate, or even exceed, the maximum recovery rate which is considered biologically feasible (see Best 1993) indicating that impacts are sustainable at present.

Brown et al. (1995), using biopsy sampling of humpback whales at 27°S, reported a predominance of males to females (2.4 males:1 female). This bias had been noted in commercial whaling statistics (Chittleborough 1965) but was attributed to selection against females with a calf. Brown et al. (1995) argued instead that some females do not migrate every year. This finding suggests that the size of the stock is larger than the present estimates.

The dwarf minke whale is widespread throughout the southern hemisphere (Best 1985, Arnold et al. 1987, Zerbini et al. 1996) but there is no information on stock structure or abundance for any population. Present attempts to photo-identify individuals in the northern Great Barrier Reef may give some indications of local numbers but will not lead to reliable estimates of population size because the study area is only a small part of the species' range.

Marsh (1990) and Marsh et al. (1993, 1994) provided estimates of dolphins throughout the Great Barrier Reef, based on sightings in aerial surveys for dugongs. However, due to an inability to identify dolphin species from the air, the estimates pooled at least four genera (*Orcaella, Sousa, Stenella, Tursiops*) which have difference school and metapopulation structures, ranging behaviours, habitat requirements and population abundances and anthropogenic impacts. This lack of resolution is particularly crucial for inshore dolphins which are exposed to several human impacts.

Values of the megafauna

Indigenous values

The intrinsic spiritual and social importance of the megafauna to Indigenous peoples is based on their relationship with and respect for these species, especially green turtles and dugongs. Dugongs and turtles have totemic importance and totemic restrictions still influence most hunters. Some traditionally affiliated groups will not hunt dugongs under any circumstances because they are part of their creation stories. The meats of green turtles and dugongs rank highly as ceremonial foods for celebrations ad other important cultural or family gatherings. Dugong oil is also a highly valued property and is used as a panacea for almost any ache, pain or illness. The meat from one dugong can sustain a family for up to several months and the dugong and green turtle have economic value for the Indigenous peoples of the Region including the traditionally affiliated inhabitants and those with a historical association. A skilled hunter enjoys considerable prestige in his community.

Index of reef quality

The presence of megafauna is an important index of perceptions of reef quality. B.Breen,

S.Shafer and D. Breen (unpublished data 1996) surveyed 460 regular visitors to and workers in the Cairns Section of the Great Barrier Reef Marine Park representing a wide selection of reef user groups including recreational and commercial fishing, sailing, snorkelling, SCUBA diving, tourism and scientific research. Each respondent was asked to rate the quality of two reef sites of their choice according to 18 different biophysical and social variables. A principal components factor analysis with varimax rotation identified a reduced number of dimensions. The ecological landscape dimension which was best represented by the variables `coral cover' and `underwater topography' explained the greatest proportion of the variance (30%). The megafauna dimension explained the next highest proportion (11%), while convenience (to port and other reef sites) and shelter both explained 7%.

The megafauna dimension was best represented by the presence of marine mammals but also included turtles, sharks and big fish. The ribbon reefs off Cooktown and Port Douglas and a few inter-reefal sites off Cairns received the highest scores for this dimension. The sites off Cairns and Port Douglas are commonly referred to as `whale alley' by the local tourism operators who frequently observe minke whales at these sites during the winter.

Commercial values

Turtle-watching
Residents of the Bundaberg district in the southern Great Barrier Reef have spent summer nights observing nesting loggerhead turtles for over 70 years. This activity was initially linked with a low level of egg harvest, but by the 1960s, the emphasis for many had shifted totally to turtle-watching. By the 1990s, an organised tourist industry had developed with some 25,000 person nights of turtle watching over a three month period each summer. This industry is estimated to be worth more than $2 million annually to the Bundaberg district economy and caters to local, national and international visitors. These estimates do not include the value of the industry on the offshore islands in the Capricorn Bunker Group.

Whale-watching
Whale-watching has become a major industry world-wide; Hoyt (in Carlson 1996) estimated an annual participation of at least 5.4 million people in 65 countries and overseas territories. Within Australia, a recent review estimated at least 530,000 dolphin and whale watchers generated a direct value of $A9.5 million for the 1995 calendar year (ANCA 1996). Within the Great Barrier Reef, whale-watching is based on humpback whales (primarily to the east of the Whitsunday Islands) and dwarf minke whales near the outer reefs between Cairns and Lizard Island (14°40' – 16°55'S). Humpback whales are observed by visitors onboard charter vessels which operate under permit. Dwarf minke whales are observed both at the surface and underwater from dive charter vessels. Encounters with minkes have been generally opportunistic, when the whales approach vessels at anchor and maintain contact with the boat and divers. However, the chance of underwater encounters with minke whales is increasingly promoted in dive industry advertising.

Impacts

For long-lived, slow breeding species such as marine turtles and mammals, the rate of population change is most sensitive to changes in survivorship. Even a slight reduction in adult survivorship can cause a chronic decline. In the recent past, the major impacts on the sea turtles, dugongs and humpback whales which use the Great Barrier Reef was commercial and/or traditional hunting. As activities change, the impacts are becoming more indirect. The incidental effects of commercial fishing on marine mammals and reptiles are generally unquantified but are of major concern for some species. More insidious impacts are increasing: loss of habitat from coastal developments, pollution and collisions with boats to name just a few. Because marine mammals and reptiles are so long-lived and of such high conservation value, it is ethically unacceptable and logistically impossible to conduct experiments to disaggregate the relative importance of multiple impacts on the megafauna in the Great Barrier Reef Marine Park. This discussion will concentrate on the impacts of tourism, fishing, habitat loss and traditional hunting. Marsh and Corkeron (1996b) provide a more complete account of the impacts on dugongs in the Region. Many of these impacts also apply to the other megafauna.

Fishing impacts

The bycatch of megafauna in trawls and mesh nets is a significant source of anthropogenic mortality in the Great Barrier Reef Region. In addition, shark nets set on Great Barrier Reef beaches to protect bathers catch turtles, dugongs and dolphins as outlined below.

Trawl fishery
Accidental drowning of turtles in trawl nets catches an estimated 1769± s.e. 960 turtles in the Great Barrier Reef each year of which between 29 and 138 are estimated to drown (Robins unpublished data, see also Poiner and Harris 1994 and Robins 1995). The catch composition is flatbacks (38%), greens (30%), loggerheads (14%), olive ridleys (13%), hawksbills (3%) and unidentified (2%). However, this catch composition is unlikely to reflect the probability of drowning which varies with species. For example, loggerheads are three times more likely to drown than loggerheads in the northern prawn fishery (Poiner and Harris 1994). Few dugongs or cetaceans drown in commercial prawn trawls.

Mesh net fishery
The incidental catches of dugongs in mesh nets in the southern Great Barrier Reef has received widespread publicity with 15 of 30 dugong carcasses reported between January and September 1996 being probable net kills (A.R. Preen personal communication). It is likely that the bycatch of dolphins and turtles is also a problem although few data are available. In September 1996, two Irrawaddy dolphins one Indo-Pacific humpback dolphin and three turtles were reported dead in the Mackay area in net related incidents (*Mackay Daily Mercury* 24.9.96).

Shark nets
A total of 2140 turtles, 552 dugongs and 216 dolphins has been caught in shark nets in the Great Barrier Reef Region since they were introduced in the 1960s (Baden Lane unpublished data 1996). Only 6.9 % of dugongs and 10.2% of dolphins were recorded as being released alive. The corresponding percentage for turtles is much higher (37%). Many shark nets have been replaced with lines of baited hooks and the only remaining nets in the Great Barrier Reef Region are at five locations near Cairns, two near Townsville and three near Mackay. Since the program was re-organised in 1992, five dugongs, 16 dolphins and 68 turtles have been caught. Very few data have been collected on the specific identity of the dolphins. This is a serious omission, especially as Irrawaddy dolphins are thought to be the cetacean most frequently caught north of Mackay (Paterson 1990). The replacement of nets with baited lines does not eliminate the bycatch of megafauna; loggerheads are caught on drumlines set as part of the Shark Protection Program in southern Queensland.

Tourism impacts

Turtle-watching
People on a nesting beach temporarily disturb nesting turtles but this does not appear to affect nesting productivity. Indeed as a result of tourism-related activities at the Mon Repos Conservation park in 1995–1996, an additional 250,000 loggerhead hatchlings were produced that would have been destroyed by natural flooding and erosion.

Whale-watching
Participants of a workshop on the scientific aspects of managing whale watching (IFAW 1995) noted that 'to date, there is almost no evidence of significant long-term negative impacts (of whale-watching) on cetacean individuals, groups or populations, but while studies continue, it is prudent to adopt a precautionary approach'. However, this conclusion does not acknowledge the methodological impediments to evaluating the direct impacts of tourism on whales and assessing the significance (if any) of short-term behavioural response to tourists. The objective should be to ensure that whale-watching does not cause adverse changes in population dynamics or impede patterns of activity or habitat use, including feeding and reproduction. Research that would allow improved assessment of long-term effects is essential (IWC, 1996).

Research in Hervey Bay, immediately south of the Great Barrier Reef, has demonstrated short-term changes in humpback whales' behaviour in the vicinity of whale watching vessels (Corkeron 1995). Although there are indications of temporal and spatial changes in the whales use of Hervey Bay (Corkeron et al. 1994), inconsistency in the survey techniques prevents determination of any trends (Corkeron 1993). Monitoring and photo-identification

studies have also been carried out in the Whitsunday Islands. The results are not available generally. The cumulative effects of whale-watching at several locations along the migration route of humpback whales along the east coast of Australia remains unassessed.

The impacts of vessel noise in Hervey Bay were documented by McCauley et al. (1996), who recommended speed limits and vessel manoeuvring protocols to minimise noise levels. The general results could be applied elsewhere, but it should be recognised that: (1) some areas of the Great Barrier Reef already have extensive tourist vessel traffic completely unrelated to whale-watching activities (e.g. dwarf minke whales are seen near high use areas such as Agincourt Reef complex and Cod Hole/Ribbon Reef 10), and (2) cetaceans may react differently to whale-watching vessels from other vessels (Janik and Thompson 1996).

Only preliminary observations are available for dwarf minke whales on the Great Barrier Reef (Arnold, unpublished data), concentrating on seasonality of sightings, pod size, contact time, behaviour with divers and feasibility of individual photo-identification. Better data are needed on the proportion of stock which approaches vessels anchored on reefs, the proportion of mature animals and the abundance of mother–calf pairs. A dedicated study would be extremely expensive but preliminary data could be collected with the cooperation of the dive charter industry.

Habitat loss and degradation

The most serious impact of habitat loss on the megafauna of eastern Australia was the disappearance of more than 1,000 km^2 of seagrass from Hervey Bay adjacent to the southern boundary of the Great Barrier Reef in 1992/1993 (Preen and Marsh 1995). The cause is not known although it is thought that high turbidity resulting from the flooding of the Mary and Burrum Rivers and run-off from a cyclone were responsible (Preen et al. 1995). Aerial survey estimates indicate that the dugong population of the Hervey Bay region plummeted from about 2,200 in 1988 to 1,100 at the end of 1992 and 800 in 1994 (Marsh et al. 1996). The proportion of calves declined from 22% in 1988 to 2% in 1993 and 1.5% in 1994, presumably because the dugongs that remained in the region were not getting enough to eat. A total of 99 dugong carcasses was recovered. It is likely that the adverse impact on green turtles was also significant but this was not documented.

Camping, resort and residential development on the southern Great Barrier Reef turtle rookeries alienates turtles from nesting areas that are primarily female producing habitat. The harbour and associated erosion at Heron Island have resulted in the construction of rock retaining walls and rubble banks excluding nesting over 22% of the Island's circumference, mostly from female producing habitat. Street and house lighting particularly at mainland rookeries has caused increased hatchling mortality through disorientation.

Indigenous hunting

In the Great Barrier Reef Region, green turtles and dugongs are hunted by members of remote communities on the coast of Cape York and by the Indigenous inhabitants of the urban coastal communities from Cooktown south. Turtle eggs of all species are also harvested.

There are few hunting statistics from the Great Barrier Reef and most of these are out of date (see Marsh and Corkeron 1996b for details of dugong harvest). Hunting is limited by weather and the small size of boats used and fuel costs. Extensive travel to hunting grounds is currently limited by road access in the northern Great Barrier Reef. The establishment of outstations may change the spatial pattern of hunting. Although this is likely to diminish the refugial value of areas where hunting does not currently occur, there may be benefits such as additional local control of hunting and a reduction of in the number of dugongs hunted near established communities.

Hunting pressure has presumably changed spatially in the Great Barrier Reef in the last 30 years or so (Ponte et al. 1994) as a result of forced removal or more recently the migration of Torres Strait Islanders to mainland Australia in large numbers. Some 10,500 Indigenous males now reside in the southern Great Barrier Reef Region (Ponte et al. 1994) including many Islanders who are used to having turtle and dugong meat in their diet (Johannes and MacFarlane 1991; Harris et al. 1994). This is almost ten times the number of Indigenous

males in the northern Great Barrier Reef. How many urban Indigenous males aspire to hunt turtles and dugongs is unknown. There is an established practice of selling turtle and dugong meat in several centres, even though this is illegal.

The number of green turtles hunted in the Great Barrier Reef Region is but a small component of the harvest of this stock in neighbouring countries. The total harvest may be of the order of 100,000 annually. Most turtles harvested are large females. Similarly, the annual harvest of tens of thousands of hawksbills from the Great Barrier Reef breeding stock in neighbouring countries is not sustainable. These harvests are serious threats to green and hawksbill turtle populations in the Great Barrier Reef Region.

Management

Overall approach

Because of the complex jurisdictional arrangements, the management of the megafauna in the Great Barrier Reef relies on close working arrangements between the Great Barrier Reef Marine Park Authority (GBRMPA), other groups within the Commonwealth Department of Environment, Sport and Territories, the Queensland Department of Environment, the Queensland Department of Primary Industries, the Queensland Fisheries Management Authority and stakeholder groups including local government, Indigenous peoples, commercial and recreational fishers, conservation groups and local communities. In addition, the management of turtles and cetaceans which undertake lengthy migrations requires international cooperation.

As discussed above, it is difficult to determine population trajectories for turtles or marine mammals, hence a precautionary approach is required. This is virtually impossible to achieve in the current complex jurisdictional environment. When declines are detected, and they have to be large before they are detected (Marsh 1995b), it is impossible to disaggregate the relative importance of multiple impacts. Thus when there is evidence of a problem, it is necessary to address all impacts. This approach is also necessitated by the reluctance of the stakeholder groups causing the impacts to respond unilaterally.
The greatest challenge is the control of indirect impacts when the causal links are not well established. Experience has shown that it is hard to convince a prospective developer that a resort may have adverse impacts on dugongs in nearby habitats. It will be even harder to convince a farmer that erosion from his property may threaten the survival of dugongs and green turtles grazing on submarine pastures many kilometres downstream. Nonetheless, some progress has been made in addressing impacts in which the causes are established as summarised below.

Indigenous hunting

In the Great Barrier Reef Region, traditional hunting can be carried out under permit in all zones except Preservation Zones. A large inshore Preservation Zone was established primarily to protect dugongs in the Far Northern Section of the Park in the region south of Cape Melville. Some modifications of the boundaries of this Zone are likely as a result of the rezoning of this Section but hunting will still be banned in coastal waters over at least one third of the coast between Murdoch Island and Cape Melville under cooperative arrangements with local Indigenous peoples.

In conjunction with the Queensland Department of Environment, GBRMPA has been consulting with Aboriginal and Torres Strait Islander groups for over a decade regarding the traditional use of turtles and dugongs. Consultation initially focused on remote Cape York communities (Smith and Marsh 1990) but has recently involved other groups including urban Indigenous peoples. In view of the development of the outstation movement and the improvement of roads on Cape York, the future sustainability of Indigenous dugong hunting in the remote areas of the Great Barrier Reef Region will depend on the development of effective co-operative management arrangements. These need to be developed as a matter of urgency.

Over the last few years, GBRMPA and the Queensland Department of Environment have assisted Indigenous groups in urban Queensland to establish Councils of Elders to address traditional hunting issues (Cook 1994). Since the Councils became aware of the decline of

the dugong in the southern Great Barrier Reef, most Councils have voluntarily agreed not to harvest dugongs and there is currently no permitted take south of Cooktown. The Darumbal–Noolar Murree Aboriginal Corporation for Land and Culture of Rockhampton has signed a formal agreement with the GBRMPA and has agreed that it would be inappropriate for Indigenous hunting to occur in that part of the Great Barrier Reef Marine Park within the Shoalwater Bay Military Training Area. Many Indigenous groups are supportive of the concept of a chain of dugongs sanctuaries in the inshore waters of the Great Barrier Reef.

Tourism

Turtle-watching

A direct consequence of the turtle-watching industry in the Bundaberg area has been the creation of a local community educated in turtle biology. This community has in turn been instrumental in enhancing the management of the turtle nesting area through their advice to local and state governments. Turtle-watching can be managed as long as the nesting turtles are not disturbed to the level of reducing egg production or hatching success. These are the performance indicators that can be used in developing a monitoring program to guide management of tourist numbers and activities. At the same time, as a safeguard, the entire nesting populations of a genetic unit should not be exposed to tourism impacts. In the southern Great Barrier Reef, public access is managed to exclude tourist visits to the nesting loggerhead and green turtles at Wreck, Erskin, Hoskin and Fairfax Islands while encouraging visitation to rookeries such as Mon Repos and Heron Island.

Whale-watching

Although guidelines for surface observation of whales are widespread (Carlson 1996) and apply in the Great Barrier Reef, there is no generally accepted protocol for swimming with whales. Dive charter operators have developed some procedures for minke whales in the northern Great Barrier Reef. These are in the process of being refined with the aim of developing an industry code of practice. In the meantime, experiential data may be the most effective management tool. Passengers swimming with minke whales in the northern Great Barrier Reef observed that infringements of protocol (e.g. swimming directly at the whale) caused avoidance behaviour by the whale and diminished the quality of the encounter (Birtles and Arnold, unpublished). This influenced their behaviour on subsequent dives and increased compliance with the protocol outlined in pre-dive briefings.

Fishing

Despite the calls of the conservation movement, turtle excluder devices are not yet compulsory in Queensland, management agencies electing to encourage compliance with education rather than regulation because of the difficulties of enforcement. Mesh netting is banned in some inshore waters of the Great Barrier Reef Region as a result of commonwealth or state marine park zoning. Since 1995, mesh netting in Shoalwater Bay has been subject to stricter control under Queensland fisheries legislation and the Draft Management Plan for the Bay proposes to ban gill netting (GBRMPA 1996). The conservation movement has demanded additional closures but none has been announced as yet.

The Queensland Commercial Fishermen's Organisation has acknowledged that the incidental capture and drowning of dugongs in mesh nets and turtles in trawls are a problem. It has developed a Code of Practice for dealing with entangled turtles and is developing a parallel code for dugongs. This Organisation has advocated the development of an education program to inform commercial fishers on aspects of the conservation biology of endangered species and management and on methods to minimise their take. It is hoped that attendance at this program will become part of the Trainee Master Fisherman's course and compulsory for Master Fishermen with net endorsements.

CONCLUSIONS

The endangered and charismatic megafauna of the Great Barrier Reef is spectacular and diverse and highly valued by Indigenous Australians and the wider community. Australia has international obligations to protect the World Heritage values of the Region including its megafauna. Best practice standards need to be established for all activities which impact on

the megafauna including fishing (see Valentine et al. this volume), with severe penalties for non-compliance. At present, the management standards for fishing in the Great Barrier Reef are no different from anywhere else in Queensland.

There is also an urgent need to acknowledge that the green turtle and the dugong are animals of special significance to Indigenous peoples and that their interest extends far beyond the management of hunting. They must be empowered to take a leading role in the development of all management initiatives for these species based on an exchange of information between Indigenous Elders and scientists.

South-east Asian turtle populations are in decline (Limpus 1994b). The prospects of dugongs surviving outside Australian waters are considered slim (Bertram 1981). Recent evidence for decline in the abundance and range of coastal marine mammals throughout south-east Asia, especially Irrawaddy dolphins, while largely anecdotal, is compelling (UNEP(W)EAS WG1/2 1996). The declines in loggerhead turtles (Limpus and Reimer 1994) and dugongs (Marsh et al. 1996), the signs of decline in green (Limpus et al. 1996) and hawksbill turtles (J. Miller and K. Loop personal communication), and the uncertain status of the inshore dolphin fauna, all suggest that the Great Barrier Reef will not be an effective global refuge for the charismatic megafauna of the tropical coastal Indo-West Pacific under the present management regime. Special management measures are clearly required, perhaps along the lines of the United States *Marine Mammal Act 1972* which details explicit reporting requirements and timelines for action. The present complex arrangements involving agencies with different legislative responsibilities make it impossible to resolve issues quickly and effectively as is demonstrated by the current attempts to initiate emergency measures for dugong conservation and recovery in the Great Barrier Reef. Consideration should be given to placing the management of the megafauna under a single jurisdiction as has been done for some fisheries.

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SESSION 3

Pressures on reefs, islands and cays

Chair: Carden Wallace

Rapporteur: Jamie Oliver

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Keynote Paper:
Issue-driven research for managing the Great Barrier Reef: progress and future directions
T Done*, L Bode, R Coles, C Crossland, U Engelhardt, M Furnas and K Woolfe

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Population and community dynamics of corals: implications for management of the Great Barrier Reef
T Hughes
(abstract only)

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Environmental implicaions of waste-water management on resort islands of the Great Barrier Reef
R Volker*, M Gallagher* and A Johnston

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Threats, status, trends and management of seabirds on the Great Barrier Reef
K Hulsman*, P O'Neill, T Stokes and M Warnett

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The effects of line fishing on the Great Barrier Reef: available evidence and future directions
B Mapstone*, C Davies and J Robertson

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Issue-driven research for managing the Great Barrier Reef: progress and future directions

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ABSTRACT

The CRC Reef Research Centre is conducting a broad ranging program of research which underpins the management of the Great Barrier Reef Marine Park and World Heritage Area as a multiple use marine protected area. Ecological survey and monitoring projects have provided baseline descriptions of status and variability in seagrass areas and coral reef communities in relation to natural environmental gradients and disturbance by severe, broad scale episodic events, such as cyclones, floods, and in the case of coral reefs, crown-of-thorns starfish. Studies are under way to characterise, for all parts of the Great Barrier Reef, risks of exposure and return periods, for deleterious cyclone waves, flood plumes, and crown-of-thorns outbreaks, and to hindcast likely impact distributions for particular events. These studies will assist in deciding where a change in ecosystem status warrants a response by environmental managers. Deleterious thresholds for key biota are being determined through field experiments, micro-environmental measurements, physiological studies and modeling. Integration across these projects will provide a capacity to assess the sustainability of fundamental ecosystem properties, conservation goals and production goals under future scenarios for climate change, use of the land, and use of the Great Barrier Reef. Planning for the latter will be guided by improved understanding of geographic variability in the reliability, strength and biological diversity of replenishment of populations of different species of algae, fish, coral and other biota.

INTRODUCTION

Ecologically sustainable development of the Great Barrier Reef relies on the setting of patterns and levels of use and protection which achieve both conservation and production goals in an environmental setting which is highly complex and variable in space and time. Two major goals of the CRC Reef Research Centre are 1) to improve the knowledge base for decisions which affect sustainability of Great Barrier Reef ecosystems, and 2) to systematise and communicate the knowledge and the uncertainty in a manner which ensures they are used to best effect. The latter would ideally be based on accurate information on ecological properties affected by decisions, and an assessment of the level of risk to those properties, both from nature and from the patterns of use and protection implemented.

In the Regional Environmental Status Program of the CRC Reef Research Centre, research is undertaken in six Projects (table 1) which address aspects of three major issues identified by various stakeholders: 'run-off' (the threat posed to Great Barrier Reef ecosystems by run-off from the land – Pulsford 1996; †Larcombe and Woolfe 1995) , 'patterns of use and protection' (see below); 'anthropogenic v. natural change' (the extent to which humans exacerbate natural disturbances and stresses, or introduce new ones). The Program's operational framework and relationship with decision makers are indicated in figure 1.

† These papers were produced with significant support from the CRC Reef Research Centre.

Table 1. The Regional Environmental Status Program of the CRC Reef Research Centre. Relevance of projects to issues identified by Centre partners.

Project Titles	Issues		
	Extent of impact of run-off from land on marine ecosystems	Patterns of use and protection	Anthropogenic v. natural change
1. Inputs and impacts	•	•	•
2. Hydrodynamics and dispersal	•	•	•
3. Sediments history and accumulation	•	•	•
4. Living system response	•	•	•
5. System models	•	•	•
6. Crown-of-thorns starfish	•	•	•

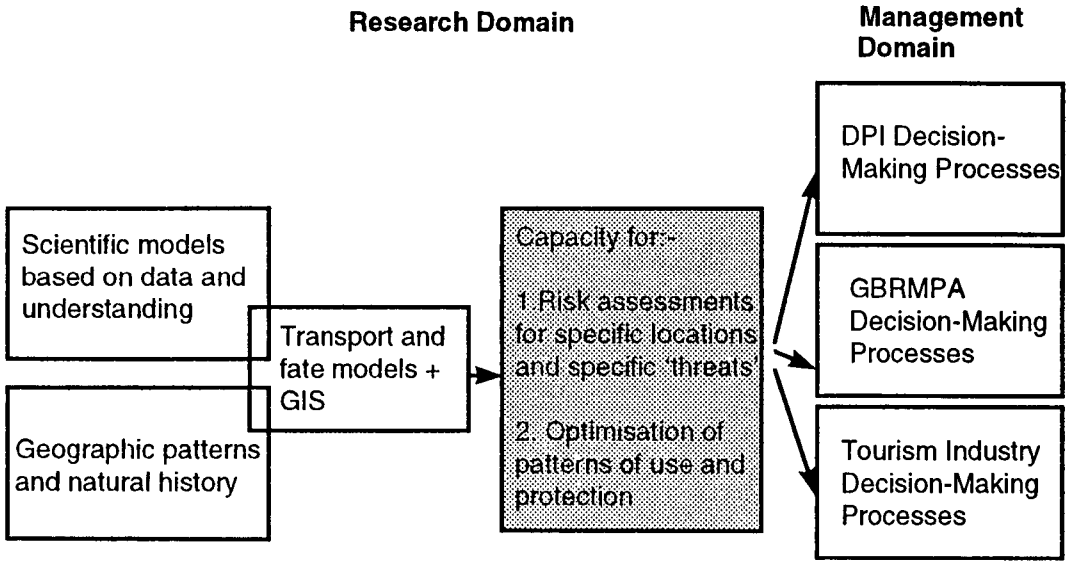


Figure 1. Relationships between strategic research activities within the CRC's Regional Environmental Status Program, and between the Program and CRC partners with decision-making roles. The shaded box indicates research outcomes of goals 1 and 2 (in text). GIS = Geographic Information Systems; DPI = Queensland Department of Primary Industry; GBRMPA = Great Barrier Reef Marine Park Authority

The research has a very broad scope. We are aiming to document where different types and qualities of habitats, some previously undescribed, occur throughout the Great Barrier Reef (e.g. †Lee Long et al. 1996; †Van Woesik and Done in press); to understand the causes and extent of variability in time and space, be they natural or human related (e.g. †McCook et al. in press; †Fabricius and De'ath in press); to assign values to living systems (†Done 1995); and assess how much additional exploitation, stress or impact living systems can absorb without compromising fundamental ecosystem properties such as viable population sizes, resilience, biodiversity, bioconstruction and productivity (†Done et al. 1996); to identify and understand spatial distributions, recent chronologies, and long-term trends and fluctuations in key threatening processes, specifically run-off (†Larcombe and Woolfe

1995; †Mitchell et al. in press), cyclones (†Puotinen 1997) and crown-of-thorns starfish (†Engelhardt and Lassig in press; †Engelhardt et al. in press).

The remainder of this paper is in two parts. The first considers the issue of patterns of optimal use and protection, and the second, the issue of run-off as a threatening process.

Optimal design for geographic patterns of use and protection which achieve conservation goals while allowing reasonable use

The Great Barrier Reef Marine Park is managed as a multiple use area with the goal of 'conservation while allowing reasonable use'. Currently, four management sectors of the Great Barrier Reef Marine Park contain both 'no take' areas and areas where different levels of access and resource exploitation are allowed. A five year objective for conservation in the Great Barrier Reef Marine Park and World Heritage Area (GBRMPA 1994 p. 16) describes the purpose of the more highly protected areas: 'To protect representative biological communities throughout the Area to act as source areas, reference areas, and reservoirs of biodiversity and species abundance.' i.e. Assuming that protection of such areas maintains both biological diversity and abundance at levels above those of surrounding areas, they have the potential to act as 'source' areas for other areas down-stream, both exploited and protected. Each area relies on input of propagules (seeds, spores, larvae and juveniles) for replenishment of its own populations, and, as a 'good' site in a network of protected areas, should export its reproductive output to places where they have a the best chance of settling and surviving.

Work within the CRC is establishing a capacity both to assess the efficacy of present provisions for protection, access and use, and to assist in their revision. This capacity is based on recognition of three things:

1. improved understanding of geographic and oceanographic settings within the Great Barrier Reef, in the context of management time frames,
2. development of measures to rank areas based on intrinsic ecological qualities (including but not limited to fishery stock assessments), and
3. approaches to rank different areas according to extrinsic threats, and design networks which best spread the risk.

1. Geographic and oceanographic settings, and management time frames

Any assessment of a particular area's contribution to an actual or proposed network of protected areas needs to be made in the context of management time frames and of spatial and temporal variability in physical and environmental settings, and in biology. Areas might be rated according to both their own replenishment (what is the likelihood that adequate supply and diversity of propagules will arrive within say 3 to 5 years?), and their contribution to areas downstream (what is the likelihood that propagules released by this area will be transported to a suitable habitat)?

Recent advances in data, models, computational power, and management processes have greatly enhanced capacity to make such assessments. New meso-scale hydrodynamic models for specific sectors of the Great Barrier Reef (grid size ~ 2 km) have been developed with CRC assistance. Their performance and resolution far exceed those of only a decade ago. To maximise realism, these models are nested within ocean basin scale models (grid size - 100 km (†Bode et al. 1997). Nested within the meso-scale models are models of near reef hydrodynamics (grid size 100s of m) and fish behaviour (†Wolanski and King 1997). Collectively, the models and data are being integrated with the ultimate goal of predict reef 'connectivities', in particular, delivery of larvae to near-reef fields of dimensions appropriate to different organisms (e.g. the actively swimming fish compared to more passive groups such as corals and crown-of-thorns starfish).

2. Qualities of representative areas

Assessment of a particular area's contribution also requires the recognition and definition of 'representative types' of each class of habitat, and of 'good' versus 'poor' examples of the type. The Great Barrier Reef's largest 'no take' zone stretches from the coast to the

outer border of the far northern section of the Great Barrier Reef Marine Park. Its large size and shape alone ensure that it includes substantial nearshore, lagoonal, mid-shelf and outer shelf variants of the major habitats – sea floor, open water and coral reefs. Recently, CRC has supported widespread surveys of the ecological character of the reef and seagrass habitats (e.g. †Lee Long et al. 1996; †Oliver et al. 1994; †Devantier et al. 1996) to supplement limited surveys of over a decade ago (e.g. Coles et al. 1987, 1989; Wilkinson and Cheshire 1988).

The CRC has also supported work on criteria for rating areas within a set of areas of the same type. On coral reefs, for example, fish stock assessments (abundance, biomass, composition, trophic structure and size structure) reflect a reef's potential contribution to sustaining local fish catch and diversity through adult spill-over, and regional fish stocks and diversity through larval supply (Russ and Alcala 1996). Moreover, an abundant, diverse and trophically complex demersal fish assemblage may be indicative of the wealth of other resources that support that biomass (e.g. plankton; sessile and motile benthos). †Done and Reichelt (1996) proposed indices which reflect a site's intrinsic values in terms of the completeness of the trophic structure (bearing in mind trophic structures and size structures tend to be over-fished 'top down - Pauly and Christensen 1995). For coral/algal communities on reefs, †Done (1995) suggested criteria based on concepts of 'replacement time' and 'uniqueness' to complement the usual criteria of 'per cent coral cover' and 'diversity' and Manthachitra (in press) defined a hierarchical series of indices describing many aspects of reef composition, health and construction.

The different indices capture different aspects of how reefs are valuable, both intrinsically, and as contributors to regional productivity and diversity. As such, they can both encourage a more critical appraisal of exactly which ecological values are to be sustained and which values of individual sites make them most suited for inclusion in particular management categories. Moreover, they provide logical performances indices, derivable form routine monitoring, of the success or otherwise of particular patterns of management and use.

3. Spreading of risk

Areas within the Great Barrier Reef vary according to the likelihood of their exposure to unmanageable, broad scale disturbances, such as flood plumes, cyclone waves or outbreak of crown-of-thorns starfish. These events can compromise the intrinsic qualities of nodes in a network of protected sites and their effectiveness as source areas. A strategy in terrestrial protected area management (e.g. Baker 1992; Turner et al. 1993), is to make reservation areas large enough to internally accommodate the patchy disturbance regime. In the Great Barrier Reef context, replication would seem to be a more prudent strategy. Either way, implementation should ideally be based on assessment of the cumulative risk of exposure to an unmanageable impact (e.g. cyclone, flood, crown-of-thorns starfish) between and within different sections of the Great Barrier Reef.

The CRC is supporting a number of initiatives which will allow that risk to be estimated. A program of measurement and modelling is in place to quantify long-term delivery regimes of freshwater, nutrients and sediments to the river mouths (†Mitchell et al. in press; †Mitchell and Furnas 1997). Hydrodynamic models are being used to define risks of exposure of any place to destructive flood plumes (†Wolanski and King 1997). The meteorological record of cyclone tracks and central pressures is being used with wind prediction algorithms and field observations (Done 1992b) to characterise parts of the Great Barrier Reef in terms of their risk of cyclone damage to coral reefs (†Puotinen 1997). An extensive sediment sampling program is improving understanding of the fate of terrigenous sediments reaching the sea (†Larcombe and Woolfe in press). Current monitoring and process studies on crown-of-thorns starfish (†Engelhardt and Lassig in press; †Engelhardt et al. in press) are being combined with earlier information (Moran 1986) and updated assessments of dispersal patterns (†Black et al. 1995; †Bode and Burrage 1996) to map and predict the geographic distribution of impact and risks crown-of-thorns outbreaks.

Spatial analysis, ecological risk assessment, and Geographic Information Systems (GIS) are seen as key tools in drawing together the elements of 'value', 'connectivity', and 'spreading of risk'; i.e. maximise the values at individual areas, maximise the connections

among the areas and with the less protected areas, and minimise the likelihood that the entire representation of a particular type of habitat within a region is degraded state at any one time.

Putting dimensions on the threat posed by run-off and eutrophication

Run-off and eutrophication are recognised as key threatening processes for Great Barrier Reef ecosystems. Statistics suggest there is significant potential for harm resulting from increased terrigenous sediments, nutrients and heavy metals in the sea. Over the last century, the development and use of land in catchments adjacent to the Great Barrier Reef has been delivering elevated nutrients, sediments and contaminants in run-off into Great Barrier Reef waters (Pulsford 1996; †Mitchell and Furnas 1997). Indeed, according to some researchers, the status of offshore planktonic and benthic assemblages on and between coral reefs over significant sections of the Great Barrier Reef show clear symptoms of eutrophic conditions (Bell 1992; Bell and Elmetri 1995).

A model based on north-temperate research provides a useful template for assessing the state and extent of eutrophication in the Great Barrier Reef. Figure 2 (Gray 1996) shows marine eutrophication as manifesting itself sequentially. Initial symptoms are simply an improvement in the growth of a wide spectrum of biota previously limited by nutrient supply. In later stages, there are changes in species composition, shading, toxic effects, behavioural effects, mass growth of benthic algae, mass mortalities and extinctions, and ultimately, anaerobic conditions and mass death. In the Great Barrier Reef context, we may ask, is there any evidence of a progression of the type portrayed in figure 2, if so how far

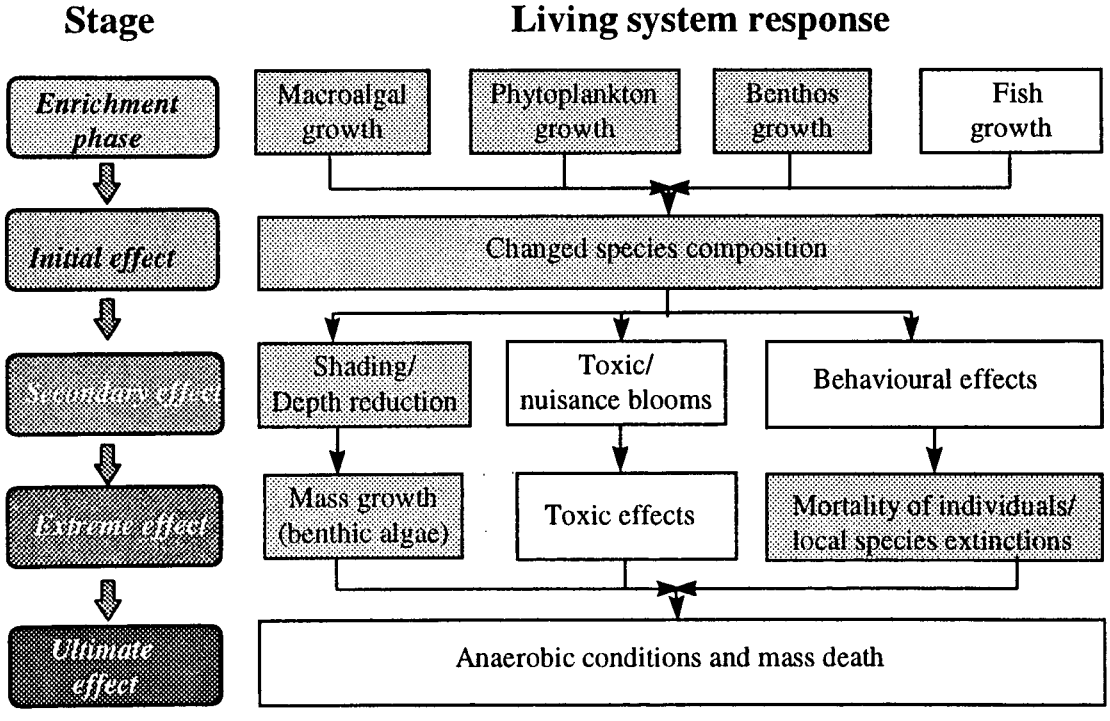


Figure 2 Stages of marine eutrophication (after Gray 1996). Shaded boxes indicate areas of active research in or associated with CRC Reef Research Centre.

advanced is it, at which geographic locations, and over what areas? What is the spatial distribution and level of risk from eutrophication in the context of different degrees of linearity and embayment of the coast, and the extreme variability in flows within and among Queensland's rivers (Lough 1994). Should the focus be more on extreme flows and potential changes in their sediment and nutrient content, and the return intervals between them (figure 3)?

Increased plant growth

For phototrophic benthic communities such as coral reefs and sea-grass beds, moderately elevated nutrients increase plant productivity and biomass (stage 1 – figure 2). Schaffelke and Klumpp (in press) have enhanced algal growth in the laboratory, for a range of coral reef macro-algae using nutrients delivered continuously and in pulses. 1Mellors (unpublished data) has achieved similar results for sea grasses using with slow release fertilisers applied to the root zones. To predict areas at risk of enrichment, it proposed that these data be combined with data and predictions about field concentrations and delivery of nutrients, not just from rivers, but also from upwelling and by fixation of nitrogen (†Furnas and Brodie in press; †Furnas and Mitchell 1996).

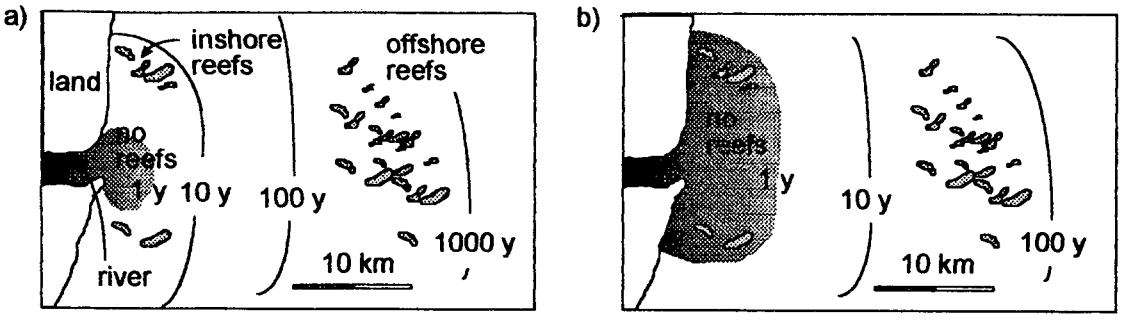


Figure 3. Changes in return intervals between extreme events. One way of formulating a range of research questions is 'Are return periods between extreme events which affect marine ecosystems now (b) shorter than they were in the past (a)?' The effect in this example could be to extend the 'no reef' zone (disturbed annually) and the 'inshore reef' zone (disturbed every decade or so), and the frequency of destruction of seagrass areas. While this example applies to influence of rivers, the same question applies to other impacts such as outbreaks of crown-of-thorns starfish.

According to figure 2, 'change in species composition' and 'mass growth of benthic algae' can signify 'initial effect' and 'extreme effect', respectively. To distinguish anomalous macroalga growth, and/or benthic species composition which is truly symptomatic of eutrophication, it is first necessary to recognise natural spatial and temporal variability. Three benthic community types, containing a distinctive taxa of macro-algae, hard corals and soft corals, characterise the reefs in shallow, often turbid waters close to shore (Done 1982). If it could be assumed that their distribution maps the extent of 'nearshore' influence, any extension of their range further offshore might reasonably be construed as evidence of an increase in the 'reach' out towards the main reef tract, of influence of river run-off (figure 3) or coastal waters generally.

A CRC supported program of ecological surveys of nearshore and outer shoals, patch reefs and fringing reefs (e.g. †DeVantier et 1996; Oliver et al. 1994; †Fabricius and De'ath in press) suggests this 'reach' model has merit. The field surveys suggest there are useful macro-algal and soft coral 'indicators' of 'nearshore influence', i.e proximity to sources of run-off and resuspended sediments (McCook et al. in press). For filter-feeding soft corals, high biomass and abundance may signify enhanced levels of particulate matter, including phytoplankton (Fabricius et al. 1995). They may be a powerful indicator group, as their response appear to be taxon-specific, and conditional on well-defined preferences for particular flow environments and reef topographies.

Potential for misinterpreting symptoms of eutrophication

However, field experiments on some macro-algae (†McCook 1996) suggest that their distributions, while influenced by terrestrial sediment, nutrient and organic inputs, are also strongly influenced by other factors. For macro-algae, the abundance or scarcity of herbivorous fishes is an important co-determinant of distribution and abundance (†McCook 1996). This observation means presence of high algal biomass is not necessarily indicative

of nutrient enrichment. In addition, long term observations (Done 1982; in press) indicate a macro-algal dominated stage can in some circumstances be either 1) a normal stages in disturbance and recovery successions which are completely unrelated to eutrophication, or 2) normal characteristics of a particular habitat or position on the continental shelf (†McCook et al. in press). That is, though the changes in figure 2 and those reported by Bell (1992) and Bell and Elmetri (1995) may be symptomatic of eutrophication, they are not necessarily so.

Direct effects of turbidity

In 1992, over 1000 km^2 of seagrass died in Hervey Bay due to storm waves (shallow seagrasses) and persistent light deprivation (> 10 m deep) caused by a turbid plume and resuspension of sediments in cyclonic seas (Preen et al. 1995). Anecdotal evidence suggested the event was unprecedented in the previous 100 years. It led to starvation, deaths and emigration in an important dugong population that will take 25 years to recover (Preen and Marsh 1995). 'Run-off' was clearly a major cause of this event, but it remains to be established whether agricultural or other land use in the catchments emptying into Hervey Bay caused the plume to be more turbid, to cover a larger area, or to persist longer, than it would have prior to the area's development for agriculture. Combining historical river flow data, flow/sediment loading relationships (†Mitchell and Furnas 1997) and hydrodynamic modelling (†Wolanski and King 1997) could establish the likelihood of previous flood plumes of similar magnitude and duration.

The CRC is supporting development of tools to capitalise on the capacity to predict the fates of flood plumes. †Stafford-Smith (in prep.) is developing empirical models to predict survivorship of a range of coral species when they are exposed to waters of varying turbidity for periods of from < 1 day to > 1 month. Some coral species are better than others in adapting to reduced light. Linked with field data and predictions about the distribution of turbid plumes under various development and eutrophication scenarios, the work will provide pointers to locations susceptible to a change in coral species composition (initial effect – figure 2) or displacement by other benthic groups (secondary or extreme effect e.g. Done 1992). The same approach could be used to make similar predictions for distribution and survival of other benthic groups such as seagrasses and macro-algae.

Discussion

In addressing priority issues for ecologically sustainable development of the Great Barrier Reef, much research effort has been put into 1) surveys and monitoring and 2) studies and modelling of pattern and process. There remains a need to continue these activities so as to ensure continued improvement of the information and interpretation base for planning and management. In addition, there is a need to 3) increase effort in making the science more geographically explicit, and more accessible to users and environmental managers. Spatial analysis, ecological risk assessment and Geographic Information Systems (GIS) are seen as key tools in communicating current advice to decision makers. However the need to continue to work on the fundamentals of structure, function, distribution and responses of the key ecosystem components and resources cannot be overstated.

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Population and community dynamics of corals: Implications for management of the Great Barrier Reef

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ABSTRACT

Scientific knowledge of the basic biology of corals has increased greatly in the past decade. In this overview, I provide a summary of recent findings from Australia and the Caribbean, and point out the consequences to management strategies.

At the community level, long-term monitoring of coral assemblages illustrates that they are extremely dynamic at spatial and temporal scales relevant to management, e.g. reef areas the size of a tourist pontoon or a snorkel trail, over timescales of years to a few decades. On the mid-shelf of the Great Barrier Reef, the most conspicuous agents of disturbance to corals are recurrent cyclones and outbreaks of the crown-of-thorns starfish. In comparison, anthropogenic impacts to coral assemblages (e.g. from nutrient enhancement, reef fishing, current levels of tourism, and scientists) are localized and insignificant.

At the population level, corals vary greatly in their susceptibility to different agents of mortality, and in their rates of recolonization following natural disturbances or acute anthropogenic impacts (e.g. ship groundings, oil spills). Clearly, protection for slow-growing species and poor colonizers (or the habitats they dominate) is more critical than for species with rapid rates of turnover. The ability of corals to recover from natural and anthropogenic disturbances depends critically on the availability of a pool of larvae. Recent genetic and recruitment data from the Great Barrier Reef illustrate that dispersal abilities of corals differ substantially among brooders versus spawners. Consequently, management zones which protect some species may be inappropriate for others.

Environmental implications of waste-water management on resort islands of the Great Barrier Reef

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ABSTRACT

Groundwater is a valuable source of freshwater on many reef islands and must be protected from contamination. Land use practices and waste disposal must be carefully managed to minimise environmental damage. This paper outlines the preliminary findings of a study that focuses on these issues and that has been undertaken within the Engineering Program of the Reef CRC.

The main objectives of the study are to; enhance the understanding of the hydrodynamics of groundwater supply and contamination on reef islands; model these hydrodynamic processes numerically; reconcile field groundwater measurements with computer model predictions; determine the effects of reef hydrodynamics on dilution/discharge characteristics; and develop computer models which predict discharge dilutions under typical reefal conditions. The groundwater components of the study include a high island study, a mainland study, and a coral cay study. The high island study incorporates a field investigation and associated numerical modelling and analysis. The study concerned with mainland groundwater contributions will be undertaken on a relatively broad scale largely using existing data. The coral cay study will also include field monitoring and numerical modelling.

The High Island study
The unsaturated zone sampling of soil moisture at Brampton Island began in 1995 and samples from porous cup soil moisture samplers have been recorded and analysed. Great Keppel Island was selected as a study site for nutrient (specifically nitrogen and phosphorus) migration, due to a proposed use of effluent irrigation on the golf-course. Groundwater samples have been taken from six monitoring wells on Heron Island and these have been analysed for nitrate and ortho-phosphate. On Dunk Island soil-core samples from the golf course environs have been taken (to be used for laboratory evaluation of saturated/unsaturated conductivity and moisture retention data), and fourteen soil-moisture samplers have been installed in and around the resort grounds.

Coral island study
Field data is being collected from existing monitoring facilities on a coral cay. Information on groundwater level and groundwater quality variations in time will be used to predict the short and long term contributions of chemicals to the immediate marine environment.

Mainland aquifer contribution study
This component involves an assessment of the contribution of mainland aquifers to the nutrient budget of the Great Barrier Reef lagoon.

Piped effluent outfall study
The water quality in the vicinity of effluent outfalls is important and the understanding of the hydrodynamic processes governing dilution is needed. To address this issue a total of 22 laboratory experiments have been performed. Analysis of the results show that there is a strong dependence of jet paths and dilutions on the free surface and bed proximities, as well as on the magnitude and direction of currents.

1. INTRODUCTION

The influence of water-borne chemicals, especially nutrients such as phosphorus and nitrogen, on the water quality of the Great Barrier Reef lagoon is assuming greater importance as pressures for development, both on the adjacent mainland and on islands in the lagoon, increase. Consideration must be given to marine water quality around the main reef structure itself and also around numerous fringing reefs often associated with islands throughout the region. The local marine environment around these fringing reefs will be influenced by discharges from the islands. Given that coral reef ecology is sensitive to relatively small elevations of nutrient above natural background levels, appropriate management of water and waste-water in resorts on these islands will rely on accurate predictions of the eventual fate of those nutrients.

This paper provides order of magnitude estimates for nutrient loadings around typical resort islands and describes the early stages of field studies which have the objective of quantifying the significance of surface and groundwater nutrient discharges from resort islands.

2. Resort island water and waste-water management

Resort island water supply is obtained from various sources including surface storages, groundwater aquifers, and barging from the mainland. Waste-water treatment methods are of either secondary or tertiary level and disposal can be by land irrigation or ocean outfall. Table 1 gives a summary of data, as supplied by various resorts in 1994 and 1995, on level of treatment, method of disposal, quantity of waste-water produced, nitrate and phosphate levels and total loads for a selection of Great Barrier Reef resort islands.

3. Great Barrier Reef Lagoon nutrient loads

In the total Great Barrier Reef lagoon, major nutrient sources include mainland and island run-off and seepage, the adjacent ocean, and local nitrogen-fixing biota. We focus on island run-off and seepage but mainland contributions need to be considered for comparative purposes when contemplating the anthropogenic induced changes from natural levels of nutrient inputs. Our study concentrates on nitrogen because, in land disposal of effluent, phosphorus is much more likely to bind to the soil and consequently its transport through soils is more difficult to predict.

Mainland sources are difficult to quantify because of the huge variability in both stream flows and nutrient concentrations and the lack of data on groundwater discharges. The eventual fate of nutrient outputs from mainland sources is also unclear as substantial amounts, especially of phosphorus, may be trapped in coastal sediments.

The most comprehensive study of river outputs of nutrient to parts of the Great Barrier Reef lagoon is that of Furnas et al. (1994) who arbitrarily defined two areas or 'boxes' of the central Great Barrier Reef shelf. The more northerly one of these was designated the Cairns box, between Cape Tribulation and Cape Grafton, and the southern one the Tully box, between Cape Grafton and Dunk Island. The total shelf areas for the Cairns and Tully boxes were 5937 km^2 and 7826 km^2 respectively, while the estimates of volume of water were 197 km^3 and 312 km^3 respectively.

Furnas et al. (1994) reported the periodic collection of dissolved and particulate nutrient samples from most of the major rivers which discharged directly into or immediately to the south of the two boxes. With the limited data available, a number of assumptions had to be made in order to produce an estimate of nutrient input to the respective boxes. Reasonably comprehensive discharge-weighted mean concentrations of nitrogen and phosphorus were available for only one major river, the South Johnstone River. Using these concentrations, estimates of the mass of nutrient exported from the other rivers were calculated using the average stream discharges determined hydrographically. The results suggested that the amounts of nitrogen transported annually on average to the Cairns and Tully boxes were approximately 2000 tonnes and approximately 4,400 tonnes respectively. As the authors indicate, due to the number of assumptions involved, these estimates should be considered as provisional. Also, for reasons given in their report, the estimates are likely to be towards the

upper end of the probable range. Corresponding estimates of phosphorus exports were 192 and 433 tonnes to the Cairns and Tully boxes respectively.

From table 1, it will be seen that the estimated nitrogen and phosphorus loads from individual resort islands are negligible by comparison, being in the range of approximately 0.1 to 0.7 tonnes per year for nitrogen and up to 0.5 tonnes per year for phosphorus. Even if the total nitrogen load on each of the islands were exported to the marine environment, the consequence for the total nutrient budget of the Great Barrier Reef lagoon is negligible in comparison with the mainland riverine inputs. It should be remembered, however, that in addition to the uncertainties introduced by assumptions made in the calculation of the river inputs, little is known about the eventual fate of the nutrients once they reach the estuarine and coastal areas. It is possible that a substantial component of the nutrient is trapped in the nearshore areas. Detailed studies of sediment and water dynamics as well as measurements of water quality in these areas will be required to clarify the ultimate fate of the nutrients.

Table 1. Summary of management strategies and nutrient loadings for selected islands

GBR Resort	Effluent Treatment Level	Effluent Disposal Method	Effluent Flow Rate [kL/d]	Total N Final Effluent [mg/L]	Total P Final Effluent [mg/L]	Estimated N Load [ton/year]	Estimated P Load [ton/year]
Brampton Island	Secondary	Effluent irrigation and reservoir overflow during extreme wet weather	55	11	12	0.2	0.25
Great Keppel Island	Secondary	Ocean Outfall	183	8.5	>4	0.6	>0.3
Dunk Island	Secondary	Land Disposal	200	9	7	0.7	0.5
South Molle Island	Secondary	Ocean Outfall	180	8	4	0.5	0.25
Green Island	Tertiary	Ocean Outfall	40	6	0.8	0.09	0.01

In spite of all these unknowns it is clear that, if the nutrient contributions from resort islands is significant at all, it will be significant only in the marine environment in the immediate vicinity of the islands from which the nutrients emanate.

4. Local environmental considerations

In order to assess the consequences for the micro-environment of resort islands, information must be available on the quantity and quality of effluent, the disposal process, surface and sub-surface nutrient transport processes on the islands, and mixing and transport processes in the sea. There are substantial gaps in knowledge especially on the storage and transport processes.

A rough order of magnitude estimate of nitrate plus nitrite load contributed by waste-water effluent from an island is now considered. Assume an effluent flow rate of 200 kL per day with a combined nitrate and nitrite concentration of approximately 4.5 mg per litre. This would give an output of 0.9 kg per day. If we assume a biota tolerance threshold of 1.31 g per litre in sea water (Connell and Hawker 1987) where the background level is 0.34 g per litre, the increase in concentration to reach the tolerance level will be 0.97 g per litre.

In order to obtain an order of magnitude estimate of the increase in concentration of nitrate plus nitrite in the sea adjacent to such an island, we need to predict how long the exported nutrient remains in a certain volume around the island. In other words, we need to determine the residence time in a defined zone so that we can calculate the net increase in concentration of nitrate plus nitrite due to the export rate from the island. For example if we

calculate the volume of seawater contained within a certain distance, say 100 m, from the shoreline and assume a time which elapses between nutrient entering the sea and when it passes beyond the 100 m line, this will then determine the mass of nutrient stored within the seawater volume and, consequently, the increase in concentration over natural background levels.

We perform the calculations for two different control volumes, one limited to a distance of 500 m from the shore and the other limited to a distance of 100 m. In an island where the volume of sea water in an area out to 500 m from the shore is 24 000 ML, the 'acceptable' increase in concentration of 0.97 g per litre gives an increase in nitrate plus nitrite mass of 23.3 kg. With a daily output of 0.9 kg, this would mean that the residence time within the 500 m distance from the shore must be less than 26 days if the tolerance level is not to be exceeded. If the total island output over 26 days or more remains in the volume specified, concentrations will exceed the tolerance threshold.

If the control volume were defined by a zone only 100 metres from shore with a water volume of say 2400 ML then the residence time must be less than 2.6 days if the threshold concentration is not to be exceeded.

It should be noted that amongst the assumptions made, one is that the total effluent output is discharged to the sea which will be a worst case scenario. However, another assumption is that there is uniform distribution of nutrient within the assumed control volumes over the period of the residence time. This will give a non-conservative estimate in the sense that concentrations may be locally higher because of non-uniform distribution.

It will be obvious that several gross assumptions have been necessary in this order of magnitude analysis which has been performed simply to establish whether further work on island effluent disposal is warranted. Given the size of the 'error bands' around the residence times calculated, one cannot be confident that local environmental impacts can be discounted and, therefore, more detailed investigations are warranted.

In these circumstances, further studies are needed on the terrestrial nutrient storage and transport processes in the case of irrigated effluent disposal since this will determine the location, extent and concentration of discharge to the sea. Similarly reliable data on currents and on marine transport processes are required in the immediate vicinity of the islands since these will govern the actual residence times and control volumes for nutrient concentration calculations.

We focus on the terrestrial transport and storage of nutrients which will vary with topography, soil type, climatic zone, hydrogeology, and vegetation on the islands. Consequently, field sites have been established on several islands and two case studies are described in more detail here.

5. Field sites

Data collection and analysis have been concentrated initially on two islands which have been instrumented with porous ceramic cup soil moisture samplers. The principle of these samplers is based on moisture transfer from an induced pressure gradient. When a suction is placed against the sampler cup, the capillary force of the soil at field capacity is opposed by the cup's internal suction. Thus, when the soil solution is less than the applied vacuum, solution is drawn across the porous wall into the cup. This solution is stored within the sampler cup until collection.

All samplers were installed using a 50 mm diameter hand-auger. Care was taken to ensure that good contact was achieved between the soil moisture sampler and the surrounding soil. This was important because poor contact could lead to accelerated (by-pass) flow adjacent to the surrounding plastic tube therefore giving a sample that is not representative of the depth at which the sampler is located.

Of the two islands on which the field studies described here were conducted, one disposes of its waste-water by irrigation of secondary treated effluent on lawns, golf courses and gardens. The other island pipes its discharge to the sea but is likely to implement an effluent irrigation program in the near future, with most of it to be applied to the golf course.

5.1 Brampton Island

5.1.1. Location, climate and geology

Brampton Island is a continental island located in the Great Barrier Reef region at latitude 20°49'S and longitude 149°17'E. The total area is approximately 500 ha, the primary land-use being National Park.

The area experiences a sub-tropical, sub-humid climate with hot wet summers and mild drier winters. The mean monthly temperature and mean relative humidity were assumed to match those of the nearby city of Mackay.

The island consists of andesitic crystal tuffs and flows which overlie granites. In outcrop the volcanics range from close jointed (25 mm – 50 mm) spacing to massive (joints over a metre apart) and are generally fresh, with little weathered rock. Dune sands are associated with Dinghy Bay and Western Bay on Brampton Island. The dunes are not extensive nor are they highly elevated above sea-level. Particle size distribution tests on various soil samples taken at one metre below surface level have shown a sandy-clay type soil, brown, fine to coarse sand with some rock fragments.

5.1.2. Groundwater

According to groundwater drilling investigations commissioned by the resort in 1986/87, the total reliable yield calculated over the dry season of July to December was estimated to be 8 ML. This was based on information obtained from pump-tests of thirteen bores installed in the vicinity of Western Bay and Dinghy Bay. Water samples were analysed for drinking suitability and general quality. Several bores contained unacceptably high levels of dissolved salts. The remainder were deemed to be of acceptable quality for general use.

Lloyd (1980) states that '...drilling in the volcanics to date has yielded supplies ranging from zero to 1.3 L/s' and further suggests that '...supplies of about 0.6 L/s would be the average yield of a bore in these rock types on Brampton.' Bore logs for two bores located in the vicinity of the resort show water-bearing rock at levels of 15m below sea-level.

5.1.3. Surface water

There are no perennial rivers or streams on the island. However, an ephemeral stream passing through the golf course has been estimated to flow at a peak of 3 m^3/s for a storm with an average return interval of 2 years. The catchment area was estimated to be 0.3 km^2. It is proposed to install a concrete flat-vee measuring weir in the future, to ascertain the stream flow rate for determining flow-weighted nutrient concentrations in stream run-off.

Three dams are present for water supply, located at Western Bay West (WBW), Western Bay East (WBE) and adjacent the airstrip. The dam at WBW has a capacity of 10 to 12 ML, while the dam at WBE can retain up to 9 ML. The dam adjacent the airstrip has a 6 ML storage potential.

5.1.4. Water use and effluent quantity and quality

Annual in-house water requirements for the resort are approximately 30 ML in the dry season and 25 ML in the wet season. This is reticulated throughout the resort for all internal uses, including washing and ablutions.

Secondary level wastewater treatment is carried out on the island. The quantity of effluent produced each day, on average, equates to 55 kL. The majority of the treated effluent is irrigated over the golf-course during the night. Treated effluent is also used on some of the lawn and garden areas. On most occasions during dry periods all treated effluent is irrigated. On the golf-course the effluent is distributed via a network of 24 sub-surface stations connected to an array of pop-up sprinklers. The irrigated area is approximately 1.5 hectares.

The nutrient (N and P) content of the treated effluent is of the order of 11 mg/L nitrate-nitrogen and 12 mg/L orthophosphate. Nitrite and ammonia concentrations are negligible.

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GREAT BARRIER REEF
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Appendix 1. Chronology of important milestones in and policy development for the assessment of tourism infrastructure in the Great Barrier Reef Marine Park

	Major Events	Policy Development
1983–84	Pontoon installed at John Brewer Reef Permit application for the Four Seasons Floating Hotel (FSFH) at John Brewer Reef	
1984–85	Draft EIS completed for Four Seasons Floating Hotel (FSFH)	
1985–86	Impact Assessment Study (IAS) on the proposed Magnetic Quays development	Permits required for structures in unzoned sections of the GBRMP Study commissioned on environmental assessment of offshore structures
1986–87	First pontoon monitoring study	Review of offshore structures by GBR Ministerial Council *Offshore Facilities Act* (QLD) passed
1987–88	FSFH issued permit to operate Public Environment Report (PER) on Magnetic Quays development Cyclone Charlie damages pontoons at FSFH FSFH begins operation at John Brewer Reef 'Fantasy Island' installed at John Brewer Reef (sinks two weeks later)	*Sea Installations Act 1987* (Commonwealth) passed Proposals for offshore structures, dredging or reclamation to be subject to public review
1988–89	Floating resorts proposed for Fitzroy Reef and Lady Musgrave Island Second PER on Magnetic Quays development Permit issued for Magnetic Quays marina (9 other marina proposals under consideration)	Contracts introduced for complex permits Two year moratorium on floating hotels Reactive monitoring introduced for construction projects Guidelines introduced for assessment of marinas, pontoons and mariculture projects Authority to manage developer-funded monitoring and site supervision Guidelines for wastewater treatment at island resorts
1989–90	FSFH removed from John Brewer Reef after financial difficulties Bund wall collapses on Daydream Island marina	Permit assessment fees introduced Duration of permits increased from 1 to 3 years
1990–91	Work ceased on Magnetic Quays Cyclones Joy pontoons at Agincourt Reef	Policy guidelines for establishment of pontoons revised after failure of several anchoring systems
1991–92	18 applications for installation or relocation of pontoons in the Cairns Section Cyclone Fran damages pontoons at Lady Musgrave Island and Wistari Reef	'No Structures Sub-Zone' introduced in rezoning of the Cairns Section Whitehouse review of Magnetic Quays
1992–93	Major foreshore and harbour works at Heron Island	Fish feeding guidelines issued Policy on establishment and maintenance of pontoons Minimum monitoring requirements supplied to consultants
1993–94		Review of the Marine Park tourist permit system
1994–95	draft EIS on Magnetic Quays redevelopment	
1995–96		Study of the impacts of fish feeding Review of pontoon monitoring studies and engineering guidelines Moratoria on new permits in the Cairns and Whitsunday regions

Solid waste from the treatment process is not stockpiled on-site, but is transported back to the mainland. However, fertiliser is applied to the golf-course at a rate of 600 kg/annum and to the resort lawns and gardens at a rate of 250 kg/annum.

5.1.5. *Soil moisture sampling results*

The unsaturated zone sampling of soil moisture at Brampton Island began in October 1995. Thirteen porous ceramic cups have been installed at depths ranging from 300 to 1400 mm below the surface. The effect of land based effluent irrigation on the subsurface water quality has been assessed by sampling of soil moisture at monthly intervals over an 8 month period. A relatively high degree of spatial variability has already been evident. The time-averaged nitrate-N concentrations have varied spatially from 0.1 to 3 mg/L.

5.2 Great Keppel Island

5.2.1. Location, climate and geology

Great Keppel Island is a continental island located in the Great Barrier Reef region and is situated 50 km north-east of Rockhampton at 20°49'S latitude and 149°17'E longitude. It has a total area of 1046 ha, the primary land-use being a resort and camping ground.

The Bureau of Meteorology could not provide any climatic information for Great Keppel Island; hence mean monthly rainfall, mean monthly temperature and mean monthly relative humidity data were obtained for the nearby coastal centre of Yeppoon.

According to Lloyd (1980), the geology of the resort area consists of three formations. Two Quaternary age formations were underlain by Palaeozoic age bedrock. The two Quaternary formations are:

(i) Holocene/Pleistocene Dune Sands
(ii) Holocene Outer Barrier Deposits

The former consists of white, uniform, fine-grained sands overlying a bed of shell grit, while the outer barrier deposits consist of darker fine-grained quartz sands overlying a similar shell grit material. Lloyd (1980) decided that both deposits should be considered as one unit for the purposes of groundwater examination, due to the indistinguishable differences in sieve analysis and similar aquifer transmissivities.

5.2.2 Groundwater

Throughout the resort lease there are nine main groundwater bores which are utilised for domestic and irrigation purposes. The yield of the aquifer system has been calculated to lie in the range 185 ML – 245 ML per annum.

The water quality of these bores is regularly checked for drinking suitability. At present, this analysis does not include nitrate or phosphate. The water quality is generally very good, although there is some evidence of seawater intrusion in older spears in the vicinity of Long Beach. Lloyd's (1980) bore-hole investigations within the present golf-course area pointed to a relatively shallow water table in this area. Two bores drilled just over a metre apart adjacent to the golf-course were shown to be have water tables around two metres below ground level.

Lloyd (1980) also gave details of pump tests conducted on each of the production bores. Water levels were monitored in adjoining observation bores enabling values of transmissivity and specific yield to be obtained. The average value for transmissivity from pump tests was found to be 110 m^2/d while the average specific yield was 7% for early time response, adjusted to 25% for long-term specific yield.

5.2.3. Surface water

There are no perennial river systems or streams on the island. Small surface flows occur for a short period after recharge events when groundwater levels are high.

5.2.4. Water use and effluent quantity and quality

Based on approximately seven months of weekly water supply data obtained from the resort, the average daily water used by the resort was 294 kL. Golf course irrigation consumed an additional 50 kL/d on average over the same period.

Secondary level wastewater treatment is carried out on the island. At the time of provision of the data effluent was being discharged to the ocean via an outfall with diffuser.

Effluent flow rates are also monitored weekly by the resort, and are measured via a flowmeter in the inlet pipe to the secondary treatment works. Examination of seven months data showed that the average effluent flow rate was 183 kL/d.

With respect to effluent quality monitoring, weekly analysis of final effluent for pH, chlorine, various nitrogen species and phosphate is undertaken by the resort. Based on fifteen weeks of data obtained from the resort in 1995, nitrate-NO3 averaged 8.5 mg/L with a range of <1 to 19 mg/L. Nitrite and ammonia values were negligible, while phosphate-PO4 always exceeded the analytical range of the instrument (0–4 mg/L).

It should be emphasised that these results reflect effluent quality prior to the recent upgrading of the treatment plant to tertiary level. Detailed information on the current wastewater quality from the upgraded facilities has yet to be obtained.

5.2.5. Groundwater and soil moisture sampling results

Monitoring of soil and groundwater has commenced and will continue over the time during which effluent irrigation is introduced and thereafter. The groundwater was sampled from several supply wells and found to have nitrate-N concentrations in the range 0.7 to 1.2 mg/L. The aquifer has a relatively high hydraulic conductivity and is well connected hydraulically to the sea.

Sixteen ceramic cup soil moisture samplers were installed throughout the six-hole golf course. The immediate purpose of these samplers was to establish estimates of the background nitrate levels at various points in the course at depths of 500 mm and 1000 mm below surface level. Figure 1 shows the general locations of the soil moisture samplers in the golf-course environs.

An understanding was sought of the change in nitrate concentration with topography from the east-side of the course to the west-side of the course using two approximate cross-sections. Samplers have been placed at two different depths at each location, to serve as a guide to the change of nitrate with depth. Soil moisture samplers at 1.0 metre depth in the vadose zone have returned samples with nitrate-N concentrations in the range 0.7 to 1.5 mg/L over a 3 month period. Even though effluent irrigation is not yet practised on this island, fertilising of the golf course does occur and the higher nitrate concentrations in the groundwater were measured under the golf course.

6. Numerical modelling

A model called SOILN, developed by Johnsson et al. (1987) has been used to predict the nitrate concentration profile below a typical turfgrass site at the Great Keppel Island resort using the limited input data available. Because of the low water and nutrient retention capacity of coastal sands, the potential for nutrient leaching was assumed to be greater at this site than at Brampton Island.

The model first requires the parameterisation of a one-dimensional soil-water submodel called SOIL which utilises Richard's equation for unsaturated flow. The model is principally driven by daily water inputs of precipitation and irrigation as shown in figure 2. Bureau of Meteorology records of daily air humidity, air temperature, wind speed and precipitation were obtained for Yeppoon.

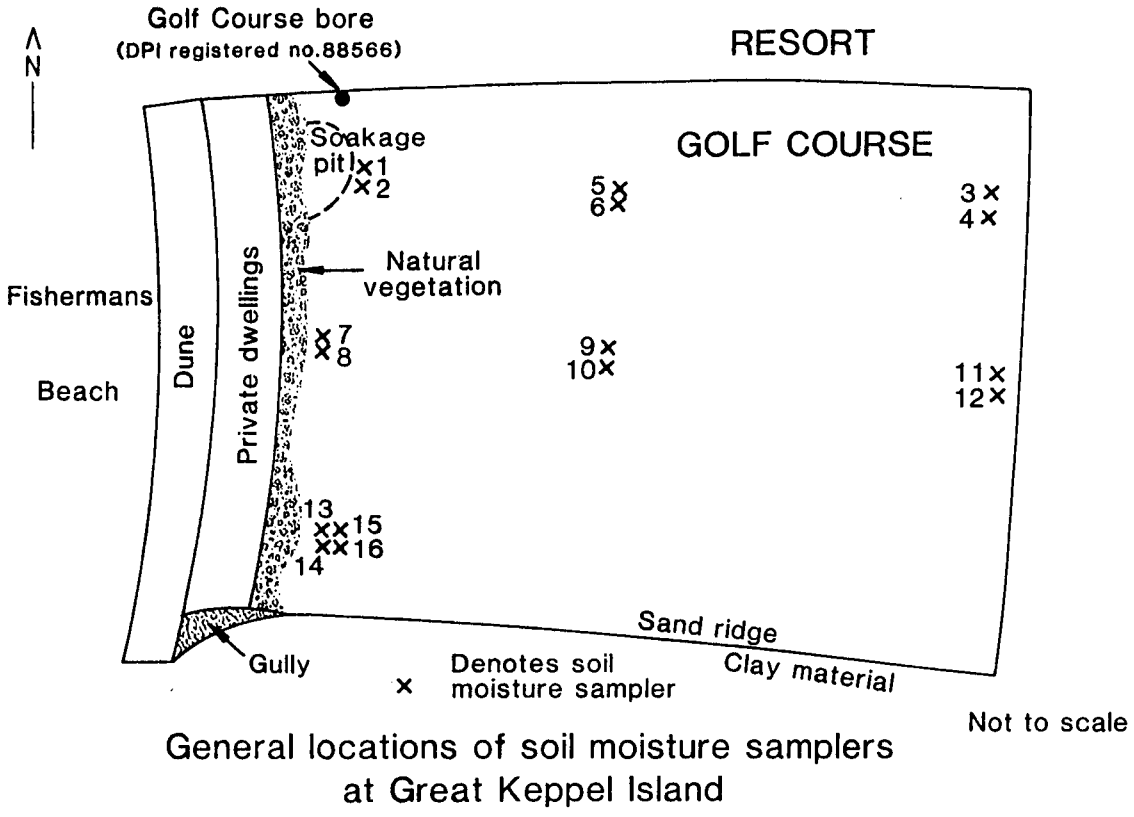


Figure 1. General locations of soil moisture samplers at Great Keppel Island

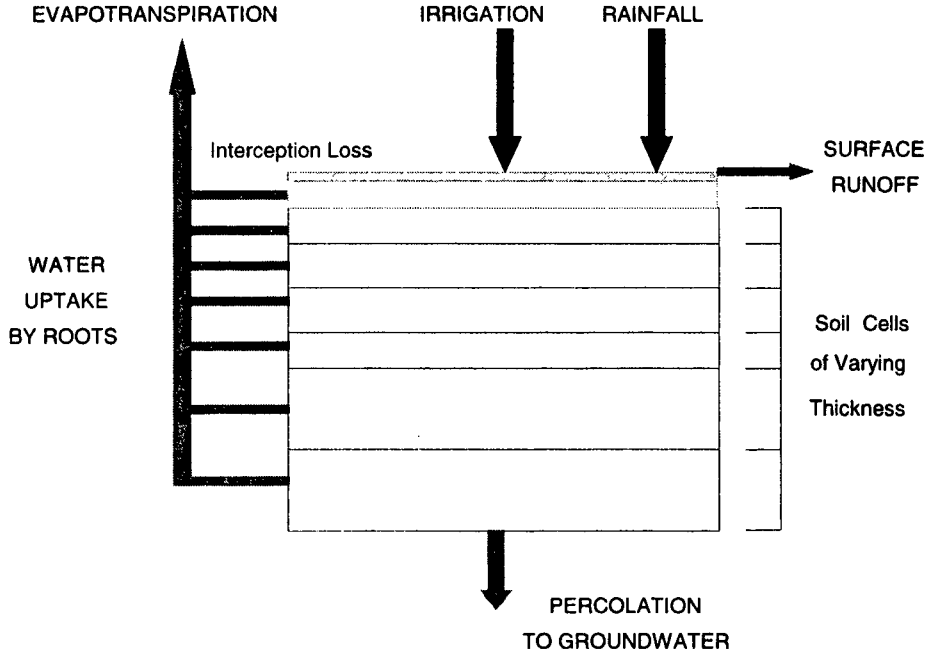


Figure 2. Conceptualised SOIL Model

The water retention curve and the unsaturated conductivity function are important model inputs in defining the hydraulic conditions at the site. Six sets of undisturbed soil cores were collected from the Great Keppel Island golf-course in order to estimate soil-moisture

retention properties, the results being given in figure 3. Samples were taken up to 850 mm below surface level, and twenty vertical soil compartments were defined over this range in the modelling process.

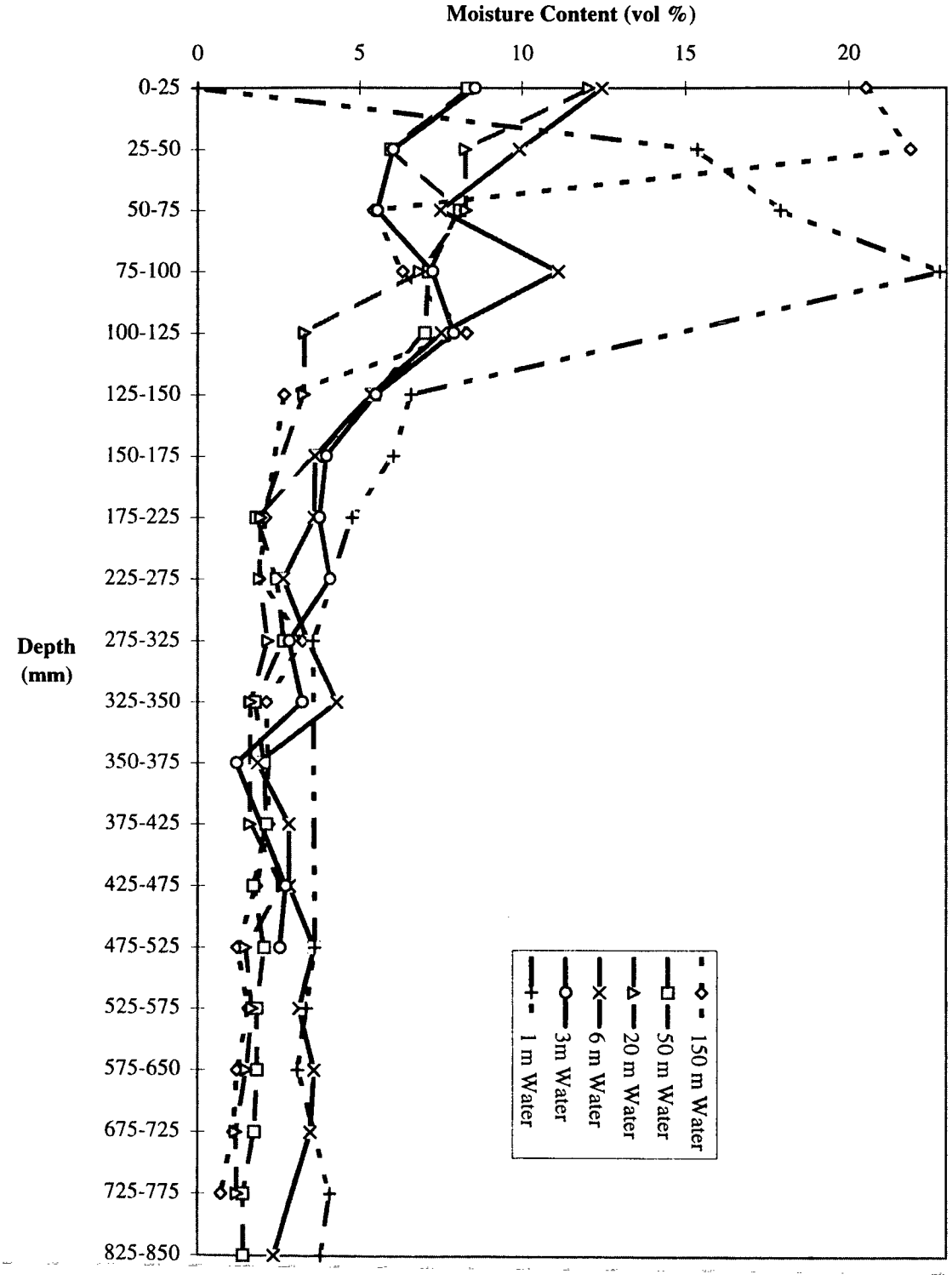


Figure 3. Water retention properties of Great Keppel Island sand samples

Calculations of coefficients for the moisture retention function were done by least squares fitting of the Brooks and Corey (1964) equations to these data. As experimental determination of the porosity and saturated conductivity has yet to be completed, estimates have been made from literature for the likely porosity and saturated conductivity of a fine

uniform-grained dune sand. The unsaturated conductivity function was then predicted using the procedure of Mualem (1976).

Parameters are also required for the vegetation to reflect the rate of water uptake from the profile through evapo-transpiration. Vertical root distribution, leaf-area index, albedo, and the leaf surface resistance to water flow between plant and atmosphere, formed most of the plant inputs. Values were based on typical results from literature for turfgrass.

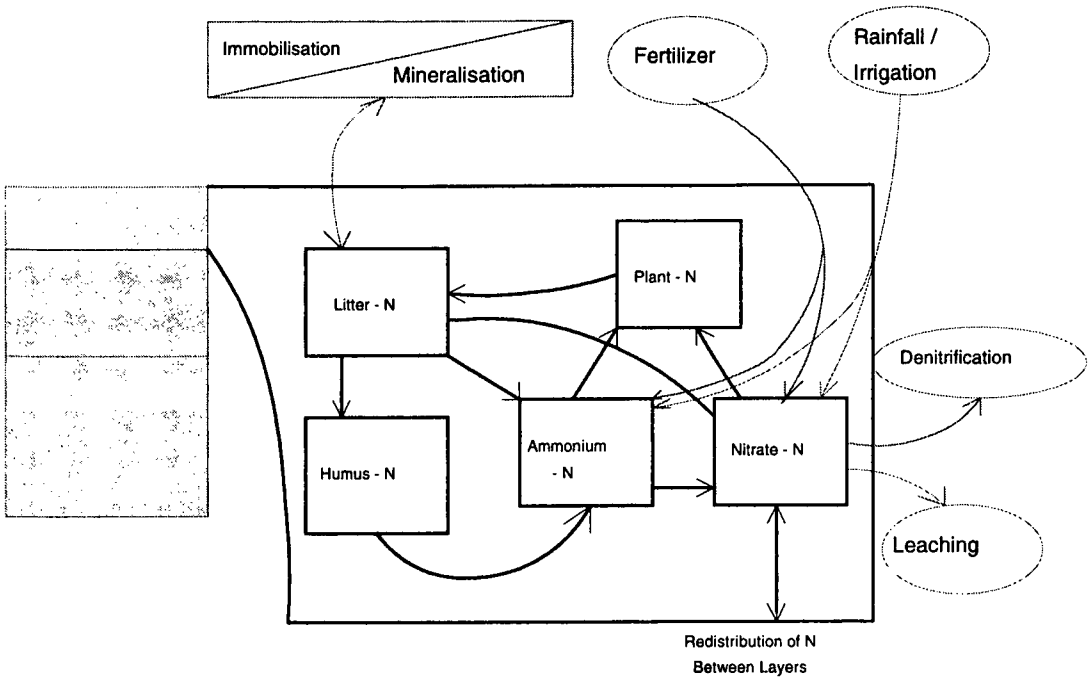


Figure 4. Structure of the SOILN model (adapted from Johnsson 1987)

The principal features of the nitrogen transport model SOILN are depicted in figure 4. It was used to simulate the processes of plant uptake of nitrate, mineralisation and immobilisation, leaching and denitrification for this site. Only nitrate was considered to be mobile within the profile. Data were obtained from the resort for the nitrogen concentration and current rate of application of fertiliser. Based on the then current effluent flow rate information, the proposed daily effluent irrigation rate over a two hectare turfgrass plot was calculated – with the assumption that all available wastewater would be irrigated at a constant daily rate. A summary of the site conditions is presented in table 2.

Simulations over a one year period produced nitrate concentration versus depth for two cases as shown in figure 5. The first case represents an initial application of fertiliser (at time = 0), while the second case considers daily effluent irrigation in addition to the initial broadcast of fertiliser. As expected, the plots show a progressive migration of nitrate to greater depths with time. For the second case, as anticipated, soil nitrate concentrations higher than for the first case are predicted with a greater proportion at depth at later times.

Future work will include estimation of the leaching of nitrate below the root-zone using measured nitrate concentration in the soil solution and the calculated drainage flux. For each irrigation area, the average nitrate concentration of the soil solution at a depth of one metre will be coupled with predictions from the SOIL model for flux of water draining past one metre. Further data collection of soil-moisture using the porous ceramic suction cups will first be necessary to enable a reasonable estimate of the nitrate available for leaching to groundwater.

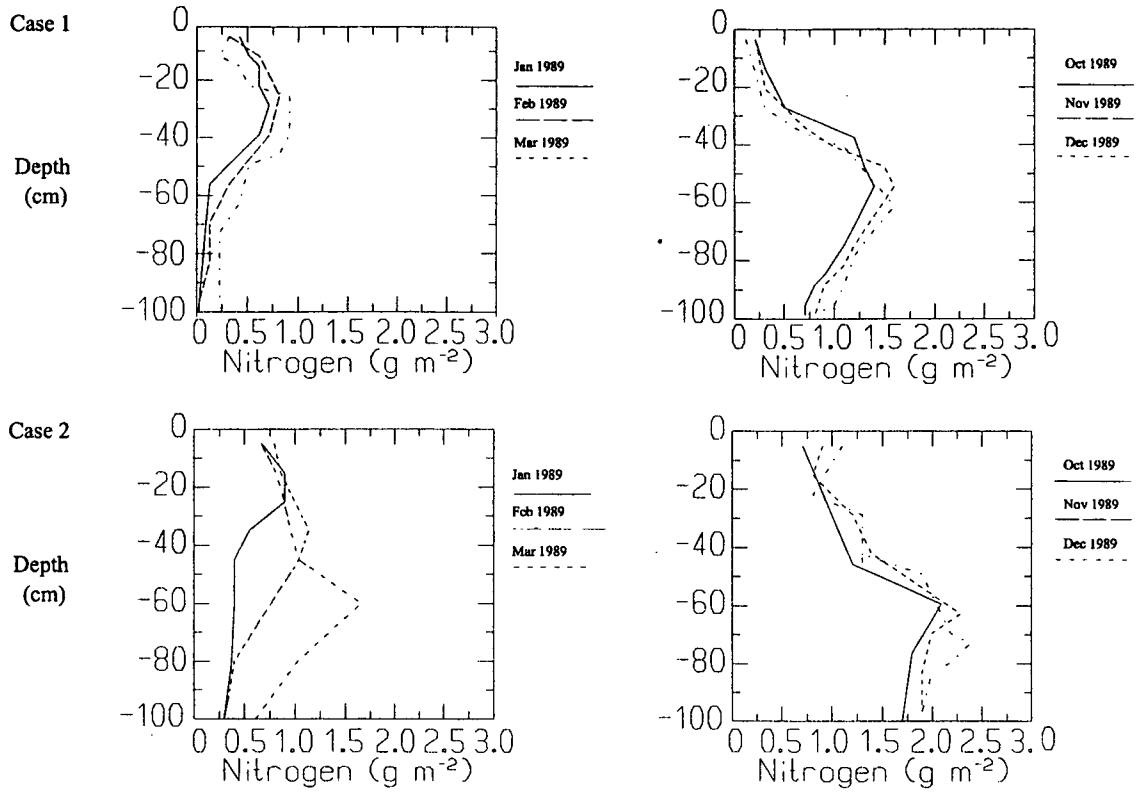


Fig 5. SOILN simulated distribution of soil nitrate in the soil profile of a typical turfgrass site on Great Keppel Island

Table 2. Summary of Great Keppel Island site conditions used in SoilN simulation

Vegetation type	Turfgrass
Root Depth	0.3 m
Management of Lawn Clippings	Removed
Total Rainfall (1989)	1450 mm
Irrigation Source	Effluent assumed (Sand spear currently)
Application Rate of Effluent Irrigation	9 mm/day
Nutrient Proportion of Effluent Irrigation : N as Nitrate N as Ammonia	 8.5 mg/L 0
Fertiliser Types	Cropking 88 Nitrophoska Blue T.E
Application Rate of fertiliser	175 kg/ha/yr of Cropking 175 kg/ha/yr of Nitrophoska Blue T.E
Nutrient Proportion of Cropking 88 : N as Nitrate N as Ammonia	 0 kg/ha/yr 25.9 kg/ha/yr
Nutrient Proportions of Nitrophoska Blue T.E : N as Nitrate N as Ammonia	 8.75 kg/ha/yr 12.25 kg/ha/yr

CONCLUSIONS

The best estimates of nutrient output of major rivers from the mainland show that the potential contributions from resort islands are minimal by comparison in terms of the overall nutrient budget of the Great Barrier Reef lagoon. Based on effluent discharges from the islands and assumptions about residence times around the coast before transport away by currents and tides, however, rises in nitrate concentrations sufficient to be detrimental to the marine ecology cannot be discounted and further detailed studies of resort island nutrient mass balances are warranted.

While the nitrate levels so far detected in soil or groundwater on islands where measurements have been made are relatively low by drinking water limits, it should be noted that fertilising of lawns and irrigation of treated effluent have been practiced for only a relatively short period, and continued monitoring and associated numerical modelling is warranted to predict longer term consequences.

Further work is also required in conjunction with physical oceanographers modelling currents in the Lagoon under different meteorological conditions to determine residence times for nutrient loads discharged from the islands.

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Threats, status, trends and management of seabirds on the Great Barrier Reef

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ABSTRACT

Climatic change, reduced food supply and increased human activity affect the viability of seabird colonies. Of these, increased human activity is of greatest concern. But it is also the source of impact that can be most easily managed.

The Great Barrier Reef accommodates over 25% of the breeding population of Australia's tropical seabirds with large numbers of Wedge-tailed Shearwater, Sooty Tern and Black Noddy.

The distribution of major and minor colonies can be related to the distribution of specific types of islands and their location on the Continental Shelf. Most major colonies occur on vegetated sand cays in the Far Northern and Mackay/Capricorn Sections of the Great Barrier Reef Marine Park.

Although our current knowledge of seabirds' distribution is satisfactory, our knowledge of their population trends is poor. This unsatisfactory level of knowledge stems, in part, from not knowing what constitutes a population, which models best approximate seabird population dynamics, and lack of data suitable to detect changes in seabird populations. For most areas, there is insufficient data about the levels of human disturbance of breeding colonies. Thus we are unable to select with confidence actions that decrease impacts threatening population viability.

Most monitoring of seabird numbers on the Great Barrier Reef has been done on an *ad hoc* basis and usually not using standardised methods. Even when the primary purpose of field trips to islands has been to census birds, they are usually too infrequent to provide the data necessary to detect net trends. To illustrate the point, data sets from two areas of the Great Barrier Reef will be compared and discussed.

Day to day Management Strategies need to be based on quality data. Not only is information about population trends needed, but also a clearer understanding of the threats to viability of seabird colonies. To date, development of management practices have been hindered by a paucity of essential data. Our best option to protect seabird colonies of the Great Barrier Reef would appear to be adaptive management practices guided by monitoring and research.

INTRODUCTION

The theme of this conference is the Science, Use and Management of the Great Barrier Reef. It is the use of the Great Barrier Reef that poses many of the significant threats to its viability. We need to use science to guide the development of effective management plans, strategies and actions to maintain the viability of the Great Barrier Reef.

In this paper we consider management frameworks and options in the context of the status of seabird populations and the threats to their viability.

The paper considers first threats to the viability of seabird populations, second, it describes the status of seabird populations, and finally it discusses how management may be used effectively to protect seabird populations on the Great Barrier Reef.

Pressures on seabirds

The pressures on seabird populations can be categorised according to their origin, i.e. non-anthropogenic and anthropogenic. Factors such as climatic change, reduced food supply because of El Niño Southern Oscillation (ENSO), increased levels of predation may be categorised as non-anthropogenic pressures. Factors such as reduced food supply because of overfishing, habitat loss because of clearing by people, human habitation, visitation and other human activities may be categorised as anthropogenic pressures. These pressures have been described and discussed by King (1993), Ogilvie and King (1993), Stokes et al. (1996) and Hulsman et al. (1996). Of these pressures, the anthropogenic ones are of greatest concern because they can have a large negative impact on the viability of seabird colonies, and moreover because they are increasing (see Stokes et al. 1996). However, they are also impacts that can be most easily managed.

All of these threats or pressures on seabird populations are disturbances. Treating threats in this way provides a different perspective on how these pressures impact on a population and how they may be controlled (Hulsman 1996). This of course is important from a management viewpoint. When considering the impacts of a disturbance on a population, one needs to consider the characteristics of the disturbance, the characteristics of the organisms being disturbed (Knight and Cole 1991), and the interactions between them (Hulsman 1996).

The characteristics of any disturbance are its nature, duration and timing (Knight and Cole 1991), intensity, frequency, predicability and scale (see references in Sousa 1984). The impact of any disturbance on a population is a result of the interaction between the characteristics of the disturbance itself and the organisms being disturbed. The relevant characteristics of the organisms being disturbed are their physiological condition (which is affected by the amount of stress to which they have been subjected), stage of annual cycle (Hulsman 1996), age and gender (Knight and Cole 1991).

Non-anthropogenic threats

Non-anthropogenic threats to seabird populations are cyclones (Hulsman 1977a, Langham 1986, Langham and Hulsman 1986, King et al. 1992, De'ath 1994), gales (Nelson 1980, King et al. 1992), reduced food supply caused by ENSO (Nelson 1980, Schrieber and Schrieber 1984, Duffy et al. 1988) and habitat loss through overwashing (Hulsman 1977a,b, Hulsman and Smith 1988), erosion (King et al. 1992), as well as windthrow (Hulsman et al. 1984).

Cyclones and gales

De'ath (1994) found that cyclones in 1986 and 1988 at Michaelmas Cay significantly reduced the breeding population of Common Noddies (by 34% and 47% respectively). In contrast, populations of Sooty and Crested Terns did not seem to be significantly affected by those cyclones (De'ath 1994). Indeed, De'ath (1994) did not detect any further significant declines in numbers to those already accounted for by the trend and cyclic occurrences. These results for Crested Terns contrast with those obtained at One Tree Island where a cyclone greatly reduced their reproductive output in a specific year (Langham and Hulsman 1986; Langham 1986).

The stage of the breeding cycle at which a cyclone or gale strikes a colony seems to affect the severity of its impact on the birds. Strong winds prevent adults from (1) finding food because of the poor visibility arising from the sea surface conditions, (2) going out to search for food, or (3) returning to the colony to feed their young. Consequently, young may die of exposure or starvation (Hulsman 1984).

Young chicks are more susceptible to starvation than are older chicks and adults during strong winds (Hulsman 1977b; Langham 1986). Chicks are most susceptible to the effects of strong winds during their period of rapid growth when they have high demand for food

(Hulsman 1977a). It is possible that the cyclones struck the Michaelmas colonies when the noddy chicks were growing rapidly, while the Sooty chicks were not.

Habitat loss

Erosion of parts of the nesting area and overwashing by storm surges may lead to increased mortality of eggs and young chicks (see Hulsman 1977; Hulsman and Smith 1988).

ENSO

The effects of ENSO events occur throughout the entire South Pacific Ocean. But there are delays in the effects occurring; first in the Eastern Pacific, then the Central Pacific and finally in the Western Pacific, including the Queensland coast.

An ENSO event significantly decrease the size of pelagic fish stocks but not that of reef fish stocks (Hulsman 1996). This is because coral reef systems are efficient recyclers of nutrients living in nutrient poor waters (see Furnas and Mitchell 1996). Consequently, offshore and pelagic seabird species, whose dietary biomass is dominated by pelagic fishes, are severely affected by ENSO events (see Schrieber and Schrieber 1984). In contrast, the inshore feeders, whose dietary biomass consists mainly of prey from coral reefs, are buffered from the effects of ENSO events. For example, the biomass of the Crested Tern diet is, at times, dominated by prey of reef origin (Domm and Recher 1973; Hulsman 1977a; Hulsman et al. 1989). Therefore if Crested Terns increase the biomass of reef species in their diet during ENSO events, they can avoid their adverse effects. This is consistent with the observation that Crested Tern numbers were not affected by the 1982 ENSO event at Christmas Island (see Schrieber and Schrieber 1984).

Anthropogenic threats

Anthropogenic sources of disturbance are habitat loss through clearing or destruction, habitat deterioration (i.e. made less suitable for meeting the organisms' requirements), direct disturbance of birds by humans. The latter may increase mortality of eggs and chicks through exposure (Hulsman 1984) and predation (Domm and Recher 1973; Hulsman 1977a,b; Ogilvie and King 1993).

Habitat loss and deterioration

Changes to the characteristics of a habitat may adversely affect a species because the habitat no longer meets the requirements of the species as well as it did previously. Habitat loss through clearing or destruction is an extreme case of changing habitat characteristics. Infrastructure associated with human habitation or use excludes seabirds from using that space. For example, buildings, roads and tracks on Heron Island reduce the area available to Wedge-tailed Shearwaters for burrowing thereby decreasing their nesting density (see Hulsman 1984).

Also compaction of the substrate, such as on roads and tracks, increases run-off which causes flooding of some burrows and drowning of eggs and small chicks (M.Preker in Hill et al. 1996). This is an example of habitat deterioration in that it no longer meets the needs of the birds as well as it did previously.

Direct disturbance

Disturbance of breeding seabirds at some colonies can be a common occurrence because seabirds are often exposed to people at close quarters. This results from the large number of people visiting a cay each year and their activities near the breeding seabirds. The birds can be disturbed even though they do not seem to show any overt signs of stress when people come too close to them (G.W. Gabrielsen pers. comm.; Tindle 1979; Wilson et al. 1991). The effects of disturbance must be measured in terms of the reproductive success of the birds in disturbed and undisturbed sections of the colony, and not whether a bird shows overt signs of being disturbed at the time of exposure to the source of the disturbance. Direct disturbance caused by people, unlike the other threats to the colony, can be directly controlled by wildlife managers.

The effects of direct disturbance can be desertion of the whole or part of the colony (e.g. Hockin et al. 1992; Hobson and Hallinan 1981). The severity of the response depends in part on the timing of the disturbance in terms of the stage of the nesting cycle (Anderson and Keith 1980; Hulsman 1984; Pierce and Simmons 1986; Anderson 1988; Hockin et al. 1992) and the intensity of the disturbance (Piatt et al. 1990). It may also cause a delay in breeding, or prompt a relaying. In either case, there is usually a lower breeding success for late breeders (Anderson and Keith 1980) because eggs are less likely to hatch (Ollason and Dunnet 1978), there is higher chick mortality because the food supply is inadequate to sustain growth and maintenance (see WBM Oceanics and Claridge 1995) or increased predation. Late breeders do not obtain the full benefit from the group defence of the colony (see WBM Oceanics and Claridge 1995). Disruption of young being fed may affect their fledging weight and that can affect the survival of birds in their first year (see Nelson 1980).

Direct disturbance may also disrupt the structure of a colony. For example, chicks that are scared away from their nest area may be attacked and killed by adult conspecifics (Dinsmore 1972; Gillet et al. 1975; Anderson and Keith 1980), or become lost and starve to death (see WBM Oceanics and Claridge 1995).

Status

The Great Barrier Reef accommodates over 25% of the breeding population of Australia's tropical seabirds (Hulsman et al. 1996). There are 24 species of seabird that breed on the Great Barrier Reef. But the Great Barrier Reef is numerically dominated by two species: Wedge-tailed Shearwater *Puffinus pacificus* and Black Noddy *Anous minutus* (Walker 1990; King 1993).

The distribution of major and minor seabird colonies can be related to the distribution of specific types of islands and their location on the continental shelf. Most major colonies occur on the mid and outer shelf on vegetated sand cays. These cays are more numerous in the Far Northern and Mackay/Capricorn Sections than they are in other Sections of the Great Barrier Reef Marine Park. It is therefore not surprising that most major seabird colonies are concentrated in the Far Northern and Mackay/Capricorn Sections (Walker 1990; King 1993; Hulsman 1996).

Although our current knowledge of seabirds' distribution is satisfactory it could be far better. We know where seabirds nest, and to an appreciable extent the size of their colonies, but our knowledge of their population trends is poor. This unsatisfactory level of knowledge stems, in part, from not knowing what constitutes a population, which models best approximate seabird population dynamics, and lack of data suitable to detect changes in seabird populations (Hulsman et al. in press). For most areas, there are insufficient data about the levels of human disturbance of breeding colonies and their impacts. Thus we are unable to select with confidence, actions that decrease impacts threatening population viability.

Most monitoring of seabird numbers on the Great Barrier Reef has been done on an ad hoc basis and usually not using standardised methods. Even when the primary purpose of field trips to islands has been to census birds, they are usually too infrequent to provide the data necessary to detect net trends. To illustrate the point, we consider data sets from two areas of the Great Barrier Reef: Michaelmas Cay and the Capricorn Group Islands.

Michaelmas Cay

King et al. (1992) recorded the numbers of eggs, chicks, fully fledged young, non-breeding and breeding birds on Michaelmas Cay over 6 years. De'ath (1994) was able to show that Sooty Tern *Sterna fuscata* and Common Noddy *Anous stolidus* populations were declining once the cyclic nature of changes in their numbers was taken into account. Sooty Tern and Common Noddy populations on the cay had decreased by 26% and 46% respectively between 1984 and 1994 (De'ath 1994). There were insufficient data to analyse the changes in the populations of Crested Tern *S. bergii* and Lesser Crested Tern *S. bengalensis* (figure 1). Neither species maintains an all-year presence on cays where they breed.

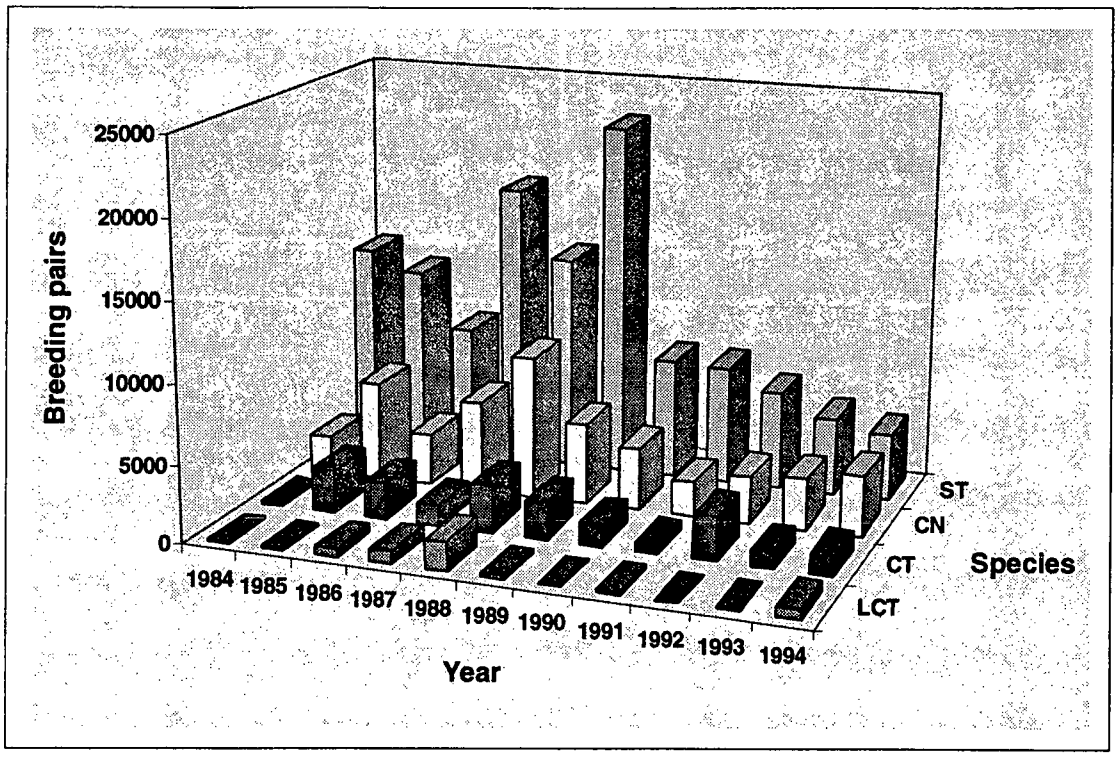


Fig 1. Numbers of pairs of four species of tern breeding at Michaelmas Cay between 1984 and 1994. Key: **LCT** Lesser Crested Tern; **CT** Crested Tern; **CN** Common Noddy; **ST** Sooty Tern Data from De'ath (1994).

The cause of the declines was narrowed to two possibilities; ENSO events causing a decrease in the food supply, and increased exposure to humans. Fortunately these two causes can be distinguished. ENSO events have widespread effects. Therefore if the declines in offshore and pelagic seabird numbers at Michaelmas Cay were being caused by ENSO events, they would also affect their numbers at other colonies on the northern arm of the East Australian Current (Hulsman et al. in press). Raine Island has large numbers of breeding Sooty Terns and Common Noddies, but their numbers have not been declining during the past 8 years (E. Hegerl pers. comm.). Furthermore, populations of inshore feeding species (such as Crested Tern) were affected at Michaelmas Cay.

By a simple process of elimination, increased levels of human visitation appear to be the most likely cause of the declines in seabird populations at Michaelmas Cay. The declines started after the peak in numbers of breeding pairs in 1988 and coincided with the increase human visitation to the cay. The increased visitation rates occurred following the 1984 opening of Cairns International Airport bringing more tourists to the area. In 1986, operators started using large catamarans to bring people to Michaelmas Cay and by the early 1990s there were an estimated 68 000 visitors per annum (King et al. 1992). There were 73 869 and 72 217 visitors per annum respectively in the 1993–94 and 1994–95 financial years (M. Haste pers. comm.). That increased visitation rate has provided a greater opportunity for birds to be exposed to disturbance by people. This has probably led to breeding birds not returning to Michaelmas Cay to breed.

Mackay/Capricorn

In the southern part of the Great Barrier Reef there are insufficient data for the type of time series analysis done by De'ath (1994) on some species at Michaelmas Cay. Most species in the south do not maintain an all-year presence at their colonies.

The two most abundant species in the region (Wedge-tailed Shearwater and Black Noddy) tend to breed on the same islands, but there have not been regular censuses of either species. The first realistic estimates of the number of burrows were made at Heron Island in 1965 (see Shipway 1969), at Masthead Island in 1972 (Jahnke 1975; Dyer et al. 1995), and at North West Island in the early 1980s (Hulsman 1983, see figure 2).

Wedge-tailed Shearwater

Dyer and Hill (1992) found that the burrow occupancy rate of shearwaters at Heron Island was 43% and at Erskine Island was 56%. It is not known whether the occupancy rate is constant or changes over time. So the trend in shearwater numbers over the past 30 years is not known (P.K. Dyer pers. comm.).

Figure 2 shows the trend in the numbers of burrows on the three islands where the largest numbers of shearwaters occur. There was a slight increase in the numbers of burrows at North West and Heron Islands but they were variable at Masthead Island. The causes of these fluctuations in numbers of burrows is not known at present.

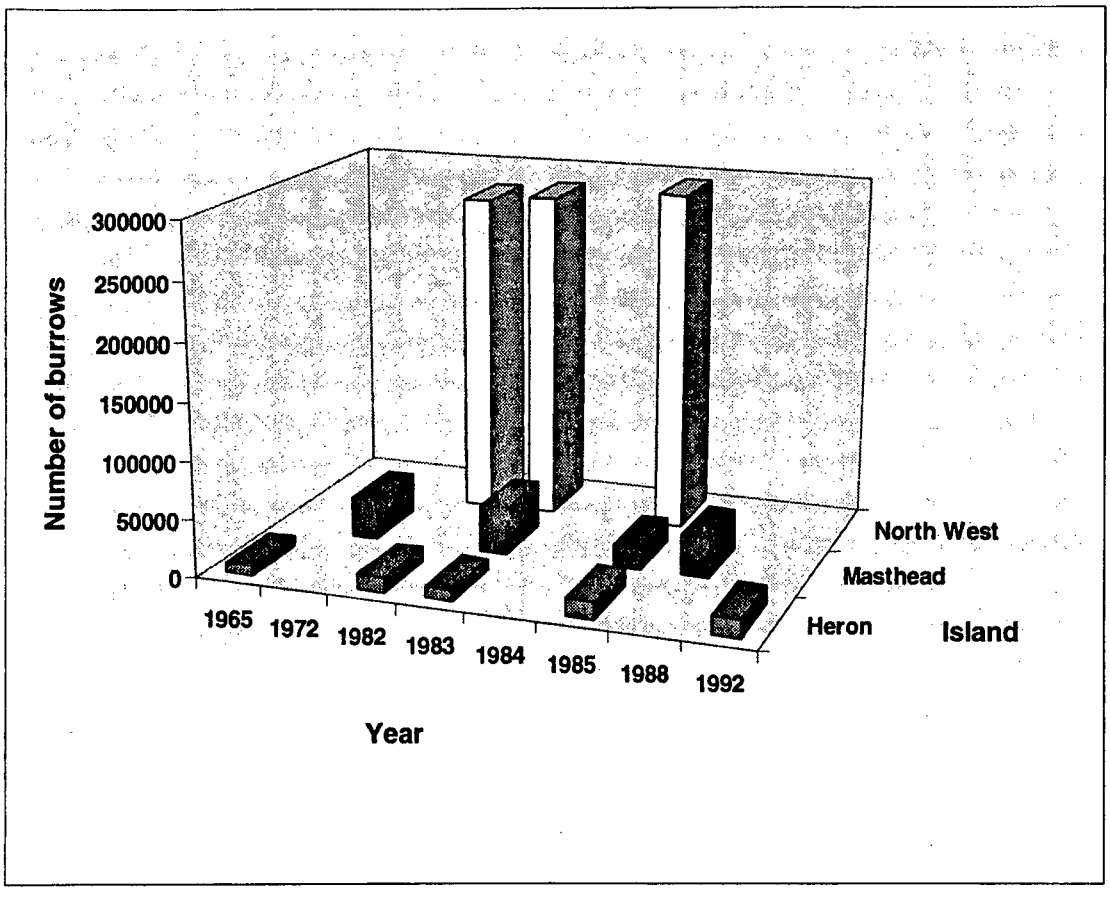


Fig 2. Number of burrows of Wedge-tailed Shearwater at three major breeding colonies on the Great Barrier Reef. Data from Shipway (1969), Jahnke (1975), Hulsman (1983, 1984), Hill and Barnes (1989), Hegerl (unpublished), Ogden (1993), Dyer et al. (1995), Hulsman and Walker (1996).

Black Noddy

The trend in the number of breeding pairs of Black Noddy on some islands is clear, e.g. at Heron and Masthead Islands. But the infrequent censuses of other colonies, such as at North West Island, make it difficult to determine the trend for the total population (figure 3). It is not clear whether there are real increases or decreases once the cyclic changes have been accounted for because there are insufficient data for a time series analysis to be done to partition these components in the data.

The number of breeding pairs of Black Noddy at Heron Island are increasing while that at Masthead has decreased (figure 3). It is not clear whether established pairs have moved from Masthead Island to Heron Island, or the increase at Heron Island is because more first-time breeders are being recruited than previously. Individually marked birds are required to help solve that problem.

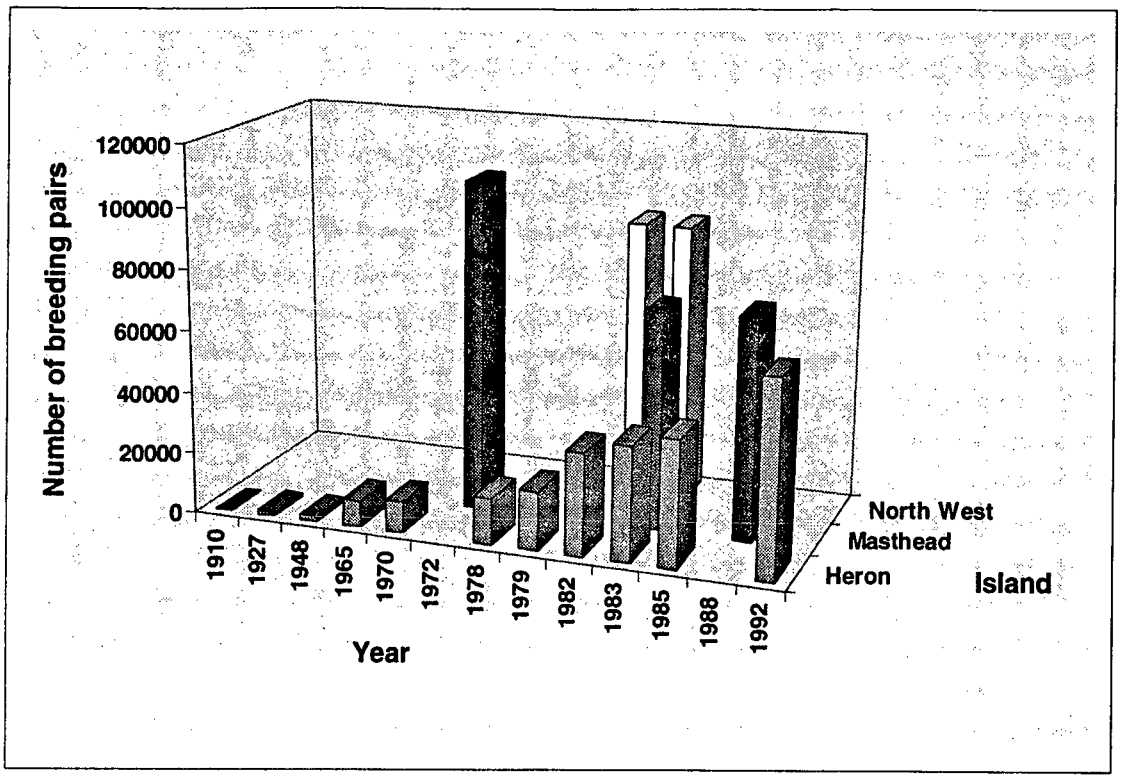


Fig 3. Number of breeding pairs of Black Noddy at three major breeding colonies on the Great Barrier Reef. Data from Shipway (1969), Ogden (1979), Hulsman (1983, 1984), Barnes and Hill (1989), Hegerl (unpublished data), Ogden (1994).

Meanwhile this uncertainty about the trends in the numbers of breeding seabirds creates a management problem. The effects of the natural and anthropogenic threats to seabird populations have not been measured.

Management

Non-anthropogenic factors may cause high mortality among specific age groups from time to time but the system may be able to recover (see WBM Oceanics and Claridge 1995). However, when additional mortality caused by human disturbance is added then recovery times may become longer or the disruption to the system is so great that it does not recover. If the system's new position is not a desired ecological outcome, then what sort of action is required to move it to a desirable ecological outcome. It is invariably cheaper to prevent an ecological disaster than it is to restore the *status quo*. Therefore the adage 'prevention is better than cure' is particularly apt for environmental management.

There are two basic approaches to managing wildlife. There is the inductive Black Box Approach and the deductive Mechanism Approach. More often than not, we are forced to use the Black Box Approach. That is, we manipulate inputs to achieve desired outcomes, but we do not understand the exact nature of the processes that shape the system. Therefore we are unable to predict with confidence the outcome of management actions.

The Mechanism Approach requires an understanding of the processes that govern how the system operates. In this situation we can predict with confidence the response to a management action. This greater certainty about the outcome allows for more refinement or subtlety in management actions than the Black Box Approach allows.

Monitoring is important for both approaches. It provides the necessary feedback about the state of the system, especially its progress towards or stability at a desired outcome. As the uncertainty associated with the outcome increases, the more important the monitoring becomes. The feedback from monitoring provides the information necessary to plan the appropriate actions.

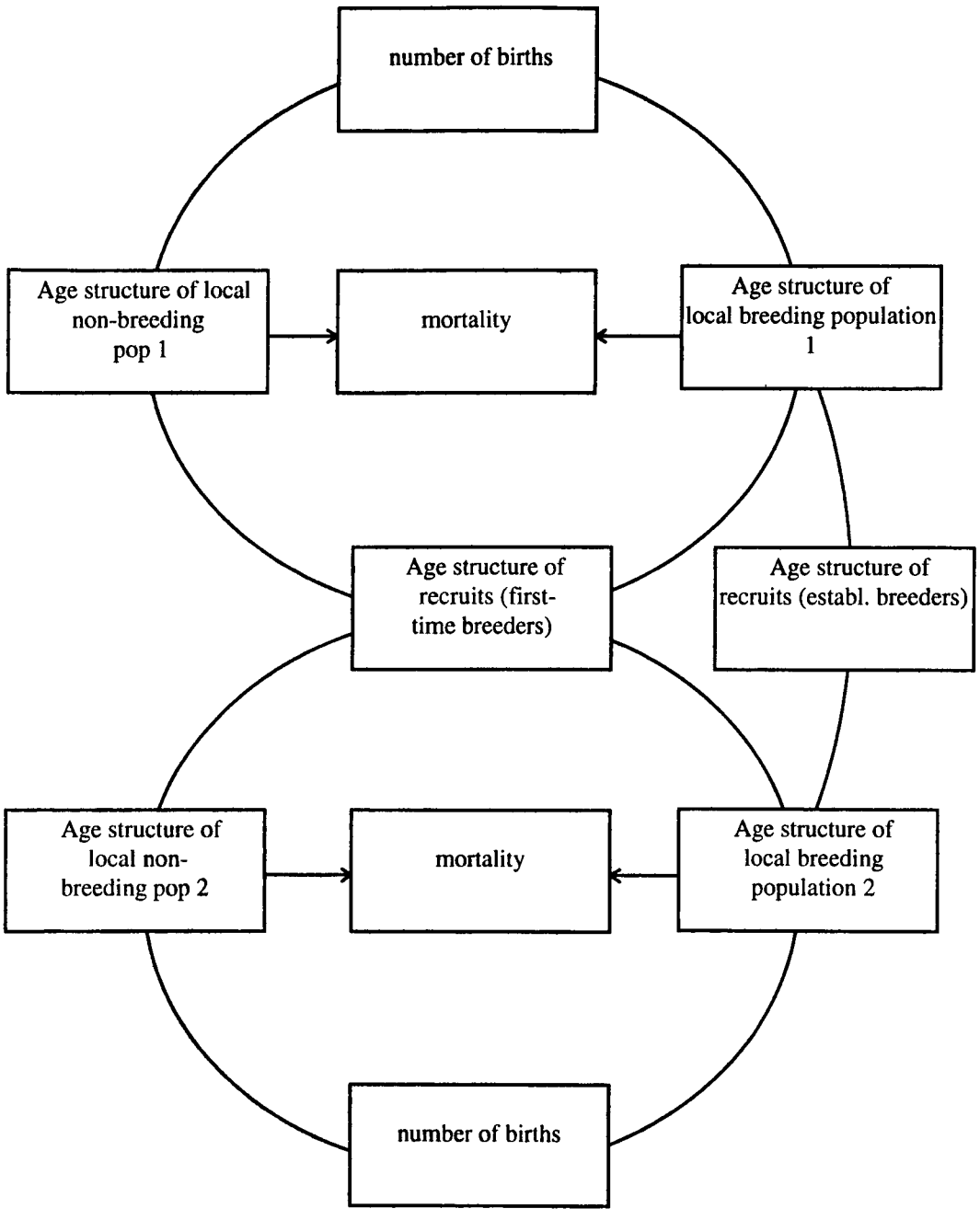


Fig 4. Relationships between population parameters of a meta-population consisting of two local populations

Day to day management of seabirds should be based on information about population trends, population dynamics and threats to viability. To date, development of management practices have been hindered by a paucity of essential data. Use of flexible management practices appears to be the best option to protect seabird colonies of the Great Barrier Reef.

Figure 4 summarises the information that is needed to manage a seabird population effectively. A population's composition determines which model best describes the population's spatial and temporal dynamics. For example, does it consist of a number of local populations grouped into a meta-population (e.g. figure 4 and see Andrewartha and Birch 1954, 1984)?

Specific details of the characteristics of the breeding and non-breeding populations are needed to help the development of an appropriate management plan and actions. For example, the number of breeding pairs in (1) the meta-population, (2) each local population, and (3) the effective breeding population. In addition to this, data about the age structure of the population, age-specific mortality and reproductive output are required. The size and age structure of the non-breeding population are important because they provide an indication of the potential recruitment rate.

Recruits to a local breeding population may be first-time or established breeders. From a management perspective it is important to know the age of the recruits and where they come from. First-time breeders have lower reproductive success than more established breeders. Therefore the proportion of breeders in each group will affect the reproductive output of the local population.

The source of the recruits is important. If one local population is a source and the other a sink, it is essential that the source population where the animals survive during unfavourable conditions, be protected (see Newsome 1969). Its protection will promote the regional survival of the species. It is also necessary to build temporal variability of recruitment into the management plan, or at least to be able to amend the management plan as required to protect the species.

Generally non-anthropogenic threats to seabird populations are not easily manageable if at all. We cannot affect the severity of the impact of a cyclone on seabirds at sea. On land however, it is possible to manage the vegetation to provide shelter for the birds and to decrease the likelihood of sections of the nesting area from being eroded by the sea. Dune stabilisation programmes are an example of this type of management.

For anthropogenic threats, we can affect (1) the nature and intensity of the threat by controlling the type of activity and the number of people engaged in it on or adjacent to a cay; and (2) the duration of the exposure of the seabirds to any activity. This greater scope for control means that we can effectively manage wildlife by controlling the impact of people and their activities.

Impacts can be controlled by restricting the numbers of visitors, the types of activities they are permitted to engage in, where those activities may occur and the timing of visits in relation to the stage of the seabirds' breeding cycles. Where indigenous people use seabirds, sustainable levels of use should be sought by defining the stage of the breeding cycle during which eggs etc may be collected for food, where they may be collected so as to minimise the disturbance, and bag limits.

Planning process for management

The current planning process for the management of seabird islands used by Queensland Department of Environment (QDoE) is summarised in figure 5. It indicates that officers responsible for sections of the Great Barrier Reef should produce island status statements based on biological composition and abundance values, accompanied by a list showing the importance of each island in terms of its threats, issues, impacts and economics (see table 6 in Hulsman et al. in press).

Officers then need to determine existing specific threats to the island. Chapter 3 of *Guidelines for managing visitation to seabird breeding islands* (WBM Oceanics and Claridge 1995) may be used as a checklist. Long term threats should also be addressed. In particular future development proposals for the coast or islands which may pose a threat to the future breeding of seabirds in the area.

Planning Process for the Management of Seabird Breeding Islands

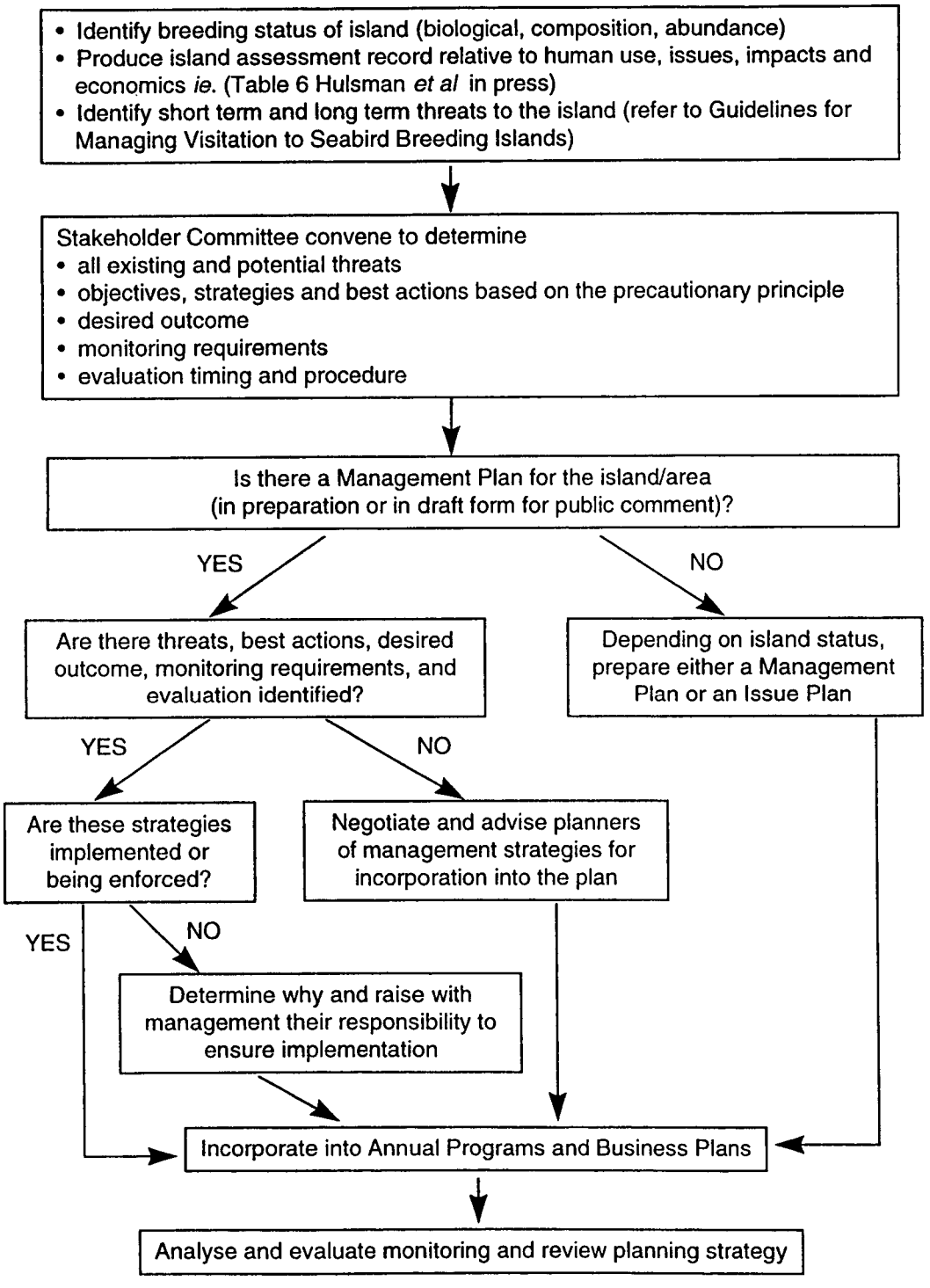


Fig 5. Summary of the Planning Process for the management of seabird breeding islands

A committee of Stakeholders should be convened to agree on existing and potential threats, as well as objectives and strategies for the area, based on the Precautionary Principle, the desired outcome, and appropriate monitoring and evaluation requirements.

Once strategies are accepted as policy, then the recommended actions including monitoring requirements should be carried over into the Annual Program and Business Plan. This

ensures scheduling of vessels and staff or contractors to carry out the recommended actions. In turn, monitoring is undertaken and data collected for analysis which is critical in reviewing, or evaluating the original objectives, strategies and actions. In such a formal process it is still possible to retain sufficient flexibility to deal with uncertainty by incorporating an Adaptive Management Framework in any Management Plan.

Adaptive Management Framework

Even with agreement between the stakeholders, the lack of information it can make it difficult to determine the most appropriate management plan. Since such information as recruitment rates, and the amount of exchange between colonies take a long time to obtain, it is prudent to adopt a flexible management strategy. An Adaptive Management Framework (AMF) can provide the required flexibility (see Hulsman et al. in press).

The AMF requires both clearly defined desired outcomes which must be measurable and stopping protocols (see Barnes and Hulsman 1995). These are required to evaluate the effectiveness of actions and provide the criteria by which decisions can be made to modify or stop the management actions. For example, if there was too great a deviation from the pathway leading to a desired outcome, then the current action can be stopped and a new one implemented after careful evaluation of the system. This flexibility is essential in a system for which there is incomplete information.

Sufficient flexibility must also be retained to enable an appropriate rapid response to unexpected change. The amount of flexibility required will depend on the degree of uncertainty associated with the system. Basically the amount of flexibility required increases with the level of uncertainty of the outcomes. It is the uncertainty that makes monitoring such a critical part of management decision making process.

The small number of major seabird colonies do not make concurrent treatments possible. Therefore sequential treatments are the only option available. Given this, we must be aware of the problems that can arise from residual effects of previous treatments and take the appropriate actions to avoid or minimise them. If we are not able to obtain data from carefully controlled experiments, then we must utilise quasi-experiments without controls. Although these quasi-experiments may have low internal validity, they often have high external validity (Kamil 1988). In other words, although it is difficult to assign causation to the result because of confounding variables, the results themselves are readily generalised.

Conclusions

There are still too many unknowns about seabird population dynamics and individual life history to enable us to use a Mechanism Approach to management successfully. It is therefore prudent to use an Adaptive Management Framework because we cannot delay management actions until we have sufficient data. This framework highlights the importance of monitoring and research in the management process. Moreover, an Adaptive Management Framework is applicable to all components of an ecosystem, not just seabirds and their habitats.

Clearly targeted research projects are needed to collect the necessary data, e.g. identify source and sink colonies and the major causes of mortality at them; the extent of migration between colonies; powers of dispersal; and the intrinsic rate of increase. These are the types of data required to determine the capacity of a species to recover from a significant disturbance.

Involving stakeholders in the decision-making process is essential for good management. People are more likely to comply with management plans if they have a sense of ownership of them. Thus fewer resources need to be committed to enforcement and more can be devoted to other tasks.

Finally, we should use theory to guide research and management plans. Conversely we should use research and management to test theory. The management of the Great Barrier Reef should continue its progress towards a common sense approach; it is the best option.

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The effects of line fishing on the Great Barrier Reef: available evidence and future directions

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ABSTRACT

The Great Barrier Reef line fishery includes both commercial and recreational sectors. Commercial reef line fishing is generally from dories, with fish marketed both alive for export and frozen. The recreational sector comprises individuals fishing from private boats, fishing clubs, and groups fishing from charter vessels. In general, all sectors use similar gears and are allowed to fish the same areas of the Great Barrier Reef.

The effects of line fishing can be considered in four categories: effects on the target stocks; direct or indirect effects on non-harvest species, including non-fishes; effects on future fishing; and effects on other (non-fishing) users. At present there are few data from which to infer exactly what the past effects of fishing have been in any of these areas.

The short history of available data about the reef line fishery present major problems for inferring effects line fishing has had on the Great Barrier Reef. Most quantitative evidence is relatively recent and incomplete, but indicates that the effects of line fishing since the mid-late 1980s have been slight. It is not clear whether this apparent stability represents a recent stable point in fish stocks and fishing after initial effects in the past. Qualitative data suggest many fishers believe that they now catch fewer and smaller fish per trip than in the early eighties. Whilst complacency about effects of line fishing would be inappropriate, because data are scant and inconclusive, there is no convincing evidence of emerging problems with the line fishery.

Calls for prudent management of the Reef Line Fishery, especially in view of recent changes in fishing practices, are confronted by uncertainty about the status of the fishery and its effects. There is great need for good information in the short term from which to implement informed and justified management. We suggest that active adaptive management strategies may be the most productive approach to answering both needs, but warn that important ethical issues need to be addressed before such an approach will be either defensible or publicly acceptable.

INTRODUCTION

Since its declaration as the world's largest multiple use marine park in 1975 (*Great Barrier Reef Marine Park Act 1975*) and World Heritage listing in 1981 (*Australian Heritage Commission Act 1975, World Heritage Properties Conservation Act 1983*), the Great Barrier Reef has been formally recognised as having special significance nationally and internationally. The emphasis in both Acts was on the natural features of the Great Barrier Reef and the need for its conservation 'in perpetuity' (Kenchington 1990). A growing tourism industry estimated to be worth $A1 billion annually has been built in part on appreciation of the natural beauty of the Great Barrier Reef. In this context, extractive activities raise special issues because they have the potential to erode the heritage and ecological values for which the Great Barrier Reef is renowned.

Notwithstanding such concerns, the Great Barrier Reef Marine Park was gazetted for multiple use, excluding only mining. Existing uses were recognised when the Great Barrier Reef was given World Heritage listing. In the absence of mining activities, fishing is the major extractive activity permitted in the Great Barrier Reef World Heritage Area. Line and

spear fishing are the fishing activities that have the greatest potential to affect the biological communities on coral reefs of the Great Barrier Reef. Satisfactory management of line and spear fishing activities, therefore, must be consistent with the conservation requirements of the *Great Barrier Reef Marine Park Act* (1975), World Heritage Values, and principles of Ecologically Sustainable Development (Anon 1987, COFI 1991, Kenchington 1990). Such management requires assessments of the effects of line and spear fishing with reference to both the biological features and the multiple (human) uses of the Great Barrier Reef. In this paper, we review the status of knowledge of such effects.

The Context: The Great Barrier Reef Marine Park

The Great Barrier Reef Marine Park comprises over 350,000 km^2 of marine habitats spread over 14° latitude from the tip of Cape York to south of the Tropic of Capricorn. There are over 2700 individual reefs and shoals in the Great Barrier Reef, occurring from sea level to over 40 m depth, ranging in size from less than 1km^2 to over 200 km^2, and mostly lying either well off-shore or considerable distances from major population centres. Coral reef habitats account for an estimated 5–7% of the area. A small area of the Great Barrier Reef, in the Torres Strait, is outside the Great Barrier Reef Marine Park.

The Great Barrier Reef Marine Park is managed for conservation and multiple use by the Great Barrier Reef Marine Park Authority (GBRMPA). The GBRMPA's management strategy is to regulate activities within individual coral reefs or larger areas of the marine park via statutory zoning plans. Zoning plans have been applied to the Great Barrier Reef Marine Park in four sections. Zoning plans first came into affect in 1983, 1986, 1987, and 1988 for the Cairns, Far Northern, Central, and Mackay-Capricorn Sections respectively. The main zones of use of the park (with relative areas) are: General Use A – all activities allowed (except mining) (79.2%); General Use B – no trawling (15.7%); Marine National Park A – no trawling or spear fishing (0.45%); Marine National Park B – no fishing or collecting ('look but don't touch') (4.5%); and preservation zones – no access, or scientific research zones – entry for permitted research only (0.15%). Day-to day management is by the Queensland Government through the Queensland Department of Environment.

Under the Offshore Constitutional Settlement, management of fisheries in the Great Barrier Reef Marine Park is the responsibility of Queensland and is overseen by the Queensland Fisheries Management Authority (QFMA) (*Queensland Fisheries Act 1994*). Enforcement of fisheries regulations is executed by the Queensland Fishing and Boating Patrol. The Reef Line (and spear) Fishery is subject to a range of management strategies, comprising: a two-tiered endorsement system for the commercial sector with a cap on effort; bag limits for individual species and total catch by recreational fishers; and minimum legal size limits for most targeted and some non-target species. A total of 1806 licences exist for commercial line fishing in the Great Barrier Reef region, with 251 of those endorsements allowing fishing from 2 or more dories in addition to the main boat, and the remainder restricting fishing to no more than one dory and the main boat. There are presently no restrictions on total catch by the commercial fishery or on the movement of appropriately endorsed vessels within the Great Barrier Reef Marine Park.

The Reef Line Fishery

The Reef Line Fishery refers to fishing for fin-fish in coral reef or shoal habitats using hook and line gear (QFMA 1996). For convenience here, we also include spear fishing under the same title because a) the spear fishery is a relatively minor component of the harvest of reef fish species (S. Nakaya unpub. data), and b) spear fishing is a recreational-only pursuit which has similar primary target species as recreational line fishing. We do not consider inshore or estuary fishing.

The Reef Line Fishery has three major sectors: commercial fishing, fishing from charter boats, and recreational fishing. The recreational sector comprises fishing by angling clubs and fishing by individuals from private boats. There is some indigenous line and hand-spear fishing in some areas of the Great Barrier Reef, but there is virtually no information about those activities (QFMA 1996).

Commercial line fishing is from aluminium or fibreglass dories (typically 4–5 m long) with outboard motors and based on main boats (7–19 m) that move among reefs during fishing

trips of 1–28 days. Main boats rarely stay at single reefs for more than 1–2 days. In most cases, fishing is by a single fisher in each dory (or occasionally from the main boat), using single baited hooks on 50–150 pound breaking strain hand line. Western Australian pilchards are the most common bait. All commercial fishers have been required to keep daily logs of their effort and catch since 1988 (Gwynn 1990, Trainor 1991), but only 535(1988)–604(1991) main boats (including line-endorsed trawlers) reported catches of reef species between 1988 and 1995. There is considerable diversity in the commercial fleet in terms of species targeted, crew skills, and annual per-boat catch and effort (Mapstone et al. 1996a,b, pers. observ).

Traditionally, fish were killed on capture and kept in the dories during each of two fishing 'sessions' (morning and afternoon) before off-loading to the main boat to be processed and frozen or chilled. There have been two significant developments in the commercial fishery over past 5–6 years. In 1992, the Commonwealth Department of Primary Industry and Energy (DPIE) Export Control Food Orders were amended, making it easier for fishers fulfilling the requirements of the new orders to export their product. The increased access to export markets resulted in a significant increase (~200%) in the price of whole and filleted frozen coral trout. Secondly, since 1993 there has been a rapid development of trade in live fish for export. This market development has seen another significant rise in the price of coral trout, with dock prices of $18–$45/kg for the highest sale category. Fish to be sold live are kept in small holding tanks on dories and then on larger flow-through systems on main boats before being unloaded to land-based holding and export facilities The shift form 'dead' to 'live' product has led to shorter fishing trips and lower catch rates because of lower holding capacities and increased handling times in keeping fish alive.

The charter and recreational sectors also use hand-held gears (rods or hand reels). In 1995, 415 charter vessel operators held permits to take fishing trips into the Great Barrier Reef Marine Park. Some carried more than 20 passengers for day trips but most carried about 8–15 passengers for trips of up to 1–2 weeks. It is not clear how many charters actually involved fishing. Thirty two fishing clubs have records of fishing off-shore reefs in the Great Barrier Reef (Higgs 1996), though most probably do so only infrequently. The more active clubs have their own vessels and make up to 20 trips (1–2 days long) per year to the Great Barrier Reef (Higgs 1993). In a recent telephone survey of 21,000 households in Queensland, it was estimated that 34% of Queenslanders fished at least once per year, but only 6% of those were involved in fishing clubs (S. McCormack pers. com.). These figures were similar to results from an earlier survey by the Australian Bureau of Statistics (1986) which indicated that approximately 30% of Queenslanders fished at least once per year and about 34,000 people fished 'offshore waters' in the Great Barrier Reef region at least once per year. Blamey and Hundloe (1993) estimated that 270,000 fishing trips were made in private trailer boats in the Great Barrier Reef Region in 1989–90, but that only 5.4–13.5% of those were to 'open waters'.

Preliminary results from a recent study of the response of fishers to the re-opening of Bramble Reef (off Ingham) to line fishing after 3½ years of closure demonstrated that only a small fraction of the total recreational fishing effort from small boats in the region ventured to the offshore islands and reefs of the Great Barrier Reef (Mapstone et al. 1996c). The vast majority of effort was concentrated in estuaries and inshore waters (fig. 1).

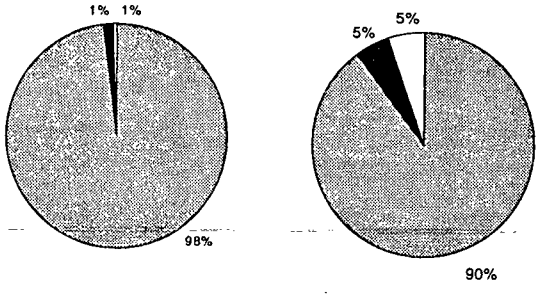


Figure 1. Percentages of recreational boating trips from the Ingham area in May–July 1995 that went to near-shore islands (black), off-shore reefs of the Great Barrier Reef (white), or inshore areas (grey). The pie on the left was derived from interviews at boat ramps, that on the right from voluntary angler logbooks (Mapstone et al. 1996c).

Over 125 species or species groups have been reported in landings from the commercial sector of the fishery (Mapstone et al. 1996a,b), and it might be expected that as many species would be landed by the recreational sector, although few detailed data exist (Higgs 1996, but see Higgs 1993; Nakaya unpub. data). The main target species for all sectors of the fishery over most of the Great Barrier Reef are coral trout (*Plectropomus* spp), red throat emperor (*Lethrinus miniatus*), red emperor (*Lutjanus sebae*), other cods (serranids), snappers (*Lutjanus* spp) and emperors (*Lethrinus* spp), and pelagic species such as spanish mackerel (*Scomberomorus commersoni*) (Mapstone et al. 1996a; Williams and Russ 1993). A greater diversity of species is targeted in the southern (Capricorn-Bunker) region of the Great Barrier Reef than elsewhere (Mapstone et al. 1996a).

METHODS

We have restricted this review to consideration of effects of line fishing as it is practiced on the Great Barrier Reef, and therefore also focused primarily on information from the Great Barrier Reef. Although various forms of artisinal, blast, net, trap, and cyanide reef fishing occur in other tropical nations, most do not have parallels in the Great Barrier Reef and, therefore, offer only peripheral or general points of reference for considering the potential effects of (over)fishing on coral reefs. For accounts of effects of fishing on coral reef assemblages in other tropical regions, see Alcala (1988), Koslow et al. (1988), Munro (1983), Polovina and Ralston (1987), Russ (1991) and Russ and Alcala (1989).

In compiling the review, we have included considerable reference to 'grey' literature, mostly in the form of refereed reports that have not been formally published. In most cases, however, the reports are available from the agency that commissioned them. We have adopted this strategy simply because most of the data relevant to the topic reside in such reports, with relatively few data so far published in the mainstream scientific literature. We did not approach this review as a technical review of research methods. In general, therefore, we focused on the putative results of the studies we considered and the authors' interpretations of them, without extensive discussion of the methods by which data were collected.

We considered the potential for effects of line fishing on the Great Barrier Reef in four categories: i) Effects on harvested species (both targeted and by-catch species); ii) Effects on non-harvested species; iii) Effects on the fishery; and iv) Effects on non-fishing activities. In categories i) and ii), we were interested mainly in effects on the biology and population dynamics of reef species, whereas in categories iii) and iv), we were interested mainly in effects on fishing activities (such as catches, catch rates) or satisfaction of fishing or other activities. We found no clear data, however, on effects of line fishing on non-fishing activities, except anecdote that large cods, groupers and wrasse were less visible to divers now than they used to be, and that this had negatively affected the quality of the dive experiences. We do not consider further the potential for interactions between line fishers and non-fishers, except to suggest that it may become an area of increasing importance as community awareness rises and the eco-tourism industries expand into new areas.

Research from which effects of fishing on harvested species were assessed fell into three categories: a) Underwater visual surveys (UVS) of abundances and sizes of fish; b) Studies of their biology or population dynamics; and c) Examinations of the sizes of fish in landed catches. Both a) and b) mostly involved the comparison of data from reefs on which fishing was allowed under the GBRMPA zoning plans (hereafter 'open' reefs) with data from reefs that were notionally closed to fishing (hereafter 'closed' reefs). Assessments of effects of fishing on sizes of fish in catches came from historical data such as fishing club competitions (Higgs 1993) or from 'recall' data from fishers (Blamey and Hundloe 1993). Effects on non-harvest species were gleaned exclusively from UVSs, whilst effects on fishing activities were assessed from interview studies (*e.g.*, Blamey and Hundloe 1993) and logbook data.

RESULTS

Effects on abundances and size structures of target species

There have been many UVSs over much of the Great Barrier Reef since 1983 in which target species of the fishery were counted (Ayling 1983a,b, Ayling and Ayling 1984a,b,

1985, 1986, 1989, 1992a,b, Ayling et al. 1991, Oliver et al. 1995). Only some were designed to assess whether notional closure of reefs to fishing had affected the main target species of the line fishery, in particular the common coral trout (*Plectropomus leopardus*), the red throat emperor (*Lethrinus miniatus*), and the stripey bass (*Lutjanus carponotatus*) (Ayling and Ayling 1992c,d, 1993, 1994a,b, 1995, Craik 1981, Mapstone, Ayling, and Choat unpub. data).

Most of these surveys failed to detect significant differences in total population densities of *P. leopardus, P. maculatus, P. laevis, L miniatus*, or *L. carponotatus* between open and closed reefs, with total densities of coral trout generally differing between open and closed reefs by less than 15%. The earlier surveys (1983–1986) in regions other than the Capricorn-Bunker region, however, occurred either before or shortly after the introductions of zoning plans and so no effects would have been expected (Mapstone et al. 1996d, Walters and Sainsbury 1990).

Several of the later surveys did indicate, however, that the size structures of populations of *P. leopardus* differed between closed and open reefs after several years of closure. Ayling and Ayling routinely estimated the sizes of all coral trout seen during their surveys, and their estimates were generally calibrated against model fish of known size and were reasonably accurate (Bell et al. 1985, Ayling and Ayling 1994b). Densities of legal sized fish (> 35cm Total Length (TL) before 1993, > 38cm TL since) tended to be consistently lower on open reefs than closed reefs, whilst the reverse was true for under sized fish. For example, in 1986, after 2.5–4 years of closure, densities of legal sized *P. leopardus* were nearly twice as great on closed reefs as on open reefs in the Capricorn Bunker group, whilst open reefs had almost twice as many under-sized fish on them as closed reefs (Ayling and Ayling 1992a,b, Ayling et al. 1991). A similar result was found after surveys of 50 reefs in the Cairns Section of the Great Barrier Reef Marine Park in 1991 (Ayling et al. 1991), though the suggested (but not statistically significant) effects were restricted to back reef habitats, where reef line fishing pressure tends to be heaviest (pers. obs.).

Ayling et al. (1991) considered several potential explanations for such patterns and speculated that they might have resulted from compensatory increases in survival of juvenile *P. leopardus* when populations were harvested. Work by Choat (1968), Goeden (1978), and St John (1995) indicated that the piscivorous coral trout are catholic predators and cannibals, providing evidence of a potential mechanism for such a compensatory response to harvesting of larger individuals. Recent UVS under the CRC Reef Research Centre Effects of Line Fishing Project (unpub. data) also indicated greater densities of undersized fish and lower densities of legal sized fish on open reefs than on closed reefs in the southern central Great Barrier Reef (off Mackay, 22°S, and Rockhampton, 23.50°S), but no such pattern was evident on reefs off Townsville (19°S) or Cape Flattery (14°S). For all of these studies, however, no detailed data were available about the amount of fishing pressure the open and notionally closed reefs (through illegal fishing) had experienced historically. The inference that the observed patterns reflected an effect of line fishing, therefore, must still be considered a working hypothesis at this stage.

In only four studies were target species surveyed repeatedly over a period when access to reefs for fishing changed. The first was done by Beinssen (1988, 1989) and focused on the re-opening to fishing of Boult Reef (in the Bunker group) after 3Ω years of closure. Beinssen used UVS before opening and after 2 weeks of (sponsored) fishing following the opening, together with tag-release-recapture studies, to measure the rate of stock reduction and changes in catch rates. He estimated that in 14 days intensive fishing removed approximately 25% of the standing stock of *P. leopardus*, but that catch rates dropped exponentially to less than 10% of their initial values over the same period. It was estimated that the stock size of legal size *P. leopardus* on the reef prior to opening was 8,613 fish (±873 SE). UVS 18 months later indicated that densities of legal size *P. leopardus* had dropped to 25% of their pre-opening level (Beinssen 1990).

Ayling and Ayling (1992c, 1994b) surveyed abundances of target and non-harvest species on five offshore reefs between Innisfail and Cairns that were opened to fishing in 1992[1] after 8 years of closure and compared data from those reefs to reefs that had always been open to fishing. Surveys were completed on all reefs (once) 2 months before and again 11

[1] The reefs were re-zoned when the Cairns Section Zoning Plan was reviewed, for reasons unrelated to research.

months after the 5 reefs were opened to fishing. Surveys involved counts along 5 transects at 2–12 m depth at each of 6 sites distributed around the perimeter of each reef. The surveys produced ambiguous results. There were no significant differences in population densities of *P. leopardus* between open and closed reefs after the 8 years of zoning, nor were there the apparently compensatory shifts in abundances of legal size and sub-legal *P. leopardus* seen in previous studies. Densities of legal sized coral trout decreased on two of the five closed reefs after they were opened to fishing, but remained relatively unchanged on the other three. Ayling and Ayling (1994b) speculated that this variation in the results may have arisen from variation in fishing pressure applied to the reefs after opening, but they presented no data to support that contention. Although Ayling and Ayling (1992d) claimed 'order-of-magnitude' differences in densities of *L. miniatus* between historically open and closed reefs, counts were too low (<10 per reef) in all surveys to make reliable inferences about the effects of past zoning status or changes in zoning on their abundances.

In the same study, Ayling and Ayling (1994b) recorded substantial differences in the abundances of *L. carponotatus* between the open and closed reefs, with considerably higher densities on the open reefs. This pattern did not change significantly following the opening of the previously closed reefs. This pattern was corroborated in a concurrent study by Brown et al. (1993,1996) which examined the effect of the re-opening of the closed reefs on the size and age structure of several harvested species (principally *P. leopardus* and *L. carponotatus*). Ayling and Ayling (1992c, 1994b) attributed the pattern to an 'artefact of reef selection', citing as evidence high densities of *L. carponotatus* on a closed reef not included in the analysis. Brown et al. (1996) speculated that the observed pattern also might have been consistent with an effect of 'predator release' arising from harvesting piscivores on the fished reefs and resulting in increased survivorship of juvenile *L. carponotatus*. The lack of contrast in population densities of *P. leopardus* between the open and closed reefs, however, does not support such a hypothesis. Thus, whilst worthy of further pursuit, these hypotheses should be considered carefully because a) there were no reef-specific fishing effort data available to verify that there was a significant difference in fishing pressure between the open and closed reefs, and b) there is little evidence that coral trout (or other harvested species) eat juvenile *L. carponotatus*.

In a situation similar to that studied by Beinssen (1988, 1989) at Boult Reef, Ayling and Ayling (1992d, 1993, 1994a, 1995), Mapstone et al. (1996c), and Benzaken (unpub. data) studied the effects of a 3Ω year 'replenishment area' closure at Bramble Reef off Lucinda. Bramble Reef was closed to fishing in January 1992 and re-opened to fishing on July 1 1995. Ayling and Ayling (1992d, 1993, 1994a, 1995) used UVS to monitor abundances of target and non-harvest species at 12 sites around Bramble Reef and 12 sites on each of 3 (1991–92) to 6 (1993–96) reefs nearby that remained open to fishing over the same period. Surveys were done in May–June of each year, with an additional survey 2 months after re-opening the reef.

Abundances of *P. leopardus* on all reefs increased consistently until 1994, driven substantially by a strong cohort of settlement in 1992 and smaller recruitment each year thereafter (Ayling and Ayling 1995). Population densities on the 6 'control' reefs dropped by 16–44% after May 1994 as a result of reductions of 31–57% in the densities of legal sized *P. leopardus*. Such drops would be consistent with the harvest of the strong 1992 cohort, which would have been attaining legal size in 1994–95. Population density, and density of legal size *P. leopardus* in particular, continued to increase on Bramble Reef between May 1994 and June 1995. Within two months of Bramble Reef being opened to fishing, population density of *P. leopardus* dropped by 27%, driven by the harvest of 57% of the legal sized stock (Ayling and Ayling unpub. data). One full year after re-opening Bramble Reef to fishing, an estimated 78% of legal sized *P. leopardus* had been harvested from Bramble Reef, equating to a reduction of 45% in total population density (Ayling and Ayling unpub. data). The resultant population densities on Bramble Reef were similar to those on the six 'control' reefs in 1996. No similar effects were observed for other target species, though this could be attributed, in part at least, to the unsuitability of UVS for counts of the larger mobile snappers and emperors resulting in low counts and very low statistical power to detect spatial or temporal patterns.

Effects on biology of targeted species

There are two main published studies of the effects of fishing on the biology of harvested species on the Great Barrier Reef. Brown et al. (1993, 1996) completed a study of the effect

of re-opening reefs on the size and age structures and rates of total mortality of *P.leopardus* and *L. carponotatus*. The four study reefs (2 previously closed, 2 historically open) were among those surveyed by Ayling and Ayling (1992c, 1994b). Brown et al. (1996) found that total mortality estimates from the open and closed reefs were almost identical, and that there was no difference in the age structures of *P. leopardus* populations between open and closed reefs prior to, or after, the re-opening of the reefs which had been closed to fishing for eight years.

Four reefs off Townsville also have been the subject of a relatively long-term study of the effects of notional closure on the age and reproductive structures of coral trout populations in recent years (Ferreira and Russ 1995, Russ et al. 1996a, in press). Two of the reefs had been notionally closed to fishing since 1987, three and a half years prior to commencement of sampling for the study. Each reef was sampled by line fishing on two occasions (June–July and September–October) in each year from 1990–93. Over the four year study no significant differences were found among reefs open to or closed to fishing for any of the population parameters estimated. These included mean size, mean age, mean size and age at sex-change, and sex ratio. Ferreira and Russ (1995) suggested that the lack of significant differences between open and closed reefs reflected: i) the short period of closure relative to the longevity of *P.leopardus*, ii) high variation among reefs within treatments, and iii) the influence of an exceptionally strong year class, which was evident only on the closed reefs and dominated their populations throughout the study.

Effects on non-harvest species

Many of the UVSs discussed above included counts of many species that are not harvested by the line fishery (although some are harvested by divers for the aquarium trade). Although differences between closed and open reefs were occasionally evident for some species (e.g., Ayling and Ayling 1992c, 1994b, Mapstone, Ayling and Choat unpublished data), most differences between open and closed reefs were not consistent among surveys or natural strata such as habitats.

Recent work by St John (1995) provided a clear depiction of the diet of *P. leopardus*, indicating which non-harvest fish species might be expected to first show secondary effects of fishing via reduction in abundances of one or more of their predators. Caesionids (fusiliers), small (<30cm TL) scarids (parrotfishes), clupeids (bait-fish), and some pomacentrids (damselfish) were the main components of the diet of *P. leopardus*, with some regional and seasonal variation in their relative contributions. Unfortunately, only the pomacentrids were usually counted in UVS, and in many cases the main pomacentrid prey species were not among those pomacentrids counted. The absence of clear evidence of secondary (or higher order) effects of fishing may simply indicate that observers have been (unknowingly) surveying the wrong species. Current work under the CRC Effects of Line Fishing Project is specifically targeting the key prey species groups of coral trout in UVSs, but the results of that work are not yet available.

Endean and Cameron (1990) and Ormand et al. (1990) suggested that overfishing on the Great Barrier Reef may have resulted in greater frequency and/or intensity of outbreaks of crown of thorns starfish (COTS, *Acanthaster planci*), but no data exist to test this hypothesis directly. Sweatman (1995) rigorously studied the potential for such an interaction by considering the degree to which juvenile *A. planci* were likely to be prey to reef fish, especially the lethrinids and lutjanids. He analysed the gut contents of *Lethrinus miniatus*, *L. atkinsoni* and a number of other common lethrinid and lutjanid species and found little evidence of any of the species feeding on *A. planci*. Well controlled caging experiments also failed to show significant effects of predation on the survival of juvenile *A. planci*, indicating that the large fishes excluded by the cages were not major predators of juvenile COTS. Sweatman (1995) therefore inferred that line fishing was unlikely to have had important effects on the occurrences of COTS outbreaks.

Effects on fishers

Aside from data from fishing clubs, historical data about the Great Barrier Reef line fishery are either scarce (for the small boat sector, Blamey and Hundloe 1993; Higgs 1996), almost non-existent (for the charter boat sector, Higgs 1996, but see Thwaites and Williams 1994 for 1 year of data), or relatively recent (for the commercial sector, Mapstone et al 1996a,b,

Gwynn 1990; Trainor 1991). It is difficult, therefore, to infer how fishing activities have changed with fishing pressure.

Higgs (1993) reviewed the data held by off-shore fishing clubs from four regional centres along the Great Barrier Reef coast, extending earlier work by Zann-Shuster (1990). The records from one club in Townsville showed initial declines in catch rates and average sizes of fish in the first few years of records (early 1960s), but thereafter both catch rates and average sizes of fish were annually variable around a constant rate until the early 1990s. Catch composition changed between 1989 and 1992, but after interviewing the club record keeper and long standing members, Higgs concluded that the change in catch composition was attributable to a shift in activity from day-fishing around shallow reefs (mainly for coral trout) to night fishing on deeper shoals for 'red' fish (small mouth nannygai, (*Lutjanus erythropterus*), large mouth nannygai (*L. malabaricus*), hussar (*L. adettii*), and red emperor (*L. sebae*)) rather than because of changes in the availability or size of coral trout. Only data from fishing clubs in Mackay showed a slight downward trend in catch rates (1971–89), with data from Cairns clubs showing increased catch rates and average sizes of fish between 1975 and 1992 and data from Rockhampton clubs showing no change in either catch rates or average sizes of fish landed (1956–89).

Blamey and Hundloe (1990) surveyed anglers fishing from small private boats in four regions of the Great Barrier Reef to compare anglers perceptions of their fishing activities with similar surveys done 10 years previously (Craik and Fallows 1979, Fallows and Craik 1980, Driml et al. 1982, Hundloe et al. 1980). Blamey and Hundloe (1993) found that anglers perceived their catches to have fallen in both numbers of fish landed and sizes of fish landed over the 10 year period. The significance of the results for coral reefs of the Great Barrier Reef is not clear, however, because most of the fishers interviewed fished in estuaries or inshore waters and did not fish on off-shore reefs. Whilst anglers indicated several factors that they believed had caused these apparent declines in their catches, most factors were unrelated to their own fishing activities, and all were speculative.

Commercial catch and effort data from compulsory daily logbooks kept for the QFMA by commercial fishers are available from 1988 to present. Mapstone et al. (1996a,b) recently reviewed those data, but found little evidence of change in effort or catch throughout the period. Even when considered at regional scales, effort, catch, and catch rates, though variable inter-annually, mostly showed no monotonic increases or decreases. Two exceptions were for most catch groups in the Swains region and for spanish mackerel in the Townsville region. Declining effort in the Swains lagged behind declining catches and was accompanied by declining catch rates, possibly indicating an effect of previous fishing on current catches. The declining catches and effort targeted at mackerel in the Townsville region, however, were concurrent, and accompanied by stable catch rates. Discussions with fishers active in the fishery over the past 8 years indicated that the observed decline in effort may have arisen because of a shift by many fishers from targeting spanish mackerel to targeting coal trout as a result of coral trout market prices increasing whilst mackerel prices remained relatively constant (pers observ).

Finally, in both the Boult Reef study (Beinssen 1989) and the Bramble Reef study (Mapstone et al. 1996c), fishing on the reefs immediately after re-opening resulted in a rapid decline in catch rates. At Boult Reef, both recreational and commercial fishing catch rates declined sharply over 14 days after opening, whilst at Bramble Reef it was only commercial catch rates that declined sharply over the first two weeks after re-opening the reef to fishing. Catch rates by recreational fishers at Bramble Reef were highly variable and showed no trend over 2 months after opening.

DISCUSSION

The Reef Line Fishery on the Great Barrier Reef is clearly a diverse fishery of great recreational and commercial importance. Given the potential for mobilisation of considerable inactive effort in the commercial (and perhaps charter) fleets, and likely increases in population and tourism in the Great Barrier Reef region, the dearth of conclusive data about the effects of the line fishery on the target species, non-harvested species, and current and future fishing is cause for considerable concern. The need for rapid improvement in the information base for management of the fishery has been flagged by many management, industry, and scientific spokespersons recently. Explicit in these calls is the assumption that fishing is a legitimate and, to many, desirable use of the Great Barrier

Reef. As a result, assessing its effects, and the effectiveness of protecting areas from fishing, is a productive aid to sustainable practice. Assessing the effects of line fishing, however, must encompass considerations of both the direct and indirect effects on the ecosystem and the feed-back effects on the users subject to management.

In the main, available data that might be used to assess effects of line fishing lack contrast, either between open and closed reefs or through time, and at face value suggest 'no effects'. We emphasise, however, that there are important pitfalls potentially disguised by such an inference. For example, many of the data were not collected with assessment of the effects of fishing in mind, and so are of limited use for such assessments. Further, because there are generally no prior data about reefs before they were closed to fishing, it is impossible to reliably infer whether closure has had any effect. Reefs that appear similar now may have been quite different prior to closure, or reefs that appear different now may have always appeared different. Confounding between notional differences in fishing pressure and other variables, lack of sequential measurements of stock density during periods of closure or exposure to fishing, and an absence of reef-specific fishing effort data further complicate inferences of effects of fishing. There is much anecdote and some circumstantial evidence (Davies 1995a,b) that closed reefs are fished to varying degrees, but no solid data from which to assess the level of such infringement relative to legal fishing on open reefs. Under these circumstances inferred effects of fishing, or inferences of no effects, must be regarded as speculative and circumstantial at best.

The lack of long-term studies of target species, non-harvest species, or the fishery with a view to monitoring the behaviour of the fishery and its effects is also cause for caution when interpreting relatively recent data. The studies of Bramble Reef and Boult reef clearly indicated that there were conspicuous effects on coral trout populations when fishing commenced on relatively unfished ground, but that measures of stocks and fishing stabilised fairly quickly. It might be expected that the major initial effects of line fishing over most of the Great Barrier Reef had occurred well before the collection of data began, and so available data simply reflect monitoring relatively stable conditions over a (short) period of fairly constant fishing effort. Such data provide little basis for inferring either stability or change in the fishery (Hilborn and Walters 1992).

Those studies that have directly focused on the effects of fishing on population structure have been plagued by relatively small sample sizes and high spatial and temporal sampling variation (Brown et al. 1993, 1996, Ferreira and Russ 1995, Russ et al. 1996). It is clear from these studies that rigorous comparisons of open and closed reefs and analyses of trends in population parameters will require carefully structured sampling that yields large sample sizes over many years to account for much of the natural variation evident on reefs (such as depth or habitat related variation in sizes and ages of fish). Without better resolution in the sample data, future results are likely to be as equivocal as past ones.

Emerging issues

Recent information about the Great Barrier Reef line fishery and the main target species, especially coral trout, suggest that the potential for deleterious effects of line fishing is increasing. There is virtually no information, however, about the by-product species, either in terms of their potential to replace the current target species or about their basic biology. These deficiencies are of particular concern in such a clearly multi-species fishery.

The recent growth in the live fish trade coupled with apparent increase in demand for existing line fishing endorsements indicate growing capital investment in the fishery (Mapstone et al. 1996a, Johannes and Riepen 1995, Squire 1994). Such investment brings with it added fishing pressure and greater need to maintain catches in the short to medium term (Hilborn and Walters 1992).

Evidence elsewhere of targeting spawning aggregations of coral reef fishes clearly demonstrates the potential for such targeted line fishing to seriously jeopardise the long term yields and ecological viability of stocks (Colin 1992, Johannes and Squire 1988). Recent work by Samoilys (1996), Samoilys and Squire (1994), Zeller (unpub. data), demonstrates that *P. leopardus* forms small spawning aggregations, and modelling by Fulton (1996) indicates that such behaviour can result in increased harvest rates even when targeting by fishers is negligible. Anecdotal information suggests that other species, such as *P. laevis, Chelinus undulatus, L. miniatus,* and *L. nebulosus*, form considerably larger

aggregations that represent large proportions of local spawning stocks, and that these aggregations have at times been heavily harvested by commercial and/or recreational fishers. The potential for major effects of such harvesting is great and has raised concern among scientists, managers, and fishers. There is virtually no data available, however, to verify the anecdote or substantiate concerns.

It is now clear that many tropical reef species have longevities exceeding 10–15 years, and are characterised by episodic and highly variable recruitment (Brown 1994, Doherty 1991, Doherty and Williams 1988, Ferreira and Russ 1994, Fowler 1990, Russ et al. 1996). Where strong cohorts are separated by lengthy intervals, such life histories render these species highly susceptible to over-fishing, but the potential for periodic surveys to detect effects of fishing will likely be obscured by recruitment variation. Given the growth characteristics of many of the target species, effects of exploitation will be evident only from detailed longitudinal studies of the age structures of populations under different regimes of fishing (Russ et al. in press).

Finally, there is considerable anecdote that over-fishing has occurred in some local areas, most notably between Innisfail and Port Douglas. There are no data to verify these views, however, even though they are shared by fishers from all fishing sectors.

Future directions

There is a clear need to gain sound longitudinal data about all sectors of the Reef Line Fishery on the Great Barrier Reef, including biological studies of the target and by-catch species and fishery independent measures of stock abundances. The QFMA has recently begun a sampling strategy to gain state-wide data on recreational fishing, including the recreational and charter vessel sectors of the Reef Line Fishery (QFMA 1995). Though only partly implemented, this scheme is the most significant step to date towards gaining the necessary data about recreational fishing in the Great Barrier Reef region. The key limitation of the data is that they will not provide historical perspective (except for clubs) and so will provide little basis for the inferring trends in the fishery within 10–15 years.

It has been repeatedly suggested in the fisheries and ecological literatures that whilst monitoring is a necessary aid in devising and assessing the performance of management strategies, it is not sufficient to resolve the key underlying dynamics of natural systems and their responses to harvest (Walters and Hilborn 1976, Walters 1986, Collie et al. 1991, Walters and Holling 1990, Ludwig et al. 1993, McAllister and Peterman 1992, Peterman and McAllister 1993). The most secure and rapid mechanisms to provide definitive information for management is by well designed experimental manipulations, or 'active adaptive management' (Walters 1986, Hilborn and Walters 1992, Ludwig et al. 1993). Active adaptive management incorporates aspects of management and fishing practice into experimental treatments, with the intention of precipitating responses in the fished stock, non-harvest species, and/or the fishery, thereby reducing uncertainty about the response of the system to harvest and regulation. Such an approach offers great benefit over more passive monitoring in systems which are complex, information poor, and about which conclusions on the effects of fishing are difficult or impossible with current knowledge (Petersen and McAllister 1993, Walters and Holling 1990).

Management as experiments

The use of manipulative experiments, even in the interests of acquiring management relevant data, has proved controversial in the Great Barrier Reef recently. In part, the controversy has arisen from the use of reefs that have been zoned to exclude fishing. In part, the ethical implications of increasing fishing pressure, even at a local scale, in order to measure the system response have also been challenged. One perspective that seems to have been overlooked in this debate so far is that management of the Great Barrier Reef (or any other deliberately regulated system) inherently involves manipulations of the natural system or its use (Hilborn and Walters 1992; Walters and Holling 1990). By definition, management is manipulative in that strategies are devised to modify the behaviour of users in the interests of precipitating responses (in use and in the natural system), especially in fisheries management. Ludwig et al. (1993) and others (e.g. McAllister and Peterman 1992; Peterman and McAllister 1993) recently argued strongly that management is usually also experimental in that the manipulations are made without certainty about the result. This is especially the case where management strategies are devised in information poor

environments: '*Every major change in harvesting rates and management policies is in fact a perturbation experiment with highly uncertain outcome, no matter how skilful the management agency is in martialling evidence and arguments in support of the change*' (Walters and Holling 1990).

In such situations, management amounts to the implementation of 'best guess' strategies based, at best, on poor information. A situation Walters (1986) defined as 'passive adaptive management'. The application of such strategies is often accompanied by optimism that they will be 'the right option', but the success rate of first 'best guesses' generally has been poor. The result is that management becomes the sequential trial and error of best guesses, with each new strategy starting with the (usually unsuccessful) remnants of the prior strategy. In most systems, because of the spatial structure of the fishery and/or the environment on which it is based, there is no alternative to applying these sequential strategies to the whole system, meaning that poor best guesses place the entire fishery, and perhaps substantial parts of the environment, at risk.

Hilborn and Walters (1992) and others (Walters and Hilborn 1976; Walters 1986; Collie et al. 1991; Walters and Holling 1990; Ludwig et al. 1993; McAllister and Peterman 1992; Peterman and McAllister 1993; Sainsbury 1988) have argued that such approaches to management are usually not viewed formally as either experimental or as instruments of learning. The same authors have emphasised that the potential for successful management will increase considerably if management strategies *are* seen as experiments, and designed to maximise learning and the delivery of useful information from each 'best guess'.

Designed management experiments

In view of the shortage of information about the history, performance, and effects of the Great Barrier Reef line fishery, its management would seem to fit well into the 'experimental' category. We suggest that management of the fishery, and other aspects of the Great Barrier Reef where management is information poor, should be approached explicitly with its manipulative experimental characteristics in mind. Strategies should be designed, at least in part, as experiments with the purpose of delivering direct management information in the short–medium term (3–10 years). Because of its large geographic extent, its highly fragmented spatial structure, and the management regimes already in place, the Great Barrier Reef provides perhaps the greatest opportunity of any marine system to implement formal active adaptive management experiments – and it is perhaps one of the areas for which such an approach is most critical. In the Great Barrier Reef system exists the potential to avoid the sequential experimental constraints of other systems and implement alternative management treatments concurrently in a designed strategy. Properly designed, such an approach will shorten dramatically the learning period for management compared to the sequential application of management regimes to the whole system because the results of different strategies can be compared concurrently, in an un-confounded way. Further, with concurrent management strategies, errors in one or more of them do not place the entire fishery and/or Great Barrier Reef system at risk. In effect, we are suggesting the active adaptive management of the short-term risks for the Reef Line Fishery and its effect on the Great Barrier Reef, engendered by the conspicuous lack of information, in the interests of making more secure the longer-term status of the system and the fishery.

Such an approach would doubtless precipitate debate on a range of ethical and operational issues about management of the environment and the role of manipulative work (research or management) in it. Such issues include the ethics of manipulative field research, use of 'protected' areas for research (or management) experiments, the need for quantitative performance measures by which to assess the effectiveness of management strategies, and the balance between a desire for non-interventionist management verses the need for information to reduce the uncertainty in management decisions. Apart from consideration of performance indicators, the above issues have mainly been considered in relation to research, even though they could, and should, be considered also in relation to existing and future approaches to management. Resolution of such issues in relation to the Great Barrier Reef World Heritage Area may represent the difference between a future of information poor management decisions precipitated by proximal emotive debate and information rich management decisions made with considered reference to their longer term consequences.

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SESSION 4

Large-scale phenomena and organism response

Chair: David Yellowlees

Rapporteur: Ove Hoegh-Guldberg

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Keynote Paper: Massive corals: grand archives of Australian paleoclimate
M Gagan*, S Anker, L Ayliffe, D Barnes, J Chappell, D Hopley, P Isdale, J Lough and M McCulloch

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Coral bleaching: implications for the Great Barrier Reef Marine Park
O Hoegh-Guldberg*, R Berkelmans and J Olive

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Geoscience issues on the Great Barrier Reef: time scales for reef and shelf processes
D Johnson*, P Larcombe, B Carter, A Orpin, P Ridd and K Woolfe

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Organism level response of corals to increased nutrients concentrations
D Yellowlees
(abstract only)

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A review of the possible causes and consequences of outbreaks of the crown-of-thorns starfish (*Acanthaster planci*) on the Great Barrier Reef - an Australian perspective
U Engelhardt* and B Lassig

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Physical oceanography
E Wolanski and B King*

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Massive corals: grand archives of Australian palaeoclimate

MK Gagan[1], S Anker[2], LK Ayliffe[1], DJ Barnes[3], JMA Chappell[4], D Hopley[2], PJ Isdale[3], JM Lough[3] and MT McCulloch[1]

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ABSTRACT

Massive corals growing in the reef ecosystems of Australia provide some of the richest palaeoclimate archives in the world. This paper summarises Australian coral research designed to develop a multi-proxy approach to coral-based palaeoclimatology. A new understanding of coral growth mechanisms has led to a refined 237-year record of average calcification in 10 corals from the Great Barrier Reef. This record indicates that the fifty-year periods of highest calcification (sea-surface temperature) were 1746–1808 and 1927–1976, while the lowest growth occurred from 1877–1926. Mid-20th century average sea-surface temperatures (SSTs) were the second highest over the past 237 years. UV fluorescing bands in massive corals provide a highly resolvable and accurate proxy for the magnitude of run-off from mainland rivers. A 342-year reconstruction of annual run-off for the Burdekin River shows climatic extremes not evident in the instrumental record (1922 onward). The record clearly defines dry spells lasting several years and much wetter monsoon seasons. High-resolution, tandem measurements of coral Sr/Ca and $\delta^{18}O$ can be used to reconstruct changes in SST, precipitation, evaporation, and wind velocity. Such records provide month-by-month documentation of the dynamics of monsoonal rainfall and the evolution of the El Niño-Southern Oscillation. Sr/Ca, $\delta^{18}O$, and UV fluorescence measurements have been made on a 100-year core from a fossil *Porites* micro-atoll which grew near Orpheus Island about 5,800 yBP. Interpreted together, these tracers suggest that SSTs were about 1°C warmer than present, less variable from year-to-year, and that droughts / floods were rare. The lack of variability in the SSTs and rainfall suggests that the Great Barrier Reef may have been characterised by a weaker El Niño-Southern Oscillation during the mid Holocene.

Climatic significance of coral records from the Australian region

Extension of the instrumental climate record backwards in time is a high priority in the face of climate change (e.g. IGBP, 1990; CLIVAR, 1995). High-resolution proxy climate records are needed to: (1) help detect climate change; (2) to test, tune and validate climate models; and (3) to describe and understand the nature and causes of natural climate variability, particularly on decadal and longer time scales. Corals can contribute to the palaeoclimatic data base both for the past several centuries and (with comparable time resolution to living corals) for well-dated windows of the more distant past.

Australia has ready access to coral reefs positioned within key components of the global climate system (figure 1). For instance, interannual variations in summer monsoonal rainfall in northern Australia and the western tropical Pacific are strongly influenced by the El Niño-Southern Oscillation (ENSO) phenomenon (e.g. Hastenrath 1991; Glantz et al. 1991). In the vicinity of the Great Barrier Reef (GBR), for example, ENSO events (associated with warming, El Niño, in the eastern Pacific) are linked to a greatly weakened summer monsoon and drought, reduced tropical cyclone activity, and enhanced surface radiation receipt. Anti-ENSO events (associated with cooling, La Niña, in the eastern Pacific) are linked to a more vigorous summer monsoon and flooding, more tropical cyclones, and reduced surface radiation receipt (Lough 1994). These two extremes of ENSO give rise to major changes in surface climate, sea level and the strength of ocean currents throughout the tropical western Pacific (Allan 1988).

Recent research has shown that SSTs in the eastern Indian Ocean strongly affect winter rainfall in Australia (Nicholls 1989) and complicate drought predictions based simply on our understanding of ENSO. The so-called Indian Ocean 'dipole' consists of warmer than average SSTs north of Australia that form in conjunction with unusually cool SSTs extending west into the Indian Ocean from Australia's west coast . The dipole effect enhances winter rainfall by pushing cold fronts northward where they interact with moist tropical air to produce cloud banks which travel across the country towards the southeast, bringing winter rain. It will be crucial to document both the ENSO and the Indian Ocean dipole, accurately and over long time scales, if we are to understand how these systems interact to enhance or mitigate drought in Australia.

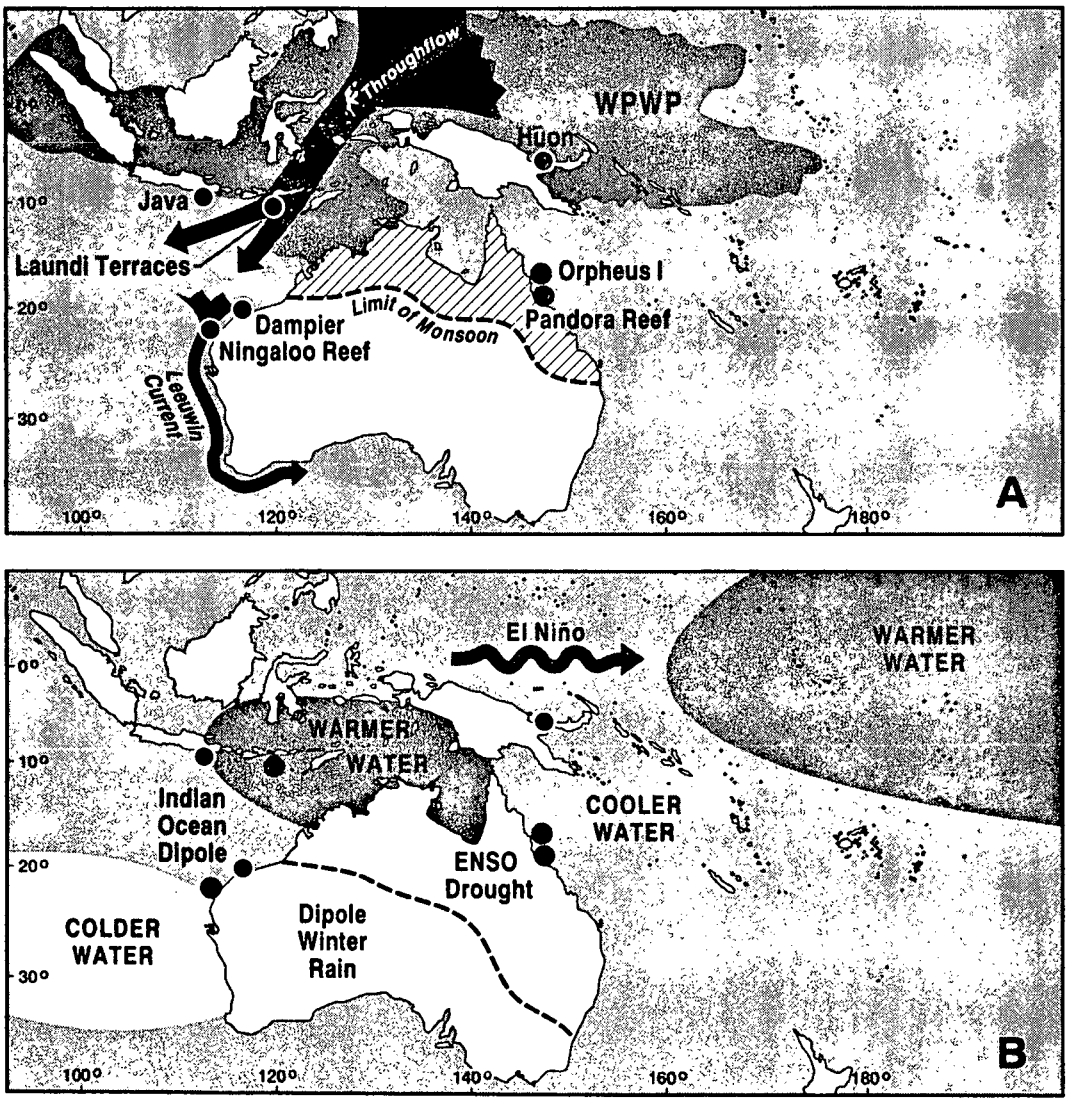


Figure 1. (A) Physiographic map showing the location of coral study sites, the Western Pacific Warm Pool (*WPWP*, mean SST > 28°C), and schematic ocean circulation patterns. (B) Summary of SST patterns and rainfall anomalies produced by the ENSO and the Indian Ocean dipole.

The purpose of this paper is to summarise the types of records that have been extracted from massive corals to document the dynamics of these important climate systems. Using a multi-tracer approach, it is now possible to use corals to reconstruct both the oceanic and atmospheric response to climate change, including SSTs, precipitation, evaporation, and wind velocity. Corals are rich climate archives and the potential for more and better records is enormous.

Understanding coral growth mechanisms: a key to realising the full potential of coral records

We are still in the early (and exciting) stages of the development of the science of scleroclimatology (cf dendroclimatology). Our goal is to be able to routinely develop from corals high-resolution proxy climate records of known reliability. As new climatic tracers are identified and more sophisticated techniques developed for data extraction and measurement there is an ongoing need to understand fully the processes whereby massive corals record information about their environment. This is because there are no accurate or precise proxy environmental recorders. All proxy climate records are biased and contain errors unrelated to climate. The best existing proxy climate recorders are those for which procedures have been developed to make some allowances for their shortcomings (e.g. Briffa 1995).

Three demonstrable mechanisms of coral growth (Barnes and Lough 1993) are: (1) the colonial skeleton extends by growth at its outermost surface, (2) the scaffolding created at the outermost surface is thickened through the depth of the living tissue layer (which may occupy skeleton formed over the previous 2–10 months), and (3) the tissue layer remains as a relatively narrow band around the outer surface of the colony because of periodic and abrupt lifting of its lower margin (see figure 2). Numerical modelling of these growth

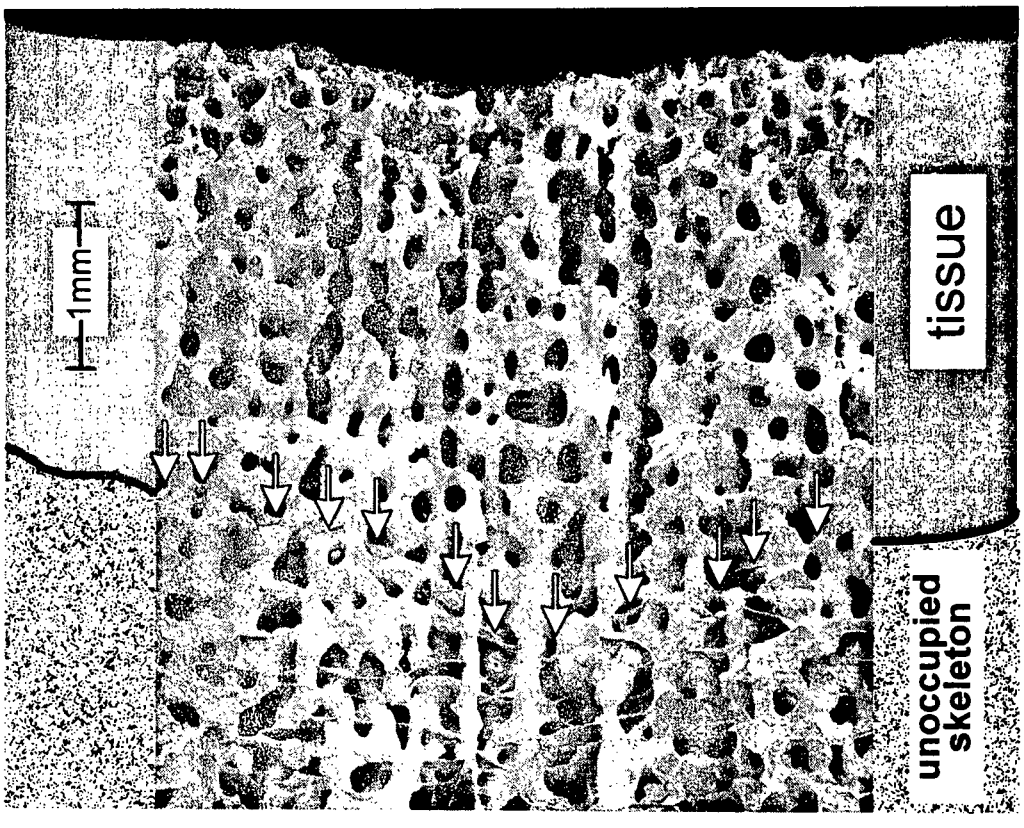


Figure 2. Mosaic of scanning electron micrographs showing the outermost region of skeleton in a colony of *Porites*. The arrows indicate the line of the most recent dissepiments at the base of the tissue layer. Note that the skeletal elements become thicker and more robust from the colony surface towards the most recent dissepiments. From Barnes and Lough, in press.

processes with a simple sine wave forcing function (representing light or temperature) has provided useful insights into how both measurements of density variations and materials included in the coral skeleton may be biased and distorted (e.g. Taylor et al. 1993; Barnes et al. 1995). For example, density bands can appear to anticipate their forcing function as well as appearing to be formed some months out-of-phase with the forcing function. These difficulties in dating density bands can account for problems with linking density bands to environmental factors. Similarly, environmental signals varying with an annual cycle and

recorded in the coral as geochemical or isotopic tracers may also be distorted by these coral growth processes. For example, the record in the coral skeleton approximates the causative annually cycling environmental variable only where the tissue layer is thin and skeletal extension is constant through the year. Records in corals of short-term environmental events are likely to be best recorded by optical techniques. By sampling the skeleton, the same short-term event can appear to be of different magnitude due to subsequent thickening of the skeleton.

These process and modelling studies help us to understand the limitations of present techniques for routine recovery of environmental information from coral skeletons. They provide guides to new or improved methods for recovery of the wealth of information stored by corals. At the very least, such studies indicate the variability that coral growth processes can introduce to any proxy environmental record. Thus, it is unwise to consider a record from a single coral as anything other than a record of itself. We can increase our confidence in the reliability of a particular record by comparing and combining information from different corals.

A 237-year record of sea surface temperature and calcification for the Great Barrier Reef

One of the original applications of coral density bands envisaged by Knutson et al. (1972) was the study of coral growth histories. Measuring how fast corals grow and how and why coral growth varies in space and time is a fundamental problem in coral reef research. Prior to the discovery of annual banding, elucidation of such factors depended on time consuming *in situ* (and manipulative) experiments. The presence of annual growth cycles opened the way to the use of corals 'to extend retrospectively our baseline data on change, variability, and biological responses in coral reef environments' (D'Elia et al. 1991). The real and perceived degradation of coral reefs in response to human activities in the near-shore zone (Wilkinson and Buddemeier 1994) has highlighted the potential importance of massive corals as 'retrospective monitors'.

To better understand long-term coral growth variability on the Great Barrier Reef annual extension, average annual skeletal density and annual calcification were measured in 35 massive colonies of *Porites* (Lough et al. 1996; Lough and Barnes, in press). The colonies were located at sites along the complete length of the Great Barrier Reef from 9°–23°S. The oldest dated sample (1479 A.D.) came from an 8 m high coral in the southern Great Barrier Reef. Although present techniques for extracting coral growth variables are not optimum (e.g. Barnes and Lough 1990, 1993; Lough and Barnes 1990; Taylor et al. 1993) reasonable estimates can be obtained by appropriate averaging in space and time. Possible inaccuracies in the dating of the samples (due to distortion of the densitometric profile by coral skeletal architecture) means that we are most confident of the coral time series when filtered to emphasise periods of 5 or more years. The complete set of records from the 35 corals provides a new perspective on long-term coral growth variations of the Great Barrier Reef. Annual extension and calcification, for example, can vary by up to 30% of the mean from year-to-year; whilst coral skeletal density typically varies by up to 10% of the mean.

Ten of the longest coral records covering the period 1746–1982 A.D. were averaged together (after standardisation with respect to 1934–1982 mean and s.d.) to form a single coral calcification time series representing the Great Barrier Reef from 14°–22°S (figure 3). This average series was significantly correlated with the instrumental record of sea surface temperatures (SSTs) for the Great Barrier Reef over the period 1906–1982 (30% variance in common). Thus, this long-term record can be viewed as both a record of coral growth variability and SSTs over the period 1746–1982. Features of this 237-year record include a significant spectral peak at periods of 15–17 years; high calcification (high SSTs) in the late 18th century and low calcification (low SSTs) in the early 19th century. This low-growth period is not matched in any of the subsequent record. The 20th century witnessed the second highest 50-year period (1927–1976) of coral calcification (SSTs) after the period 1759–1808. The decline in coral calcification since the early 1970s may simply reflect a return to more 'normal' or average conditions over the past 237 years, at least.

This 237-year record is a first step in applying analysis of density bands to understanding coral growth and SST variations of the Great Barrier Reef. Improvements in the quality of the records will be made as better techniques are developed to allow for the distortions of coral growth processes on the density band information.

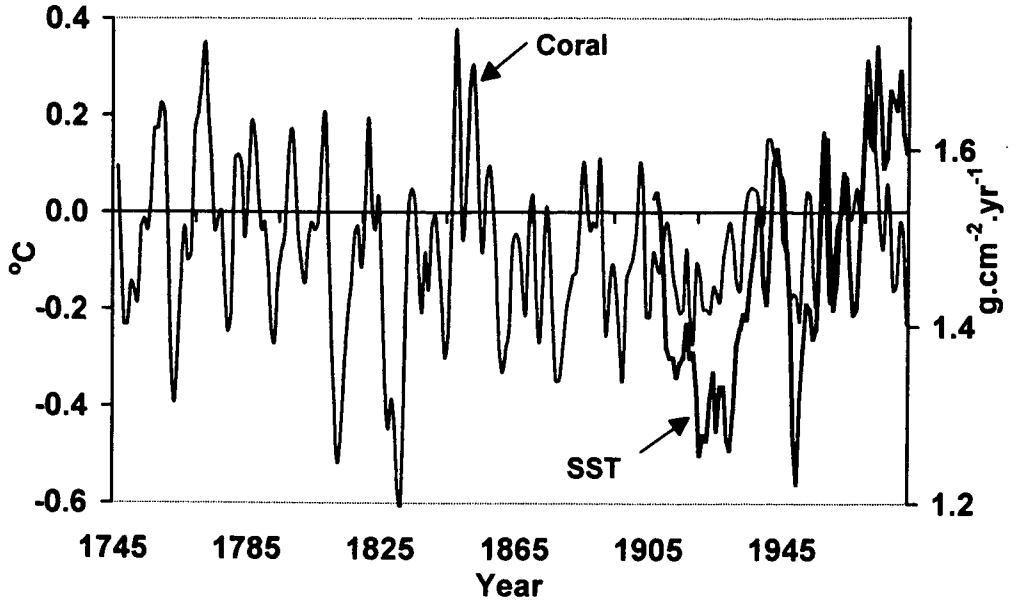


Figure 3. Average annual calcification for 10 *Porites* corals from the Great Barrier Reef, 1746–1982

A 342-year proxy record of mainland run-off to the Great Barrier Reef using UV fluorescence

The annual hydrological behaviour of tropical river systems can be mapped in time and space by reference to a proxy for discharge contained in long cores extracted from massive *Porites* spp. growing in inshore reef waters. Yellow-green fluorescing bands which appear under ultraviolet light are formed by the adsorption of terrestrially derived humic compounds onto the aragonite crystals of the skeletal matrix. UV fluorescence in corals provides long, highly resolvable, and accurate records of humic compounds delivered into the marine environment by river discharge.

The discovery in 1983 of the prominent fluorescent banding pattern in the skeletons of inshore corals was followed in the succeeding dozen or so years by work in which many corals from different parts of the world have been examined for fluorescent bands, with variable consequences. The relative success of hydrological reconstructions based on fluorescence analysis has been affected by the poor quality of fluorescence data available from some coral samples, a lack of qualitative rigour, variability in methods of obtaining the data from the corals, and a limited understanding of the complex sources of the fluorescence. Site selection is critical. The optimal sampling locations are those which endure a seasonal wet-dry climate, and which are proximal to the outflow of dominant river systems. In such places, the annual fluorescence quanta are highly ($r > 0.9$) correlated with the annual terrestrial run-off of the adjacent river.

Coral skeletal fluorescence

When slices of some massive coral colonies are irradiated with long wave ultraviolet light, fluorescent bands appear as yellow-green phenomena which lie parallel to the growth surfaces. They most often overlie a weak background fluorescence which is found throughout the skeleton. The yellow-green appearance to the human eye, however, masks the true spectrophotometric colour of the emission, which lies mostly in the blue region of the spectrum, but contains a prominent shoulder in the yellow-green region at about 510 nm. (Boto and Isdale 1985). The fluorescence is extremely weak, emitting at only about 10 lux from even the brightest bands.

Experiments have demonstrated the causal linkage between the appearance of fluorescent bands in coral and the nature and volume of discharge of nearby rivers. Incubation experiments have shown that fast growing branching corals incorporated humic and fulvic

acids in their growing tips (Boto and Isdale 1985), and that these tips emitted the characteristic yellow-green fluorescence under UV excitation. It appears that rainfall in coastal river catchments dissolves soil-accumulated humic compounds resulting from the decay of terrestrial vegetation, and provides them to river systems, perhaps attached to soil particles in suspension (Susic et al. 1991). The humics are transported to nearshore marine waters where they are freed to be co-deposited with the aragonite during skeletogenesis. While the method of incorporation is not clear, it seems reasonable to assume that, because the skeletal fluorescence can only be attenuated by photo-oxidation, or by physical destruction of the skeleton, the humics are incorporated in the aragonitic crystal structure.

The supply of humics to the coral in the marine environment is affected by catchment availability, river discharge rates, residence time in the marine system, uptake by marine sediments, and perhaps resuspension during high energy events. While many of these parameters are yet unquantified, the high correlation between shorter river discharges and co-incident skeletal fluorescence indicates that the terrestrial supply is non-limiting, and that the residence time in the water column is low. Further, high-energy events not associated with large river discharges do not result in bands being formed, revealing resuspension of sediments to be unimportant.

Skeletal fluorescence may be quantified in either a solid sample (by incident-beam spectrometry; Isdale 1984) or by extraction (e.g. HPLC; Susic and Boto 1989). The solid sample method has much to recommend it, having the advantages of being non-destructive, much faster and cheaper, and relying on the huge fluorescence efficiency of humics trapped in crystal structures in recording the presence of very low concentrations of the contaminant. The drawback to this method lies in the need to purpose-build a fluorescence detection and quantification system which works with very small increments along large solid samples, such as coral cores.

A useful record of coral fluorescence depends not only on the accurate establishment of skeletal humic concentrations at small intervals, but on the ability to time those inclusions accurately. The recent discovery of reproduction-related carbon isotope spikes in the skeletal carbonate (Gagan et al. 1994), and the use of isotopic thermometry to provide an SST-based seasonal calendar, has helped to resolve difficulties in estimating annual periodicities in skeletogenesis, and reduced the need to rely on sometimes confusing time markers such as density bands. In highly seasonal systems, heavily banded corals often show undeniable single-fits between fluorescence intensity and timing and river activity. In any case, most work to date has been based on interpretations of river activity at Òwater-yearÓ intervals.

Since fluorescence analysis can be used to hindcast annual river discharge in selected locations throughout the world's tropical regions, those environmental events which can be correlated with, or derived from, such information are available from the coral record. In particular, using rainfall-run-off models, we can derive proxy annual rainfall values for a period equalling the age of the corals, which may be up to one thousand years in some cases. From this we can derive estimates of drought size/frequency, length of period, and runs. These data help to estimate impacts on the marine environment of materials for which rivers are vectors, and aid in planning for extreme events in such fields as agriculture and engineering.

Reconstructing Burdekin River run-off

In the Great Barrier Reef region, Isdale's group has determined low frequency periodicities in the paleohydrological data set which may impact on the present discussions on climatic change. Reconstruction of the annual run-off of the Burdekin River during the past 342 years shows annual-scale climatic extremes which are not evident in the instrumental record (1922 onward). Longer dry spells spanning several years and much wetter monsoon seasons are apparent (figure 4). This reconstruction is based on a model in which more than 80% of the variance in the annual river discharge can be explained by reference to the annual quantum of fluorescence.

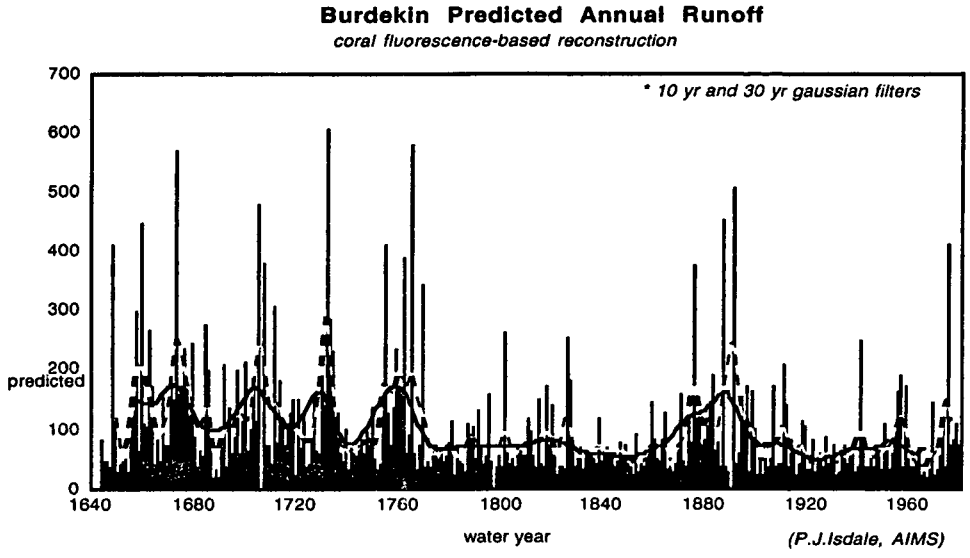


Figure 4. 342-year record of UV fluorescence as a proxy for annual run-off from the Burdekin River. The record is a composite derived from massive *Porites* corals growing at Pandora Reef and Havanna Island, central Great Barrier Reef.

Successful use of fluorescent bands to reconstruct paleohydrological regimes have usually developed or used methods which digitally quantify and time the proxy signal. While it is possible to see non-correlation between any two high-detail visual sequences of fluorescence, it is also easy to miss significant, coherent low frequency variations. If present, information about low frequency variability can best be gained by mathematically manipulating a digitally-expressed signal which can be obtained by rigorous, standardised, and repeatable instrumental measurement techniques.

In the Burdekin example above, the pathways (causality) of the river-humics-fluorescence link are understood, if unquantified. However, as long as a strong empirical correlation is obtained, and is robust, a valid reconstruction can be made. Careful use of these proxy records at key sites in the world's tropical oceans can yield an excellent, detailed knowledge of our paleohydrological history (and consequent phenomena) for at least the past millennium.

Sr/Ca thermometry and $\delta^{18}O$ reconstructions of ocean-atmosphere freshwater exchange

One of the most promising new developments in tropical palaeoceanography involves the precise measurement of Sr/Ca and $^{18}O/^{16}O$ in coralline aragonite to determine past SSTs and the surface ocean hydrologic balance. Oxygen isotope ratios in corals have been used extensively to reconstruct the oxygen isotopic composition of seawater and make inferences about the tropical hydrological cycle (Dunbar and Cole 1993; Cole et al. 1993; Linsley et al. 1994). However the fractionation of $^{18}O/^{16}O$ in corals is also strongly temperature dependent (Epstein et al. 1953; Weber and Woodhead 1972) which, in many oceanic settings, complicates reconstructions of the oxygen isotopic composition of seawater.

Coupled measurements of coral skeletal Sr/Ca and $\delta^{18}O$ should make it possible to reconstruct tropical surface ocean $\delta^{18}O$, as well as SSTs, by removal of the temperature component of the coral $\delta^{18}O$ signal (McCulloch et al. 1994). The groundwork for Sr/Ca thermometry was laid by Smith et al. (1979) who showed that, within measurement resolution, the Sr/Ca ratio in coralline aragonite correlated with temperature. An important breakthrough in coral Sr/Ca thermometry has been driven by making high precision Sr/Ca measurements using thermal ionisation mass spectrometry (Beck et al. 1992). Because the ocean residence times of Sr and Ca are both long (Broecker and Peng 1982), the marine

Sr/Ca ratio remains essentially constant, particularly in oligotrophic reef environments (deVilliers et al. 1994).

We have recently completed calibration experiments which demonstrate that it is possible to use single Sr/Ca- and $\delta^{18}O$-SST relations to uniquely reconstruct both SSTs and the surface-ocean hydrologic balance in a wide range of oceanic settings. Three calibration sites were chosen including the Great Barrier Reef, Dampier Archipelago, and southeastern Java (figure 1) which encompass seasonal SST, salinity, and turbidity ranges spanning much of the survival range for *Porites*. We tested the accuracy of the coral Sr/Ca temperatures against instrumental SST measurements for the coral *Porites lutea*, which is widely used for palaeoenvironmental reconstructions. This work showed that the average difference between the three Sr/Ca- and $\delta^{18}O$-SST regression equations is 0.4°C over much of the survival range for *Porites* (19°–31°C).

Coral records throughout the Australian region can be accurately timed using the seasonal pattern of SST, driven by the seasonal march of solar irradiance (Gagan and Chivas 1995; Gagan et al 1994; in press). Examination of instrumental SSTs for 1982–94 (Reynolds and Smith 1994) shows that the annual SST minima fall on 31 July (± 8 days, 1σ) at Orpheus Island, 6 August (± 9 days, 1σ) at Dampier, and 24 August (± 11 days, 1σ) at the southeast Java site. The consistent time-control is provided by the steep gradients in the autumn and spring SSTs which are driven by the rapid change in solar irradiance and air temperature (figure 5). The point located mid-way between the steep SST gradients, defined as the SST 'minimum', is a consistent annual time-marker because of the symmetry of the annual solar radiation cycle around the June 21 winter solstice. The coral time series are plotted by allocating equal time spans to the data points linking adjacent SST minima which, for simplicity, are assigned the mean arrival-time.

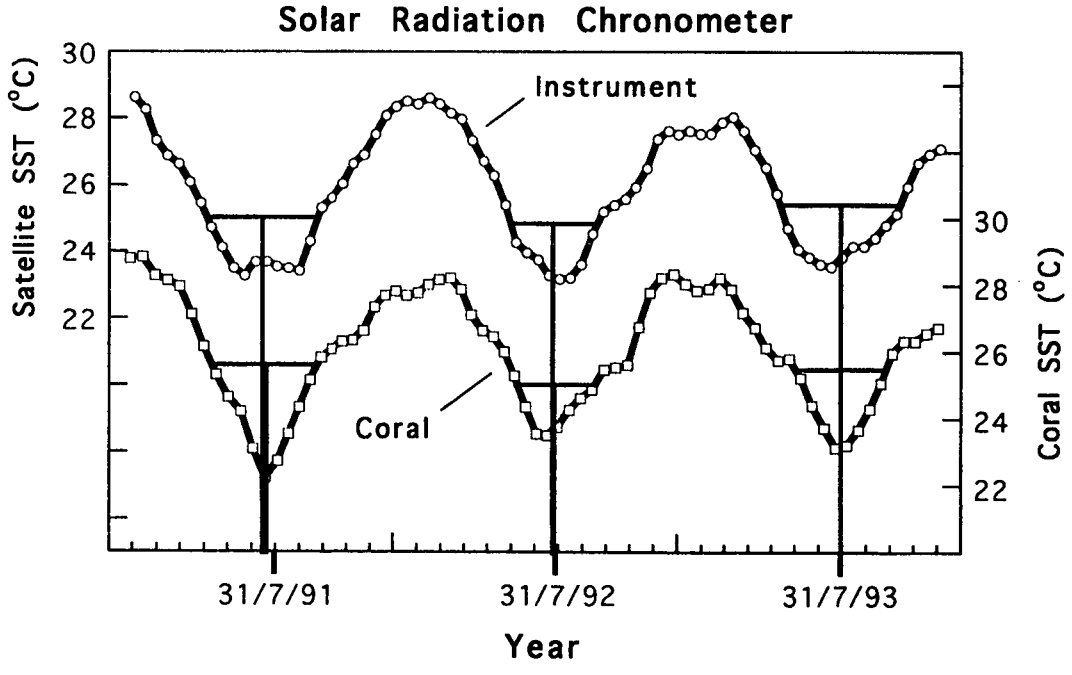


Figure 5. Graphical method for determining a coral chronology based on seasonal SSTs and solar irradiance. Top curve (circles) shows satellite-derived SSTs for the 1°x1° grid surrounding Orpheus Island (Reynolds and Smith 1994). The horizontal bars connect points that are symmetrical in time around the austral winter solstice (21 June). The vertical bar defines the winter SST 'minimum' which, for the waters surrounding Orpheus Island, lags the winter solstice by several weeks and falls on 31 July (± 8 days, 1σ). The lower curve (squares) demonstrates how the same technique can be used with coral SST data to define the winter 'minimum'.

The utility of the coupled Sr/Ca-$\delta^{18}O$ technique is illustrated in figure 6 where the single Sr/Ca- and $\delta^{18}O$-SST relations are used to define SSTs, as well as seawater $\delta^{18}O$. Sea-surface salinity (SSS) is a good indicator of the balance between precipitation and evaporation in the tropics (Levitus 1982; Webster 1994). Regional differences in seawater $\delta^{18}O$ reflect differences in SSS because tropical rainfall is depleted in ^{18}O (IAEA 1981) relative to seawater while evaporation tends to enrich the surface ocean in ^{18}O. Winter $\delta^{18}O$ residuals ($\Delta\delta^{18}O$ in figure 6) are a good indicator of the regional SSS during the absence of changes in seawater $\delta^{18}O$ associated with summer monsoonal rainfall. For example, and the $\delta^{18}O$-SST calibration in the Great Barrier Reef is centred on a dry-season salinity of 35.5ä. Global mean SSS is 35.2ä (Webster 1994) indicating the slight dominance of evaporation over precipitation in the Great Barrier Reef region. In contrast, the Java coral $\delta^{18}O$ residuals reflect the low salinity water mass (33ä) encompassing the Warm Pool region, where SSTs are the highest on Earth and precipitation greatly exceeds evaporation. The SSS indicated by the winter $\delta^{18}O$ residuals for the Dampier coral reflect the advection of low salinity Warm Pool water into the eastern Indian Ocean (34.7ä), via the Indonesian Throughflow.

Reconstructing the 1991–94 ENSO: anomalous SSTs, rainfall, evaporation, and wind

Corals from the Great Barrier Reef, Dampier, and Java are capable of tracking, virtually month-by-month, the evolution of the monsoon and ENSO throughout the Indo-Australian region. Figure 6 shows that the timing of monsoonal rainfall during 1990–91 can be tracked between Java and the Great Barrier Reef. Monsoonal rain arrived in Java in November–December 1990 followed by a distinct break in January–February 1991. Near record rainfall was recorded by the Great Barrier Reef coral at this time, suggesting the monsoonal trough was centred temporarily south of Indonesia. Resumption of monsoonal rainfall in Java in March–April marks the northward migration of the monsoon, and the end of the 'big wet' in northeast Australia.

The climatic manifestations of the 1991–94 ENSO including drought, increased evaporation, and reduced tradewind velocity are well recorded by the three coral sites (figure 6). A distinct lack of run-off to the Great Barrier Reef testifies to the severity of the ENSO-induced drought that gripped northeast Australia. The timing and magnitude of seasonal evaporation are accurately recorded by the Dampier coral. The $\delta^{18}O$ residuals become progressively more positive in spring and reach maxima in November–December. This pattern coincides with increasing air temperature and solar radiation, both of which would serve to increase ocean surface evaporation. There is a clear increase in the magnitude of evaporation during the prolonged ENSO. The impact of the ENSO is more subtle in Java where rainfall anomalies are weak (1992–93). Here, the best indicator of ENSO involves the relaxation of the southeast tradewinds during winter which reduces upwelling of cold water along the south coast of Java. The relatively warm SSTs recorded by the coral Sr/Ca and $\delta^{18}O$ during the winters of 1992–93 mark the relaxation of the tradewinds across northern Australia during the core of the ENSO. The importance of being able to document the atmospheric effects of ENSO is made clear by the 1991–94 event, which was marked by subtle cooling of SSTs in the Indo-Australian region, but distinct changes in rainfall, evaporation, and wind.

Great Barrier Reef 'Climatic Optimum' at 5800 yBP

Analysis of terrestrial palaeoclimate data suggests that north America and Europe were warmer / wetter during the early-mid Holocene (Crowley and North 1990) while a stronger monsoon was operating in northern Africa and Asia, leading to warmer / wetter summers (COHMAP 1988). The nature of the 'climatic optimum' is less clear for the southern hemisphere. Recent work on ice cores from high-altitude tropical glaciers in Peru suggests that air temperatures were warmer from 8000–5000 yBP (Thompson et al. 1995). In northeast Australia, analysis of pollen data from the Atherton Tablelands suggests that rainforests were slightly expanded in the mid-Holocene, implying warmer / wetter conditions (Kershaw and Nanson 1993). Tropical SSTs in the eastern Pacific Ocean were also warmer and less variable at that time (Sandweiss 1996) suggesting that El Niño events were absent, or not pronounced. In addition, Shulmeister and Lees 1995 proposed that

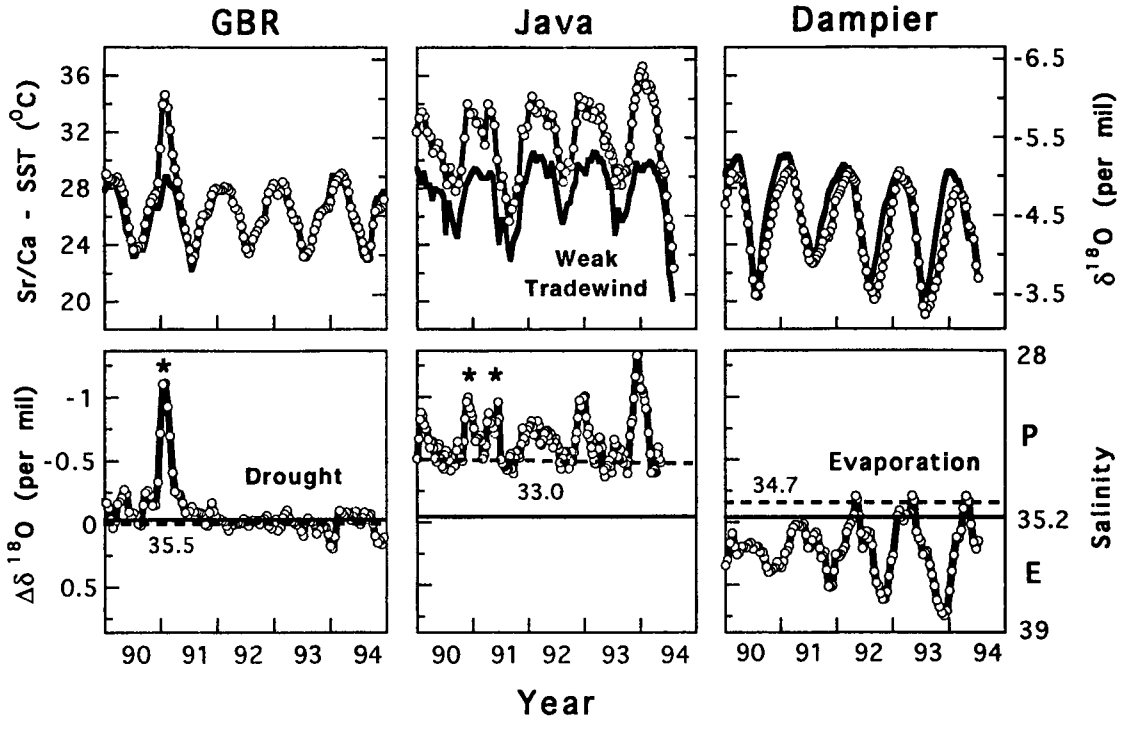


Figure 6. Upper panels: Comparison of Sr/Ca- (solid line) and $\delta^{18}O$-SSTs (dotted line) for *Porites lutea* from Orpheus Island, Great Barrier Reef, southeast Java, and the Dampier archipelago. Lower panels: Differences in seawater $\delta^{18}O$ (salinity) after subtracting the temperature component of the $\delta^{18}O$ signal ($\Delta\delta^{18}O$). Dashed horizontal lines show the regional balance between precipitation (P; negative $\Delta\delta^{18}O$) and evaporation (E; positive $\Delta\delta^{18}O$), relative to the global mean sea-surface salinity of 35.2ä (solid horizontal line). The manifestations of the 1991–94 ENSO are drought (Great Barrier Reef), weak winter tradewinds (Java), and escalating spring-summer evaporation (Dampier). Asterisks mark the 'split monsoon' in Java coinciding with the 'big wet' in northeast Australia in 1990–91.

northern Australian climate has become more variable since 4000 yBP, following the onset of the El Niño.

We have applied a multi-tracer approach to a fossil coral from the windward side of Orpheus Island, central Great Barrier Reef, to reconstruct in unprecedented detail climatic conditions in northeast Australia during the mid-Holocene. Because ENSO tends to produce cool SST anomalies and drought in the Great Barrier Reef region, combined measurements of coral UV fluorescence, Sr/Ca, and $\delta^{18}O$ can be used to detect individual ENSO events. At Orpheus, well-preserved massive *Porites* micro-atolls have been cored to reveal 100 years of continuous coral growth. The largest colony, for which preliminary data is presented, has a conventional radiocarbon age of 5800 yBP. The fossil coral data presented here have been calibrated via proxy data for modern corals growing adjacent to the fossil coral colonies, and will be discussed elsewhere (Gagan et al. in prep).

Examination of the coral UV fluorescence, indicating the intensity of run-off primarily from the Burdekin River (Isdale 1984; Isdale and Kotwicki 1987), suggests that monsoonal rainfall during this century of the mid-Holocene was much less variable than today (figure 7). Annual flow volumes rarely exceed 300 fluorescence units suggesting that high run-off events are rare (see figure 4). Furthermore, there is no evidence of drought, but it is not clear whether the higher background level of UV fluorescence is due to persistent run-off or adsorption of secondary UV fluorescing compounds subsequent to the death of the coral colony. However, the same fluorescence signal is evident in mid-Holocene corals located near the Daintree River, north of Cairns.

In order to further verify the UV fluorescence record, we measured skeletal Sr/Ca and $\delta^{18}O$ to examine fine-scale SST and rainfall dynamics, and to look for the anomolously cool SST - drought conditions linked to the ENSO. So far the record spans 16 years, including what

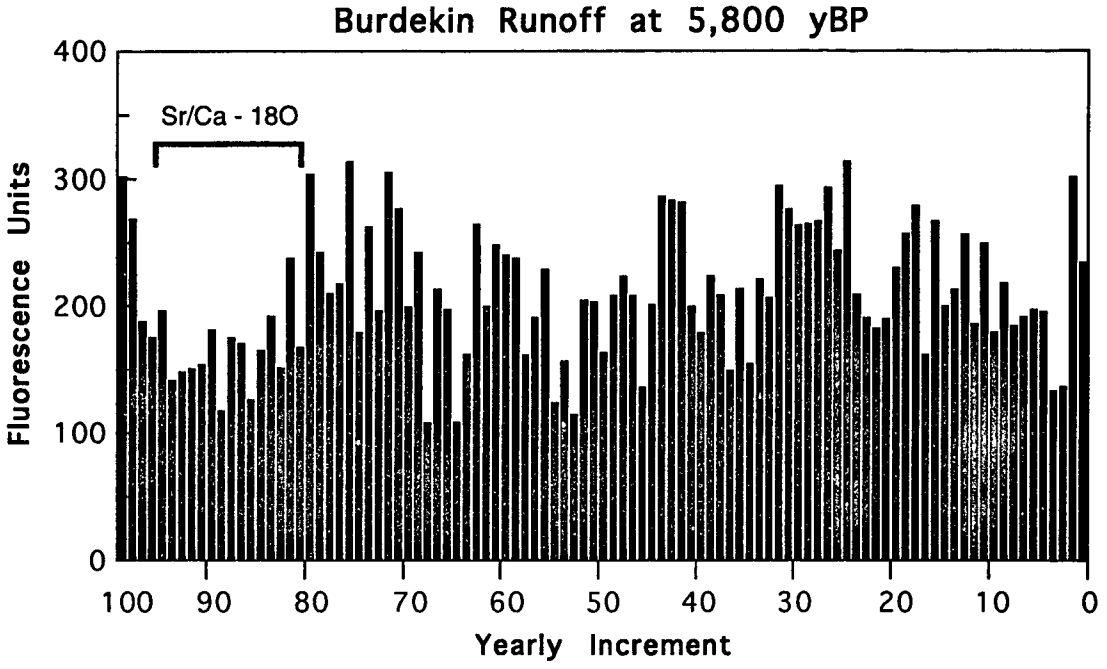


Figure 7. 100-year record of annual UV fluorescence for the 5,800 yBP *Porites* micro-atoll from Orpheus Island, central Great Barrier Reef. Bar labelled 'Sr/Ca - ^{18}O' indicates 16-year interval chosen for coupled Sr/Ca and $\delta^{18}O$ measurements.

we perceived to be the driest period of the century (years 80–96 in figure 7). We focused on this interval to determine if ENSO-induced droughts were evident.

The calibrated coral Sr/Ca-SSTs indicate that mid-Holocene SSTs were 1°C warmer than those of the last two decades (figure 8a), but had the same seasonal temperature range (5.5°C). If these elevated SSTs represent regional warming in the western Pacific, higher evaporation rates and persistent summer cloudiness should follow. Note that summer SSTs are closely confined to a mean temperature of about 29.5°C, and rarely exceed 30°C. This is the situation today further north near New Guinea where high evaporation rates produce persistent summer clouds which block incoming short-wave radiation, resulting in a negative feedback on further increases in SST. Persistent clouds also tend to damp fluctuations in summer SSTs. The warm, consistent summer SSTs indicated by the coral Sr/Ca reinforce the UV fluorescence in suggesting that summers in the Great Barrier Reef were typically cloudy with moderate monsoonal rainfall.

The 16-year record spans the three years that we perceived to be the driest in 100 years, based on visual inspection of the coral UV fluorescent bands (years 82–85 in figure 8). Contemporary ENSO-induced droughts in northeast Australia coincide with cool winter SST anomalies of at least 1–2°C. Despite this period being fairly dry, the winter cooling associated with this 'drought' is negligible, and certainly not indicative of ENSO. This record is admittedly short, but the Sr/Ca and $\delta^{18}O$ data have been extended to nearly 30 years with no sign of winter cooling or drought indicative of ENSO.

The residual $\delta^{18}O$ provides an accurate account of the magnitude and timing of individual rainfall events (figure 8b). The timing of the run-off events appears to be very similar to today, falling between December and April. Like the coral UV fluorescence, the residual $\delta^{18}O$ indicates that the monsoon was less variable than at present. One could argue that a more vigorous coastal ocean circulation during the mid-Holocene could decrease the impact

of flood-plumes on corals at Orpheus Island. However, the lack of drought is more difficult to explain and is likely to reflect a real change in the rainfall regime.

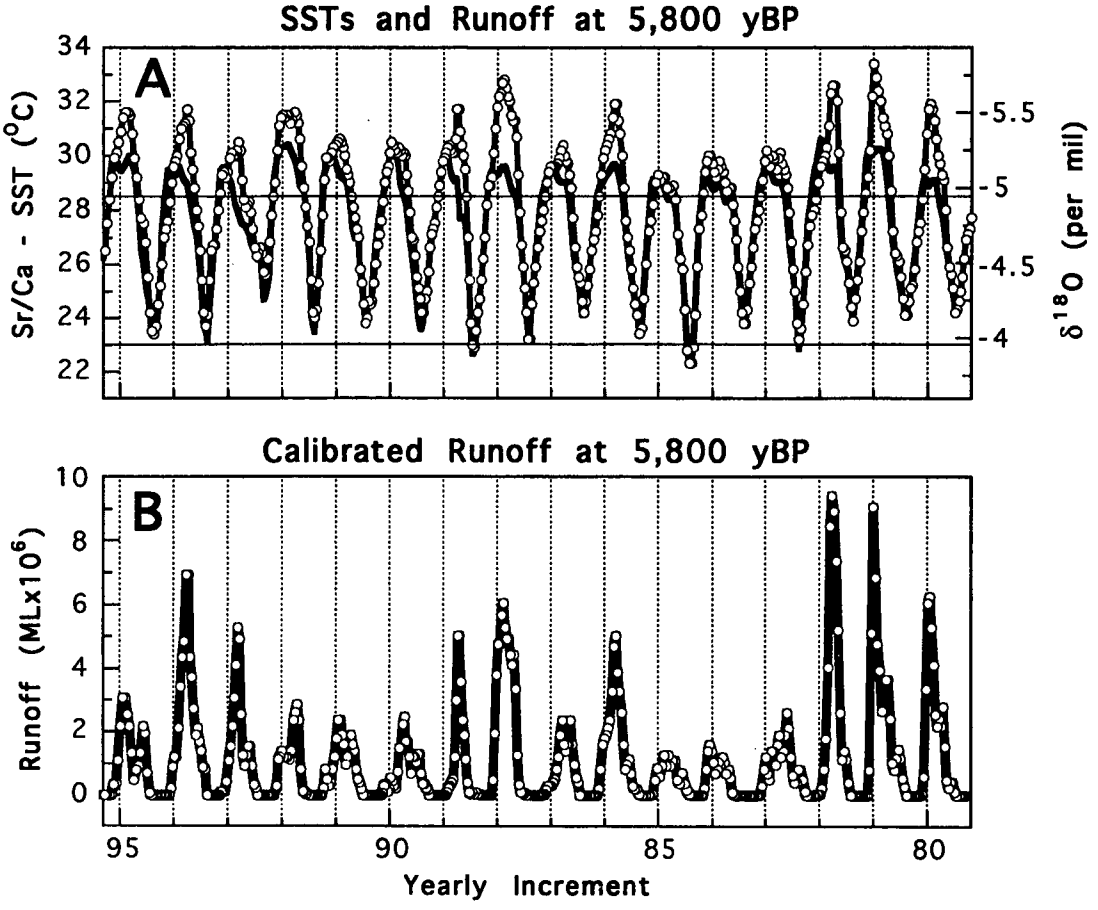


Figure 8. (A) 16-year record of Sr/Ca and $\delta^{18}O$ values (converted to SST) for the 5,800 yBP *Porites* from Orpheus Island, central Great Barrier Reef. The difference between the Sr/Ca and $\delta^{18}O$ represents the intensity of monsoonal run-off. Horizontal lines show the modern mean winter and summer SSTs for 1970–94. Vertical lines mark 1 January. (B) Coral $\delta^{18}O$ residuals showing the magnitude and timing of palaeo-Burdekin River run-off.

Development of the Orpheus Island fossil coral record, the first of its kind, is still in progress but demonstrates that fossil corals can provide palaeoclimate data available in no other way. The multi-tracer method of reconstructing past climate provides important cross-checks for evaluating the performance of individual climate tracers. Taken together, the evidence suggests that this century of the mid-Holocene was marked by warmer SSTs, more dependable monsoonal rainfall, and possibly a weaker ENSO. However over the past century even the role of ENSO as a source of climate variability has waxed and waned; the period from the 1920s to 1940s being notable for an absence of major ENSO episodes and a breakdown of local and global teleconnection patterns (Allan 1993; Lough, in press). Thus the persistence in time of the apparent weakening of the mid-Holocene ENSO is unknown but, if real, the ramifications of a weakened ENSO should be evident in high-resolution palaeoclimate records throughout much of the tropics.

Future directions

Coral-based palaeoclimatology has the potential to open the way to a new understanding of the tropical ocean and atmosphere. The field is still in its infancy compared to tree-ring and ice core research, which have proven to be so valuable for reconstructing temperate and

polar climates. Australia is well placed to be a leader in this rapidly evolving field for the following reasons:

- ¥ Australia has ready access to coral reefs positioned within key components of the global climate system;
- ¥ Sophisticated coral coring technology and the extraordinary age of some Australian massive corals provide us with some of the longest coral archives on Earth;
- ¥ A wealth of expertise in coral reef research and tropical climatology is available that ranks amongst the best in the world, and which is crucial to success in this new field;
- ¥ Australian techniques for extracting density, UV fluorescence, and isotopic / geochemical data from corals are state-of-the-art.

Co-ordination at a national level is needed to bring the research to full fruition. Each method presented in this paper has its own strength but becomes more powerful when linked in a multi-proxy approach to coral-based palaeoclimatology. In addition to improving our understanding of natural climate variability these techniques, and others, could be expanded to monitor anthropogenic inputs to reef ecosystems. Moreover, some of the tracers are sensitive to physiological changes caused by environmental stress. Corals may very well provide histories of their own health and could reveal the early warning signs of physiological stress potentially leading to ecosystem collapse.

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Coral bleaching: implications for the Great Barrier Reef Marine Park

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ABSTRACT

Bleaching is a general term for the loss of colour by reef-building corals ('coral bleaching') and other symbiotic invertebrates. In most cases, coral bleaching has been identified as due to the loss of symbiotic zooxanthellae normally resident in high numbers in the tissues of reef-building corals and other symbiotic invertebrates. Bleaching events have been reported at both small localised scales (10s of metres) and global scales (thousands of kilometres). Coral bleaching has also attracted considerable attention from reef scientists and managers given the apparent increase in the number of mass-bleaching episodes since the 1970s and the global scale of these disturbances. Five major periods of mass-bleaching (approximately 60 separate incidents in which thousands of square kilometres of coral reef including parts of the Great Barrier Reef have bleached) have been reported in the scientific literature since 1979, and there is mounting evidence that coral bleaching has not occurred with anywhere near this frequency prior to 1979 (Glynn 1993). The biology and causal factors involved when corals bleach are increasingly becoming better understood. Local scale bleaching events generally have been associated with abrupt changes to the salinity, light and temperature environment surrounding corals. Patterns of bleaching at a global scale have been tied to changes in sea temperature and/or ultra-violet radiation, with recent events coinciding sharply with increases in sea temperature. How bleaching will affect reef systems in the long term is the subject of much speculation. Coral polyps continue to live despite the absence of the zooxanthellae, and can be observed feeding within several hours after the removal of the stress condition. However, mortality tends to increase with time and in certain families of coral (e.g. *Acropora* spp.) may reach 95%. Current speculation ranges from opinions that suggest that mass bleaching is inconsequential to the vitality of reef systems to those that predict dire consequences from its impact. But what does this global scale disturbance mean for the health and management of the Great Barrier Reef? This paper reviews our current understanding of the mass bleaching of coral reefs and analyses how the global phenomenon of coral bleaching is likely to affect the Great Barrier Reef Marine Park. In doing so, this paper will cover the cell biology and causal factors associated with coral bleaching and will focus on interpreting recent evidence that coral bleaching is on the increase. From this starting point, the paper will discuss the implications and predicted impacts of this global scale event on the world's largest marine park.

INTRODUCTION

Tropical near-shore waters are dominated by one of the most spectacular and diverse ecosystems on earth. Formed in and around a structural matrix made by calcareous animals called coral polyps, coral reefs are home to the greatest number of species (biodiversity) of any marine ecosystem (Norris 1993), and are areas of high marine productivity in the otherwise nutrient-poor waters of the tropics (Muscatine 1980; Muscatine and Porter 1977). At the center of the success of the hermatypic corals in tropical waters is the relationship they form with tiny single-celled, dinoflagellate algae known as zooxanthellae. Originally, zooxanthellae found in reef-building corals were thought to belong to the species *Symbiodinium microadriaticum* but recent evidence suggests that coral zooxanthellae represent a multitude of different species (Blank and Trench 1985). Each coral host may have as many as 2–3 unique species of zooxanthellae occupying their tissues (R. Rowan, University of Guam, pers. comm.). The relationship formed between corals and their

zooxanthellae is referred to as mutualistic in that both partners derive benefit from their association, with corals receiving photosynthetic products (sugars and amino acids) from the algae and the algae receiving crucial plant nutrients (ammonia and phosphate) from host waste metabolism (Trench 1979). The key to success of reef-building corals in the nutrient-poor waters of the tropics is considered to be the continual recycling of nutrients between symbiotic partners. As a result of recycling, corals and their symbiotic algae show a reduced dependence on external nutrient concentrations.

The photosynthetic pigments of zooxanthellae give corals their characteristic brown colour. Given their central importance in the biology of reef-building corals, the apparent disappearance of the brown colour of zooxanthellae from the tissues of corals in a number of 'coral bleaching events' has attracted much attention since reports began to increase in the early 1980s. Bleaching events are characterised by the disappearance of brown coloration from coral tissues, with the resulting brilliant white colour (skeleton) earning the description coral 'bleaching'. Considerable debate has surrounded the cause(s), mechanism(s) and implications of coral bleaching. While much is known about some aspects of bleaching phenomena, many questions remain unanswered. This article is intended as an update on coral bleaching with a focus on questions that have implications for users and managers of coral reef ecosystems like the Great Barrier Reef.

Cell biology and causal mechanisms associated with the bleaching phenomenon

What is bleaching and what causes it?

The population density of zooxanthellae in reef-building corals ranges between 0.5 and 5 x 106 cell.cm^{-2} (Drew 1972; Porter et al. 1984; Hoegh-Guldberg and Smith 1989a,b). A number of physical factors can lead to gentle adjustment in the population density and pigment characteristics of zooxanthellae (light acclimation, Falkowski and Dubinsky 1981; dissolved nutrient perturbations, Hoegh-Guldberg and Smith 1989a). Under several extraordinary or 'stress' conditions, however, corals may loss their brown 'symbiotic' colour and become bleached (*sensu* Yonge and Nicholls 1931a). This type of disturbance may occur at local scales (e.g. parts of reefs, Egana and DiSalvo 1982; Goreau 1964; Oliver and Berkelmans in prep) or at larger scales (mass bleaching) that may involve entire reef systems and geographic realms (e.g. Glynn 1991; Hoegh-Guldberg and Salvat 1995; Oliver 1985; Oliver and Berkelmans in prep).

Corals normally show low rates of loss of zooxanthellae to the water column (Hoegh-Guldberg et al. 1987). Greater rates of loss of zooxanthellae can be provoked when symbiotic hosts are subjected to a range of physical or chemical disturbances (Yonge and Nicholls 1931; Hoegh-Guldberg and Smith 1989b; Glynn and D'Croz 1990; Glynn 1993; Lesser et al. 1990). Major changes in the intensity of PAR (photosynthetically active radiation) or ultra-violet light (Vaughan 1914; Yonge and Nicholls 1931; Hoegh-Guldberg and Smith 1989b; Gleason and Wellington 1993) and/or temperature (Glynn 1993; Jokiel and Coles 1974, 1977; Coles and Jokiel 1978; Hoegh-Guldberg and Smith 1989b; Gates et al. 1992) can produce characteristics in corals similar to bleached coral collected in the field. Chemical factors such as copper ions (Jones 1996) and cyanide (Jones and Stevens, in press) can also evoke the loss of cells from reef-building coral tissues. Other factors such as reduced salinity may cause colour loss but do not necessarily cause corals to lose zooxanthellae in a fashion like that seen during mass-bleaching events (Hoegh-Guldberg and Smith 1989b). Outside the laboratory, bleaching events have also correlated with changes in particular environmental variables (Glynn 1993). Of these, elevated temperature and ultra-violet (particularly UV-B) radiation have received the most attention, with higher than normal sea temperatures being the most consistent factor by far to associate with mass-bleaching events (Gates 1990; Glynn 1984, 1991; Lasker et al. 1984; Lesser et al. 1990; Glynn 1993; Gleason and Wellington 1993; Goreau and Hayes 1994; Hoegh-Guldberg and Salvat 1995). In the latter case, correlations between higher than normal intensities of UV-B and coral bleaching events are weak at best, as is any real evidence of a strong downward trends in stratospheric ozone above tropical areas. This, together with evidence from laboratory experiments (e.g. Hoegh-Guldberg 1989) suggest that elevated sea temperature is the primary cause of recent mass bleaching events while elevated UV-B radiation is a weak, secondary factor. On the Great Barrier Reef and in Tahiti/Moorea (French Polynesia), where good temperature data sets and records of bleaching events are available, there is a striking correlation between bleaching events and elevated summer sea water temperatures

(figures 1 and 2). Perhaps the most surprising aspect of these data is that only small excursions (0.5°C) in the mean temperature are associated with the onset of bleaching in both data sets.

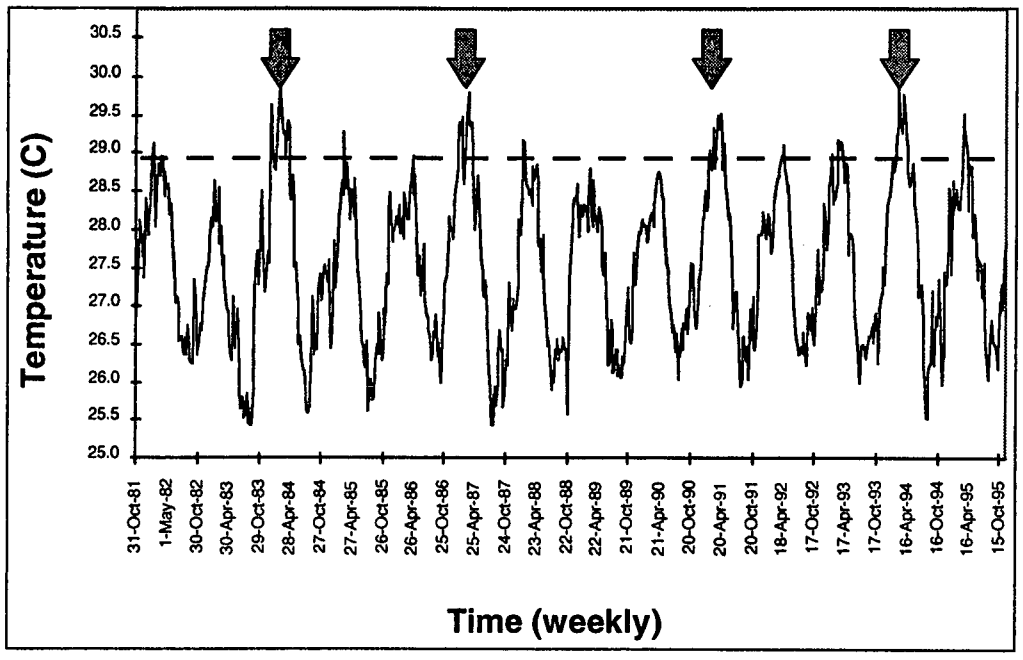


Figure 1. Weekly temperatures for Tahiti/Moorea (150.5W, 17.5 S) from the Comprehensive Ocean Atmosphere Data Set data set kindly provided by the Climate Group at the Lamont-Doherty Earth Observatory, Columbia University. Arrows indicate years in which major bleaching events occurred. Note that the arrows also coincide with years in which El Niño events happened.

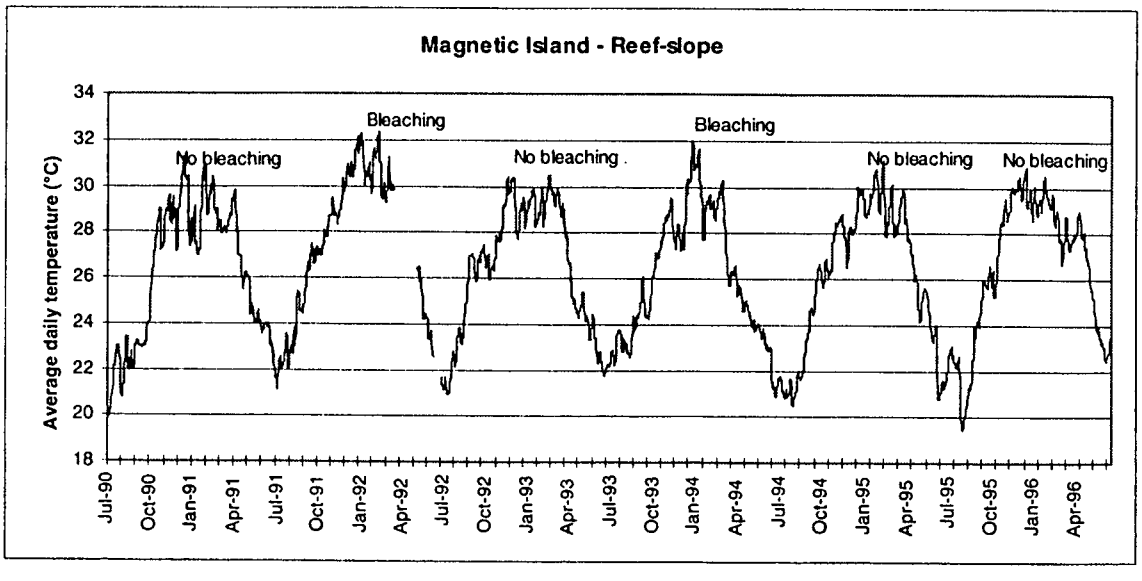


Figure 2. Daily average temperature records from *in situ* loggers, and bleaching events at Magnetic Island.

What mechanism explains bleaching?

No single mechanism describes all forms of bleaching phenomena. This is not surprising given that bleaching (i.e. pigment loss) probably occurs for a diverse range of physiological reasons. For the purposes of this paper, we will focus on proposed mechanisms that explain

how elevated UV-B and temperature cause corals to bleach. Both UV-B and temperature have received the most attention in recent studies due to the suspicion that these factors are associated with mass bleaching events, and due to the proposal that they are inextricably linked (Goenaga et al. 1988) by a common mechanism (Lesser et al.1995). As has been argued previously, temperature is probably the primary variable in causing recent episodes of mass bleaching with UV-B acts as an aggravating secondary variable (Hoegh-Guldberg 1989). The action of UV-B, however, is better understood than water temperature in causing bleaching.

Ultraviolet (UV) radiation has a range of impacts on biological systems. Membranes, proteins and DNA are among a variety of organic compounds that are directly affected by elevated UV radiation (Clayton 1977). The high UV levels of shallow tropical habitats means that coral reefs are bombarded by high levels of UV which has featured in their evolution (Jokiel 1980). Aside from the direct effects on tissue integrity, high levels of UV can lead to other less direct forms of damage. In photosynthetic organisms, the impact of UV can lead to damage due to the generation of energised superoxide radicals probably by way of the disruptive effects of UV on electron transport (Lesser et al. 1995). This is especially a problem under high concentrations of oxygen (Clayton 1977) being generated under high levels of Photosynthetically Active Radiation (PAR). Superoxide radicals, if generated in large enough quantities, can interfere with photosynthetic function principally by causing dysfunction of Photosystem II and the carboxylating enzyme Rubisco (ribulose bisphosphate carboxylase/oxygenase; Lesser 1996).

Two strategies have evolved to minimise UV-B damage. Firstly, reef-building corals (and their symbionts) and a large range of other organisms biosynthesize highly UV absorbent compounds like microsporine-like amino acids (Dunlap et al. 1985, 1986). Secondly, reef-building corals produce enzymes (e.g. superoxide dismutase and catalase) that function to convert superoxide radicals into relatively more harmless byproducts (Dykens 1984; Lesser and Shick 1989; Shick et al. 1991). Even with these protective strategies in place, high levels of UV-B radiation under hyperbaric oxygen can overwhelm these defence systems. In this case, damage to Photosystem II occurs with photosynthetic rates being severely compromised (Shick et al.1995).

Why does elevated temperature lead to coral bleaching? The link between temperature and the action of UV-B might be as follows. A series of rate processes are involved in the production and consumption of superoxide radicals. Damage to cellular processes occurs when production exceeds consumption. When the temperature of the water surrounding a coral is increased, the speed at which various processes operate increases. Some of these are enzymatic in origin (e.g. photosynthesis) and hence would double that rate of reaction for every increase in temperature of 10°C(Q10 = 2). Other processes, especially those involving diffusion, change at much slower rates (Q10 = 1.3). Consequently, any change in temperature might lead to dysfunction due to the out-pacing of diffusive processes, that might otherwise help reduce tissue oxygen concentrations, with those that produce oxygen (photosynthesis). The net result is that oxygen builds up, superoxide radicals are produced faster than can be consumed and cellular damage occurs.

The next set of steps leading to the breakdown of the symbiosis between zooxanthellae and their host cells is also equally debatable. Presumably, the action of superoxide radicals results in the changed behaviour of zooxanthellae relative to the host cell. Whether essential signals fail or whether the zooxanthellae poison the host cell is not known. The result is that zooxanthellae leave the tissues of the host. There are two models as for how this occurs. The initial explanation for the loss of zooxanthellae from bleaching corals was that zooxanthellae were expelled from host gastrodermal cells. Proposals for the cellular mechanism concentrated on deciphering how changed cell signals might influence exocytosis (figure 3) and the retention of zooxanthellae within host cells (Steen and Muscatine 1987). Careful work by Gates et al. (1992), however, has revealed the loss of zooxanthellae from many symbiotic hosts (anemones and corals) occurs via detachment of gastrodermal cells (figure 3). This universality of host cell detachment as a mechanism involved in bleaching has been recently disputed by Brown and co-workers. This conjecture aside, host cell detachment suggests a series of phenomena that may extend bleaching phenomena beyond that of symbiotic hosts. It is an intriguing idea that non-symbiotic cnidarians may also loose gastrodermal cells as well as those more obviously when loaded with zooxanthellae. In support of this possibility are maceration techniques (for separating

living cells and hence demonstrate host cell detachment) that depend on heating cnidarian tissues to temperature of 30°Cor more. To date, the possibility that non-symbiotic cnidarians undergo host cell detachment at high temperatures has not been exhaustively explored but does represent an important observation and alternative explanation as regards the site of action of bleaching phenomena.

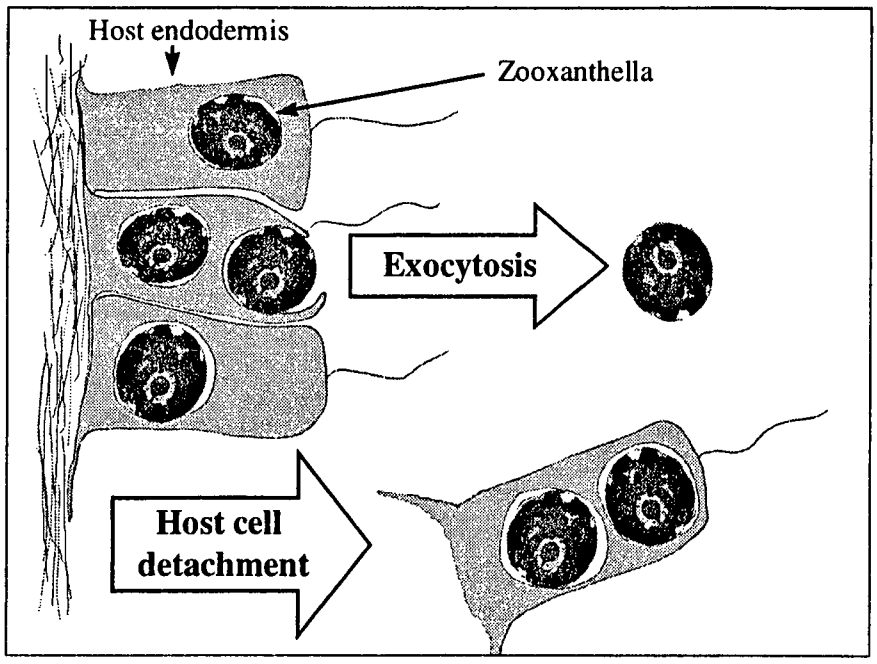


Figure 3. Two models explaining the loss of zooxanthellae during bleaching. Exocytosis involves no loss of the host cell while host cell detachment involves the loss of the zooxanthellae plus the host cell.

The influence of coral bleaching on reef systems: chronic versus subchronic impacts

Mortality estimates following mass-bleaching range from close to zero in cases of mild bleaching (Harriot 1985) to close to 50–100% in Indonesia (Brown and Suharsono 1990), Australia (Fisk and Done 1985; Oliver 1985) and eastern Pacific reefs following the 1982–83 event (Glynn 1990). Recent mortalities following mass-bleaching in the Central and Western Pacific in 1991 and 1994 have been as high as 30–50% of living corals (Salvat 1991; Gleason 1993; Hoegh-Guldberg 1994).

Reef-building corals are not all equally susceptible to the influence of increased temperature. For example, some species, such those of the massive coral genus *Porites*, are relatively resistant to temperature stress and if they do bleach, they tend to recover with little or no increase in overall mortality (Salvat 1991; Gleason 1993; Hoegh-Guldberg 1994). The opposite is true of the members of the genus *Acropora*, which show a greater sensitivity to slight increases in water temperature (but see Glynn 1993). In this case, up to 95% of colonies may bleach (Salvat 1991; Gleason 1993; Hoegh-Guldberg 1994) and die in the subsequent 3–6 months following the reduction in temperature stress (Salvat 1991; Gleason 1993). Pocilloporid corals are also highly susceptible and are usually the first and most severely affected corals during bleaching events on the Great Barrier Reef (Harriott 1985; Oliver 1985; Fisk and Done 1985).

The differential influence of sea temperature rise on species of reef-building corals indicates that mass-bleaching episodes have the potential to dramatically alter the species richness of coral reef communities (Gleason 1993; Glynn 1993). Local extinctions of coral species have also been reported (e.g. Glynn 1988, 1990) and in one case, the global extinction of a hydrocoral species has been reported (Glynn and de Weerdt 1991; de Weerdt and Glynn 1991). How changes in species composition of reefs will affect long-term stability of coral reefs is unclear.

Given that relatively short periods (several weeks to months) of unusually high temperature

(1–2°Cabove normal) impacts can have quite dramatic effects on the species richness (Glynn 1993), it is clear that prolonged warming of tropical seas (3°Cand higher above normal on a permanent basis) is likely to act to influence coral reef biodiversity in the next century.

Sub-lethal influences: reduced reef productivity and growth as a result of increased sea temperature

The influence of bleaching on coral reefs extends beyond mortality. Some of the subchronic effects of bleaching include the partial loss of zooxanthellae and their pigments, and coral protein, lipid and carbohydrate (Glynn et al 1985; Glynn and D'Croz 1990; Hoegh-Guldberg and Smith 1989b; Kleppel et al. 1989; Jokiel and Coles 1977, 1990). Although mortality might not always eventuate, reef-building corals that undergo bleaching have reduced growth, calcification, reproductive output and repair capabilities following bleaching (Goreau and Macfarlane 1990; Glynn 1993; Meesters and Bak 1993). A reduced ability to grow and reproduce may also translate into a reduced ability to compete for space with other organisms like macroalage, which may eventually eliminate reef-building corals from particular reefs. There is considerable evidence that this has already occurred in some areas of the Caribbean and eastern Pacific (Glynn 1993).

Living coral reefs represent the balance between the two opposing processes of reef growth and erosion. Coral calcification leads to reef growth, dead coral skeletons are cemented together by calcareous algae to form the primary reef matrix within which thousands of species then make their home. Opposing reef growth is the physical erosion of reefs wave action and the biological erosion through the action of invertebrate bioeroders. Thus, while bleaching may not kill corals outright, reduced productivity may cause reefs to shift the balance towards increased erosion. This has neither been explored nor demonstrated.

How relevant is the current set of experimental evidence to our understanding of bleaching?

Although there have been a number of experiments investigating the relationship between temperature and coral bleaching (Coles et al. 1976; Jokiel and Coles 1977; Coles and Jokiel 1978; Marcus and Thorhaug 1981), these studies have all tended to look for (and induce) a more or less immediate bleaching response, which has in turn led to variable levels of mortality. However, a complicating factor in defining upper thermal limits of corals is the delay in response between cessation of the stress exposure and the final effect of the exposure on corals. Although this lag phase in coral response was not evident in specific expulsion rates of zooxanthellae in *Stylophora pistillata* and *Seriatopora hystrix* (Hoegh-Guldberg and Smith 1989b), it has been shown in other experiments. *Goniastrea sp* showed a delayed response in bleaching and mortality in early work by Yonge and Nicholls (1931) and *Pocillopora damicornis* colonies continued to deteriorate in condition 34 days after removal of thermal stress, including colonies which were in good apparent health immediately after exposure (Berkelmans and Willis submitted). This has important implications for managers and researchers alike because in natural bleaching events, temperatures may have been at a critical level weeks before the onset of symptoms. Where bleaching results from a synergistic combination of temperature and anthropogenic stress, for example during dredging events, the use of bleaching may be too insensitive to be suitable as a reactive monitoring indicator of coral health (e.g. Oliver 1995).

Another problem with interpreting and comparing results from laboratory experiments is a lack of standardisation on a single response variable, and a tendency to focus more on bleaching as the primary response rather than longer term survivorship (which is more pertinent ecologically). Since the primary cause of natural coral bleaching and subsequent mortality events is temperature, a natural focus of experimental work would be on establishing the upper thermal limits of corals. However, most studies have shied away from formally quantifying upper thermal limits in the traditional physiological sense, namely the time it takes for 50% of the organisms to die at a given temperature, expressed as T50 (Schmidt-Nielsen 1990). Instead, other determinants of tolerance limits have been used, such as bleaching (Willis and Berkelmans 1994), a combination of mortality and bleaching (Coles et al. 1976; Jokiel and Coles 1977; Coles and Jokiel 1978; Marcus and Thorhaug 1981), or quantified levels of reduction in chlorophyll and/or zooxanthellae as threshold determinants (Hoegh-Guldberg and Smith 1989b; Glynn and D'Croz 1990). Although,

sub-lethal indicators of thermal limits such as bleaching and zooxanthellae density have merit, the lack of consistency in defining the limits of tolerance of corals makes it extremely difficult to compare results between studies. Furthermore, lack of data on the ultimate level of mortality resulting from this bleaching leaves an important ecological consequence undocumented.

In a recent study on the relationship between 'bleaching threshold' and 'upper thermal limit', a 32°C winter bleaching threshold for *P. damicornis* on the Great Barrier Reef, translated to an upper thermal limit of between 31 and 32°C (Berkelmans and Willis submitted). This was based on a 5-day thermal exposure period in which just over 50% of the 32°C stress sample eventually died, while none of the corals at 31°C and all at 33°C died. However, the relationship between 'bleaching threshold' and 'upper thermal limit' may be very different for different periods of exposure and for different species.

In addition, synergistic effects of temperature and other stress factors (Coles and Jokiel 1978) and our poor understanding of genetic diversity both within coral populations and their symbiotic partners (e.g. Blank and Trench 1985; Rowan and Powers 1991,1992), tend to make extrapolations from simple lab experiments based on a few species and genotypes, to the complex and variable field environment problematic. With these problems in mind, future research effort must be directed at 'tying in' existing data on tolerance limits so that they can be better interpreted and applied to an understanding of coral bleaching.

SPATIAL AND TEMPORAL IMPLICATIONS

Corals and temperature

The global distribution of coral reefs roughly maps the incidence of water temperatures that are greater than 18°C (Veron 1986). Below these temperatures (generally at latitudes greater than 30°), the number of reef-building coral species declines rapidly and reefs do not form. Correlated with the warmer temperatures of equatorial regions, is also the tendency for tropical sea temperatures to be far more stable annually. The reconstruction of paleoceanographic temperature data has revealed that stability of tropical regions has been typical for the past 10,000 years (Beck et al. 1992). Reconstructions based on faunal and 18O ratios also suggest that tropical sea surface temperatures (SST) have remained virtually unchanged (within 2°C of current tropical sea temperatures) over the past 18,000 years (Thunell et al. 1994). By contrast, sea temperatures of more temperature areas of the globe exhibit far greater changes (up to 10°C, Thunell et al. 1994) during the same period.

El Niño and coral bleaching: a connection?

While tropical sea temperatures may be relatively stable, they are influenced by changes in oceanic circulation. These changes can vary both stochastically and cyclically. The best known examples of how large scale changes to water circulation can dramatically alter sea temperatures are the El Ninõ-Southern Oscillation (ENSO) events that have occurred roughly every 5–10 years (20 have occurred since 1900) over the last couple of thousand years. ENSO events involve a weakening or reversal of the easterly trade winds that blow across the Pacific Ocean, which in turn lead to changes in the intensity of oceanic current systems in both hemispheres. In addition to substantial influences on climate (e.g. drought in Africa and Australasia, increased rainfall in the south-eastern U.S.A.), equatorial waters intrude more southerly and bring unusually warm waters (1–5°C above normal) in contact with ecosystems formerly unexposed to these sea temperatures. Correlated with the arrival of this warm water are usually striking changes such as reduced productivity and loss of kelp forests from some temperate coastlines (Glynn 1988), and the loss of reef-building corals along some tropical coastlines (e.g. loss of reef systems in Galapagos and other localities in the eastern Pacific and Caribbean following the 1982–83 ENSO event Glynn and Colgan 1992; Goreau 1992).

Mass-bleaching events in many areas have also been clearly associated with the recent strong ENSO events (Glynn 1988, 1991, 1993; see also figure 1). Mass-bleaching events occur suddenly across vast areas of the world's tropical oceans, and have been strongly linked to slight (1–3°C) increases in water temperature (Gates 1990; Glynn and D'Croz 1990; Glynn 1991, 1993; Hoegh-Guldberg and Smith 1989b; Hoegh-Guldberg 1994). Because of the convincing connection to increases in temperature, mass-bleaching of coral reefs has also

been linked to global warming (Glynn 1984; Glynn 1991; Goreau and Hayes 1994; Hoegh-Guldberg 1994).

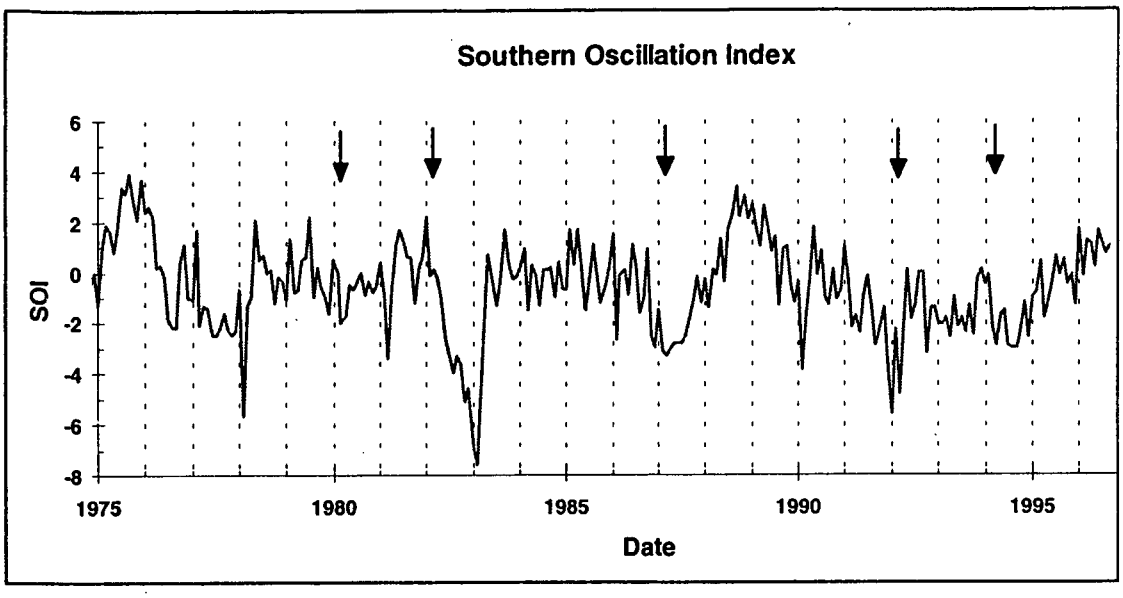


Figure 4. Southern Oscillation Index and bleaching events (arrows) at Magnetic Island

Major mass bleaching events coincide with El Niño years in some regions, as first noted by Glynn (1984) for Eastern Pacific bleaching events. This trend has been strengthened by more recent data that show an almost one to one correlation of mass bleaching with El Niño events (figure 1). The last major bleaching event in the Pacific is a case in point. However, on the Great Barrier Reef, the correlation is not nearly as strong (figure 4). Bleaching has occurred on the Great Barrier Reef both before and during ENSO events, and in once case (1980) several years distant from the nearest ENSO. Last year's Caribbean bleaching event is another example of a bleaching event that did not correlate with strong ENSO events (Hoegh-Guldberg 1995).

Great Barrier Reef and expected temperature changes.

Insufficient sea temperature data exist from the Great Barrier Reef to indicate changes in the long-term means over recent times. However, an analysis of air temperature records from Townsville shows that mean January–February air temperatures above 29°C occurred 6 times between 1980 and 1995, 5 of which coincided with bleaching events at nearby Magnetic Island. Prior to 1980 however, these conditions had occurred only 4 times in the 53 years since 1927, all occurring in the 1930s (Jones 1995; Jones et al. in press).

The immediate and strong link between air temperature and shallow reef water temperatures, especially on inshore fringing reefs, is frequently overlooked in the debate on global climate change. It is mostly assumed that any future effects of global warming will take decades to centuries to show up in the sea due to the huge thermal inertia of the oceans (Ramanathan 1988) and hence are unlikely to affect marine communities in the medium term. However, air temperatures have a large and near immediate effect on water temperatures on the continental shelf. This is demonstrated by large seasonal variation in sea temperature in reef waters. Further, the magnitude of the seasonal variation increases with proximity to land from outer-shelf to inshore fringing reefs (Berkelmans and Oliver in prep). Therefore, although our current sea temperature records are limited, we can assume that any global warming trends in surface air temperatures apply equally to reef water temperatures.

Is the connection between bleaching and upper thermal limits an oversimplification?

Although there is tempting to seek a single critical thermal threshold for coral bleaching and mortality, this would almost certainly lead to an over simplification of the real situation.

Despite a considerable period of research into bleaching and upper thermal limits of corals (e.g. Vaughan 1914; Edmondson 1928; Yonge and Nicholls 1931), only moderate progress has been made so far in determining the envelope of environmental conditions under which corals live. This lack of progress, in part, reflects the substantial spatial and temporal variation in the thermal limits both within and between species. Although small-scale intra-specific variation in the upper thermal limits of corals between habitats and between sites several kilometres away has not been detected, seasonal variation in the upper thermal limits of *Pocillopora damicornis* of around 1°C was found (Berkelmans and Willis submitted).

Over larger spatial scales, intra-specific variation in tolerance limits in corals may be considerable (Coles et al. 1978; Marcus and Thorhaug 1981; Glynn and D'Croz 1990). Enewetak corals have been shown to have upper thermal limits generally 1–2°C higher than conspecific Hawaiian corals, consistent with a difference in ambient mean summer temperatures between these locations of the same magnitude (Coles et al. 1978). Similar differences in tolerance limits have been shown between Caribbean and Hawaiian conspecific corals (Marcus and Thorhaug 1981).

The upper thermal limits of corals also depend as much on the duration of exposure as they do on the magnitude of the stress (Yonge and Nicholls 1931; Jokiel and Coles 1977; Hoegh-Guldberg and Smith 1989b). *Pocillopora damicornis* from Hawaii, for example, survived 30 minutes exposure at 34°C (Clausen and Roth 1975), but were killed after 2 days at 32.4°C (Coles et al. 1976). The same species from the same location survived 30 days exposure to 28.3°C, but was killed after 60 days at the same temperature (Jokiel and Coles 1977). The integration of thermal exposure time and temperature is therefore an important, but thus far neglected, aspect of defining upper tolerance limits in corals.

Apart from seasonal variation in the upper thermal limits of corals, there is little evidence for resistance acclimation[1] in reef-building corals and, for the most part, the evidence is circumstantial in nature. In an uncontrolled experiment, one *P. damicornis* colony and eight *Fungia scutaria* colonies showed increased survivorship at higher temperatures after 13 days at elevated, but sub-lethal temperatures (Jokiel and Coles 1977). *Montipora verrucosa* pre-exposed to 28°C for 56 days survived a short excursion to 34°C better than colonies pre-exposed to 26 and 24°C (Coles and Jokiel 1978). However, no resistance acclimation was found in *P. damicornis* or *Porites cylindrica* after 10 days of pre-exposure at temperatures 1°C below the bleaching threshold for these two species (Berkelmans unpub data).

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Does global climate change necessarily mean that impacts will occur on reef systems?

A frequently held belief is that a small increase of 1 or 2°C in the average temperature due to global warming is unlikely to affect corals because their upper thermal limits are at least 2°C above mean ambient summer levels (Jokiel and Coles 1990; Glynn 1993). This view is flawed for two reasons: (i) what matters to corals is not the changes in mean temperature but changes in the peak summer temperature at daily time-scales; and (ii) although climate models are coarse, it is likely that the extremes in climate will increase and that the time span between extreme events will decrease (Harrison and Foley 1995; Kattenberg et al. 1995).

In terms of the likely impact of global warming, it is often assumed that the Great Barrier Reef will largely escape any significant temperature changes. This is based on predictions from most climate models which consistently show that the expected global average surface temperature increase will result largely from increases in the higher latitudes and that the tropics will change little (Kattenberg et al. 1995). This scenario is not applicable to the Great Barrier Reef because much of it is situated well outside the equatorial tropics. Climate models predictions for the Great Barrier Reef region show a mean increase of between 1–3°C after a doubling in CO_2 levels (NGAC 1992; Kattenberg et al. 1995). Furthermore, recent updates on historic climate trends show that the south-west Pacific surface air temperatures have risen 0.4– 0.6°C since 1951 (much of it since 1975) and that

[1] *Resistance acclimation* refers to the ability of organisms to tolerate a larger thermal range without any adjustment to normal physiological processes, as opposed to *capacity acclimation*, which refers to the ability of organisms to undergo whole or partial compensation of metabolic function, eg in respiration rate (Precht, 1958).

temperatures in northern Australia, in a belt between Western Australia and Queensland, have risen by 0.2°C per decade for the last 40 years (Trevelyan 1994).

Is coral bleaching a sign of global climate change?

Since 1979, five major periods of mass-bleaching (some 60 separate incidents in which thousands of square kilometres of coral reef bleach) have been reported in the scientific literature. This compares to 15 reports from the period 1940 to 1979 (Glynn 1993). Although confounded to some extent by the fact that the last 3 decades have been one of intense activity in the marine sciences, the relative absence of reports during the 1960s and 1970s is curious given that biologists were still active in both the tropical intertidal and subtidal during this period (Glynn 1993). It is also remarkable given that mass-bleaching is often highly visible from above the surface of the water (Hoegh-Guldberg 1994; Hoegh-Guldberg and Salvat 1994). It should also be noted that alternative viewpoints do exist. Anecdotal information from the Great Barrier Reef suggests that bleaching was not uncommon in the '70s suggesting that increased amounts of data probably represent increased awareness and observations and reporting. Further work is clearly needed to place the current increase in bleaching reports in context. To some extent, this question may also be unresolvable as good data on the severity and extent of past bleaching events may be impossible to come by.

It is clear, however, that small increases in sea temperature have large consequences for corals and their zooxanthellae. Given the temperature increases expected in a 'business as usual' greenhouse scenario (International Panel on Climate Change, IPCC), it is clear that coral reef ecosystems are good candidates for the first of the earth's ecosystems to respond to global climate change. The estimated economic, social and strategic impact of changes of this magnitude to ecosystems as important as coral reefs, cannot be underestimated. Given the changes predicted, the study of changes to ecosystems like coral reefs, though in their infancy, must clearly be a priority of research efforts into the ecological consequences of climate change.

IMPLICATIONS FOR THE HEALTH AND MANAGEMENT OF CORAL REEF ECOSYSTEMS

Are reef systems under threat from coral bleaching?

While the causal factors of mass bleaching events are close to being understood, the influence and increased frequency of bleaching events is far from resolved. Although increased sea water temperature plays a major role in causing the symptoms of bleaching, the fate of bleached corals after such perturbations is not clear.. As has been outlined in this article so far, the effects of coral bleaching may vary from slight impacts on growth and calcification to 100% mortality of all coral over spatial scales of less than 1m to hundreds of kilometres (Williams and Bunkely-Williams 1990; Glynn 1993). Which outcome occurs is likely to be a question of the intensity and length of exposure of corals to stress. Assessing the threat of large-scale bleaching related coral mortality to the Great Barrier Reef requires an assessment of the vulnerability of corals over the full range of species and spatial scales, as well as an assessment of the number, severity and return times of 'critical' future temperature excursions, including synergistic stresses. Unfortunately, our knowledge base on which to make these assessments, at any scale, is far from sufficient (Smith and Buddemeier 1992; Glynn 1993). A first order assessment of coral vulnerability must involve quantifying thermal resistance levels for corals at several latitudes on the Great Barrier Reef for an appropriate range of species. Current information exists for only 6 species and 2 locations on the Great Barrier Reef (Hoegh-Guldberg and Smith 1989b; Willis and Berkelmans 1994; Berkelmans and Willis, submitted).

A first order assessment of the magnitude, duration and return time of temperature extremes can be obtained from probability modeling based on relatively short temperature data sets, i.e. 6–10 years (Gaines and Denny 1993). A Great Barrier Reef-wide temperature monitoring program has begun, and for a few sites, sufficient data may be available 2–3 years to undertake such an exercise (Berkelmans and Oliver in prep).

What should managers do?

Even if coral bleaching events are connected to global climate change, is there anything that reef managers can do, and therefore, does it need to be considered as 'an issue' in management circles? This is best answered at two levels. Firstly, irrespective of whether there is anything that can be done about it, reef managers have an obligation to attempt to understand the processes, whether natural or anthropogenic, which maintain and affect reef ecosystems. Without such knowledge, human impacts are difficult manage. If any of these processes are adversely affected by human activity outside the direct control of reef managers, such as global warming, they have an obligation to influence those who *do* have control. Those who have control over greenhouse emissions and other contributing factors are the national and international politicians and policy makers. Their resolve to 'do something' depends on public perception and hard evidence that something adverse is happening in real, tangible and economically important ways (Kelleher 1994). Therefore, reef managers have the obligation to acquire, interpret and effectively communicate relevant information to the public, politicians and policy makers.

Secondly, coral bleaching and the thermal sensitivity of corals also affect the day to day business of reef managers in assessing permits for developments and activities. As noted before, any stress factor which operates at or near the upper thermal limits of coral in likely to cause bleaching much sooner than otherwise would have been the case (Jokiel and Coles 1990). In assessing whether permits should be given, or the conditions under which permits should be given, regard must be had for water temperatures and the sensitivity of corals to multiple and synergistic sources of stress. Permits for activities which are likely to affect water quality parameters (even if for a brief period of time) such as dredging, construction and point-source discharge should give particular attention to these issues.

CONCLUSION

In conclusion, we submit that Great Barrier Reef waters are likely to show temperature increases of the same magnitude and in the same time frame as any increases in air temperature, whether or not such increases are exacerbated global climate change. Of most concern are increases in temperature extremes, even over short periods of time (days) and the return time of such extremes. Field observations of coral bleaching and mortality events to date clearly show that the nature and potential scale impact of temperature excursions outside the 'normal' range can be severe. Laboratory studies clearly show the high degree of thermal sensitivity of corals and the precarious nature of the relationship between corals and zooxanthellae at high temperatures. Taken together, this evidence gives sufficient reason for concern about the likelihood of large-scale changes to the Great Barrier Reef ecosystem in the future related to temperature and synergistic stresses. In the immediate term, reef managers must work at reducing anthropogenic stresses which could compound existing levels of stress in coral during summer. In the short and medium term, researchers and reef managers must work at acquiring and presenting evidence of climate change and its risk to the Great Barrier Reef ecosystem to those who are able to make a positive contribution to ameliorating such impacts, through national and international forums.

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Geoscience issues on the Great Barrier Reef: time scales for reef and shelf processes

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ABSTRACT

Three time scales are relevant to understanding the development and continued growth of the Great Barrier Reef: the origin of the Great Barrier Reef on the continental shelf (0–1Ma), the postglacial sea-level history and effects on the current cycle of reef development (0–20 ky BP), and the studies of modern sedimentary processes affecting the health and continued growth of individual reefs (0–200 years).

Drilling on ODP Leg 133 confirmed earlier seismic studies that the modern Great Barrier Reef is relatively young, perhaps less than 500,000 years old. Older carbonate systems had grown intermittently during the northward continental drift of the Australian plate, with rapid fluctuations over short time frames due to changes in ocean water temperatures.

The post-glacial sea-level rise on the NE Australian margin from a low at around -120 m 20 ky B.P. has been interpreted as both a continuous rise and as episodic. The episodic view is supported by the most recent data. Widespread initiation of coral reefs on the shelf during the sea-level rise was probably inhibited for a few centuries by inner shelf sediment wedges, with growth mainly on residual highs which survived Pleistocene erosion. The data also show sea level passed through its modern level at 6.5–5.5 ky B.P., rising to a mid-Holocene highstand at 1–2 m above present levels at ca. 5700. Recent evidence from fossil oyster beds indicates the peak in sea-level was maintained for at least the period 5.2–3.7 ky B.P., rather than falling smoothly to present over a 5,000 year period. The fall in sea level placed many reefs closer to sea-level, caused some reefs to 'reach' sea level simultaneously, and promoted lateral growth.

The modern sediments form three zones: a coastal -inner shelf zone with fringing reefs, where river influx is deposited due mainly to strong coastward seabed transport; a mid shelf starved of terrigenous and carbonate sediment; and an outer shelf dominated by carbonate sediment and reefal deposits. Contrary evidence suggested by coastal geomorphology (abundant spits, bars, tombolos and cheniers) the Great Barrier Reef shelf receives relatively little terrestrial input. Sediment is trapped in north-facing embayments, and these areas are the likely long-term repositories of terrestrial sediment and contaminants. Though visually conspicuous, muddy flood plumes from coastal rivers introduce only very minor amounts of sediment to the mid- and outer-shelf areas.

In shallow coastal areas (<5m water depth) short period waves maintain elevated suspended sediment concentrations (SSC's), which may exceed 10 mg/l for 20% of the time around fringing reefs at Magnetic Island. Long period waves (>7s) are the dominant mechanism for sediment resuspension in deeper water, where wave induced stress calculations indicate resuspension is typical in seas generated by the prevailing SE trade winds for water depths up to 20m. This sediment may be advected back towards the coast. Apart from the Whitsunday area where tidal currents are very strong, it seems tidal currents are important for sediment transport but have an insignificant influence on resuspension. Mangrove systems, comprising tidal channels, mangrove swamps and associated salt flats, provide a major coastal site of fine-grained sediment accumulation, but sand may be either accumulated or actively discharged onto the inner shelf. Preliminary fieldwork

suggests sediment transport under dry season conditions depends on the relative areas of intertidal mangrove swamp and tidal channels. Fast ebb currents in the creeks produce net seaward flux of sand, but fine-grained material suspended by turbulent tidal currents may enter the mangrove swamps and settle out during slack water at high tide.

Detailed mapping of sediment grain size distributions, especially on the inner shelf has shown distinct variations which are probably due to the combination of a range of processes: sediment input, wave and current reworking, bioturbation, and the balance between prevailing conditions and irregular events such as floods and cyclones. The next phase of research needs to concentrate on integrating these patterns with measurements of the physical processes. There is a clear need for more studies measuring SSC, and water current and wave parameters in the Great Barrier Reef region especially from water depths greater than 15 m. Cyclones have been proposed as important in sediment transport, yet there are no data on suspended sediment concentrations during these extreme events.

INTRODUCTION

This paper addresses the main advances in knowledge of the geoscience issues in the Great Barrier Reef system since the early 1980s (Baker and others, 1983). The topic requires treatment at three time-scales: the origin of the Great Barrier Reef (0–1Ma), the postglacial sea-level history and effects on reef development (0–20 ka), and modern studies of sedimentary processes (0–200 years). Figure 1 shows the area of the central Great Barrier Reef discussed in this paper. Ages less than 30 ky B.P. quoted herein are corrected conventional radiocarbon years, as used by Larcombe and others (1995).

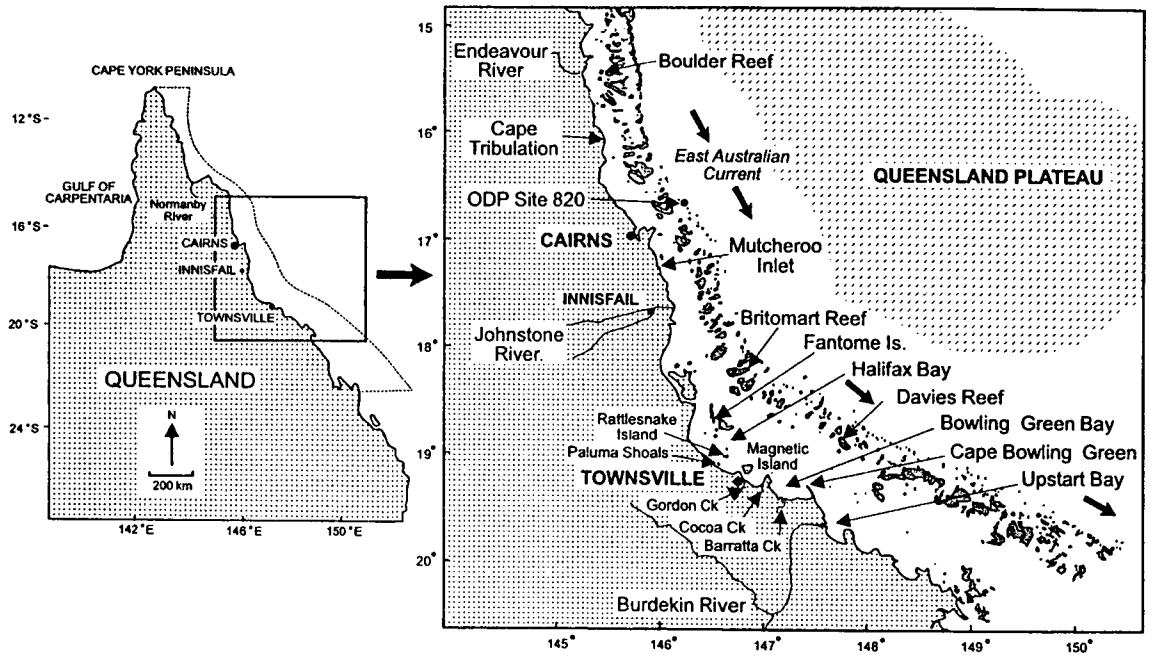


Figure 1. General map of central Great Barrier Reef with coastline and locations mentioned in text

Origins of the Great Barrier Reef

The borehole data summarised by Symonds and others (1983) indicated that carbonate, and perhaps reefal, sedimentation occurred (especially in the northern Great Barrier Reef) from mid-Cenozoic to Recent. However seismic compilations indicated that it was unlikely the Great Barrier Reef was a major reef carbonate province at any but the most recent stage of its evolution, perhaps as young as 0.5 Ma (Symonds and others 1983).

These seismic data had no age constraints until the drilling of the Ocean Drilling Program (ODP) Leg 133 (McKenzie and others 1993). The ODP drilling confirmed that long-term development of the Great Barrier Reef was strongly influenced by the northward continental drift of the Australian plate during the Cenozoic, resulting in a transition from temperate to tropical waters along the continental margin of NE Australia. Consequently the reef system is older to the north and younger to the south.

However global sea temperatures were not stable over the entire period, and rapid fluctuations over short time frames controlled reef development. There was sudden extensive tropical reef development in the early Miocene (13–14 Ma) when surface-water temperatures were high, but a major decrease in reef biota when waters cooled in the late Miocene (6–7 Ma), despite the continued continental drift northwards. Davies and McKenzie (1993) note that data from Site 820, on the shelf edge near Cairns, confirm the age of the Great Barrier Reef there as less than 500,000 years. Since then, the reef has flourished during high stands of sea-level, and died repeatedly during the low-stands caused by continental glaciations. Re-colonisation probably occurred from coral community stocks preserved on the Queensland Plateau, or further north in the western Pacific.

Post-glacial sea-level history and reef development

Since the last ice age, when ice volume peaked at ca. 18 ky B.P., the sea has risen by ca. 120 m, flooding the shelf and forming the modern Great Barrier Reef system in the last 8–9,000 years. Drilling and seismic evidence show the modern shelf reefs form caps, typically 10–20 m thick, on top of raised platforms of Pleistocene limestones (Davies and Hopley 1983; Johnson and others 1984; Walbran 1994). Fringing reefs probably grew on terraces surrounding these platforms, with the main reef initiated after sea-level had risen above the -20 m level.

The evidence for changes in sea level includes oxygen isotope curves derived from deep sea cores, which reveal global sea-level change driven by changes in ice volume. Regional detail of changes in relative sea level comes partly from interpretation of a range of types of sea-level indicator. Many are sedimentary materials sampled in sections or from cores (e.g. bulk mangrove mud, wood, palaeosols and peats) and others are in situ biological remains (e.g. coral, coral microatolls, oyster beds). Assessment of the hydro-isostatic warping of the NE Australian region by the inundation of the sea across the shelf has been made by a range of authors (Chappell and others 1982, 1983; Nakiboglu and others 1990), using coral micro-atolls as high precision recorders of mid- and late-Holocene sea levels.

Oxygen isotope evidence

One major result of ODP Leg 133 was the recovery of a high-resolution record of the last 20,000 years at Site 820A off Cairns. At this site, which was located at a depth of 278 m, on the upper slope just seaward of the outer reef tract, a little over 7 m of sediment was deposited since the last glacial maximum, i.e. an average rate of almost 0.4 mm/yr. The oxygen isotope curve which has been determined for this section of the core (Peerdeman and Davies 1993) reveals that the post-glacial oxygen isotope curve for Great Barrier Reef waters does not swing monotonically from heavier to lighter isotope values, but is rather punctuated by a number of short intervals when the isotope signature becomes heavier (figure 2).

Oceanic oxygen isotope curves have been traditionally and generally interpreted as an accurate proxy indicator of global ice volume, in that ca. 70% of the changing isotope signal is caused by melting polar ice and the consequential change produced in the 018/016 ratio of seawater (Shackleton and Opdyke 1973). However, where pelagic foraminifera are used for measurement, or where the site of accumulation of sediment is adjacent to a continental margin, some part of the changing signal is also caused by changing temperature or salinity (e.g. Nelson and others 1993). A changed temperature can result from either warming of the ocean on a global scale, or from a changed circulation pattern of major water masses. Changed salinity is caused either by changed runoff patterns of freshwater from land, or by changed ocean circulation. In general then, the overall isotope signature can be driven in a more negative direction by either increased temperature, decreased salinity, decreased ice volume, or some combination of two or three of these factors.

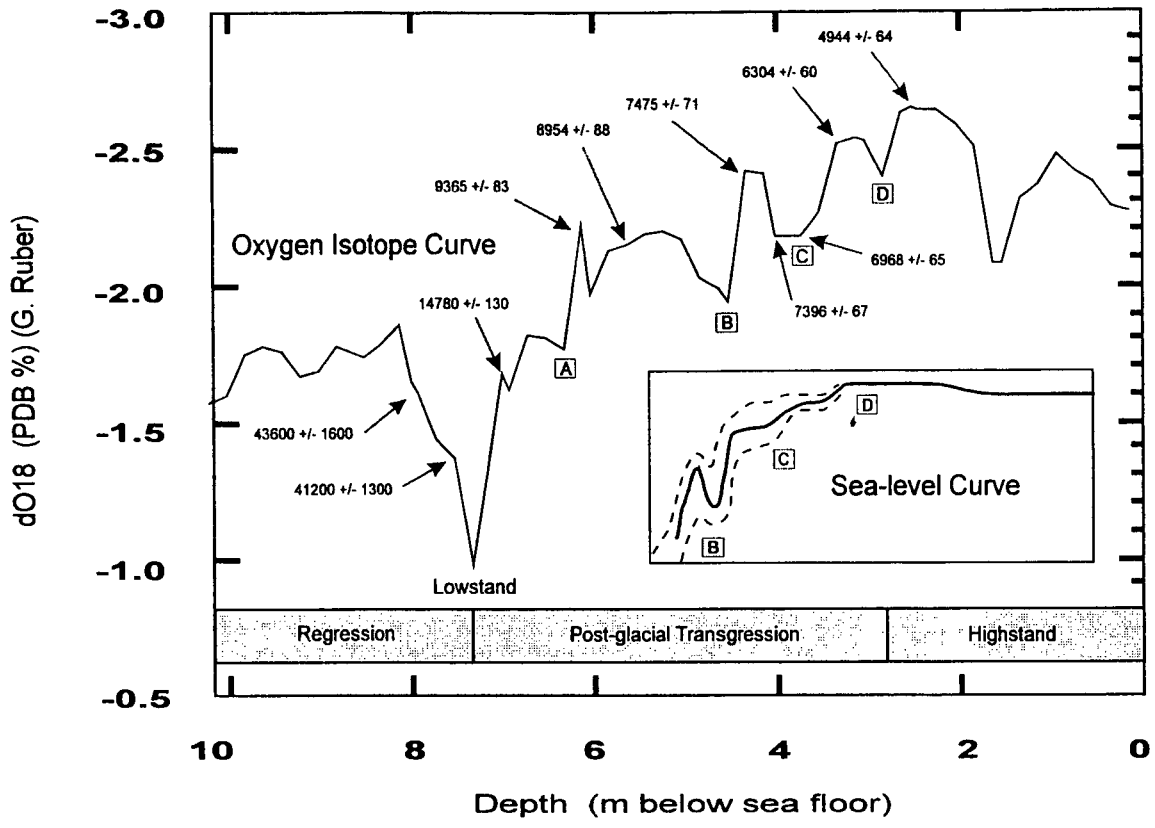


Figure 2. Oxygen isotope curve from ODP Site 820A (data of Peerdeman and Davies 1993). The ages shown are uncorrected and should be reduced by 450 years for strict comparison with the text. A–C correspond to major reversals in the post-glacial isotope trend, and date at approximately 12–10 ky B., and 7.4–7 ky P.P. respectively (corrected age). D marks a lesser feature which may be associated with a stillstand at ca. 6 ky B.P. Inset is the episodic sea-level curve (detailed in figure 3) marked with likely matching features. (from Larcombe and others 1995).

The Great Barrier Reef, and the shelf lagoon on its landward side, are bathed by generally well-mixed surface waters (depths <= 85 m). In the winter (dry) season, evaporation at the surface tends to produce a normal salinity stratification across the inshore shelf. Conversely, runoff from land during the summer (wet) season may produce an inverse salinity stratification (Wolanski and Jones 1981). Outside the reef tract, the East Australian Current (a western boundary current) transports subtropical water southwards at velocities up to 2 knots, and reaches down to depths of at least 800 m (or greater in eddies), i.e. well below the depth of Site 820A. The positive excursions seen on the post-glacial isotope curve from ODP Site 820A therefore have three possible explanations. Alone, or in combination, they could have been produced by:

- short periods of reversal in global deglaciation, with renewed ice formation and sea-level stasis or minor fall;
- short periods of climatic wetness, when freshwater runoff resulted in diluted salinities across the shelf to the reef and beyond; or
- periodic changes in the ocean circulation pattern, caused by shifts in intensity and temperature within the Pacific subtropical current gyre.

Inspection of the Site 820A isotope curve confirms that some of the excursions it displays must be due to changes in ocean temperature or salinity. This is because the major (0.4 per mile, which would imply 40 m of equivalent sea-level fall) positive fluctuation shown towards the top of the core is younger than 4.9 ky B.P. There is abundant regional evidence that at that time sea-level was at its Holocene highstand, from which it fell 1–2 m to its modern level (Chappell and others 1983; Beaman and others 1994; see discussion below).

Relative sea-level change – continuous versus episodic?

There are two end-member models for eustatic sea-level rise, continuous and episodic. The data used to determine ancient sea levels are often equivocal, and subject to considerable uncertainty, resulting in opportunity in the scientific literature for disagreement on both the broad nature and finer detail of the Holocene sea-level rise. Flexural warping of the shelf in the Holocene has probably been less than 3 m, and there is no evidence for local Holocene tectonic movements (Chappell and others 1982, 1983; Nakiboglu and others 1983). Thus the data need to be explained primarily in terms of eustatic change.

Thom and Roy (1983) revised the post-glacial sea-level envelope of Thom and Chappell (1975). The envelope and its revision were based upon data from southeastern Australia, and were used as the basis for the most widely quoted interpretations of reef growth (Hopley 1982; Davies and Hopley 1983). The envelope showed an overall continuous rising trend, though in the text the authors noted that rates of transgression may have varied, and that between 9000 and 8000 yr B.P., the sea may have even fallen. Since then, a range of publications have contributed information relevant to Holocene sea-levels (see Larcombe and others, 1995 and references therein). Much data and interpretation of the development of the Great Barrier Reef has come from cores through coral reefs, on the basis that radiocarbon dates gained from coral material in cores gives the minimum elevation of sea level (Hopley 1982; Hopley and Thom 1983; and subsequent publications). Most data have been interpreted assuming the continuous rise of Thom and Roy's (1983) envelope.

A dissenting view came from Carter and Johnson (1986) and Carter and others (1986), who assessed bathymetric, seismic and core evidence from the Great Barrier Reef in combination with a eustatic curve derived from New Zealand (Gibb 1986) and proposed an episodic model of sea-level rise. The presence of drowned shoreline-wedges and reefs are potentially important indicators of pauses or minor falls in the post-glacial transgression. However, such features are by their very nature ambiguous as sea-level indicators, because both can be developed during a phase of continuously-rising sea-level: the shoreline wedges, by pulses of enhanced sediment supply, and the reefs, by pulses of enhanced coral growth. Hopley (1987) rejected this episodic model, and Harris and Davies (1989) showed that many submarine terraces were not laterally continuous, casting doubt upon their use as indicators of ancient sea levels.

Stratigraphic evidence is critical to sea-level studies, because the lateral and vertical relationships between different sedimentary deposits form a record of changing sedimentary environments of deposition. Gagan and others (1994) documented a series of coastal sand bodies at Mutcheroo Inlet, Innisfail, and argued for a stillstand in rising sea level at ca. -5 m and 6.8 ky B.P.. This is consistent with a phase of coastal progradation and mangrove extension proposed to have persisted for ca. 1000 years along the northern shoreline of Australia (Woodroffe and others 1985, 1989; Crowley and others 1990).

In the first major reassessment of the sea-level evidence for the central Great Barrier Reef shelf for nearly a decade, an episodic model of post-glacial sea-level rise for the Great Barrier Reef shelf has recently been re-advocated (Larcombe and others 1995). The particular significance for the Great Barrier Reef shelf is that episodic sea-level rise would have included periods of sea-level rise at rates above 10 mm/yr, with important implications for coral reef growth and accumulation. Coral growth is the growth of coral colony exoskeletons (Buddemeier and others 1974) whereas accretion is the sum of constructional and erosional processes which results in overall accumulation of reef material. The maximum rate for sustained accumulation of coral reefs is ca. 5 mm/yr (Smith and Kinsey 1976; Smith 1983), although in shallow water (<5 m) rates of up to 8–15 mm/yr may occur (Hopley and Kinsey 1988; Chappell and Polach 1991; Collins and others 1993). Hence, with a rise of greater than 10 mm/yr, the growth of coral reefs will almost certainly lag behind sea level.

In this context, the Site 820A oxygen isotope curve is of particular importance, because the isotope excursions which it displays have been well dated using the accelerator radiocarbon technique (figure 2). Thus the isotope excursions marked as B, C and D on figure 2 correlate closely with inferred pauses or reversals in sea-level at those times. Furthermore, isotope excursion A may correspond to the -56 m/12 ka postglacial shoreline identified by Carter and Johnson (1986). We conclude that the isotope results from Site 820A strengthen,

but do not prove, the case for an episodic post-glacial transgression across the Great Barrier Reef shelf, and – by implication – for episodic melting of the polar ice caps.

The model proposed by Larcombe and others (1995) notes that sea-level information derived from coral cores consistently lie beneath those indicated by coastal and inner-shelf sediments (figure 3). This observation may be explained in terms of the different response of coastal sediments and corals to sea-level rise. Firstly, with rapid sea-level rise, accumulation of sediments in some cases may be able to keep up with the rise, but coral reefs will be restricted by their maximum accretion rate, and will lag sea-level rise. Secondly, with an episodic sea-level rise, some vaults between stillstands may occur at a rate above the maximum vertical accretion rate of corals. Upon reaching a stillstand, most coral reefs would thus still be catching up to sea level, but sediments will immediately be able to accumulate at the coastline. At ca. 8 ky B.P., a lag of up to 1000 years occurred between marine inundation and widespread reef growth (Davies and Hopley 1983; Larcombe and Woolfe submitted) (figure 4). Explanations for this lag have included:

- lack of available substrates for colonisation (Davies and Hopley 1983);
- lack of supply of coral larvae (Davies and Hopley 1983);
- nutrient loading of shelf waters upon initial inundation, due to reworking of soils, thereby inhibiting coral growth (Hopley 1995);
- enhanced initiation of reefs at ca. 8 ky. in relatively shallow water conditions caused by a sea-level regression (Larcombe and others 1995);
- the presence of inner-shelf sediment bodies during transgression, which blanketed potential substrates except where the local hydrodynamic regime acted to prevent soft sediment accumulation (Larcombe and Woolfe in review).

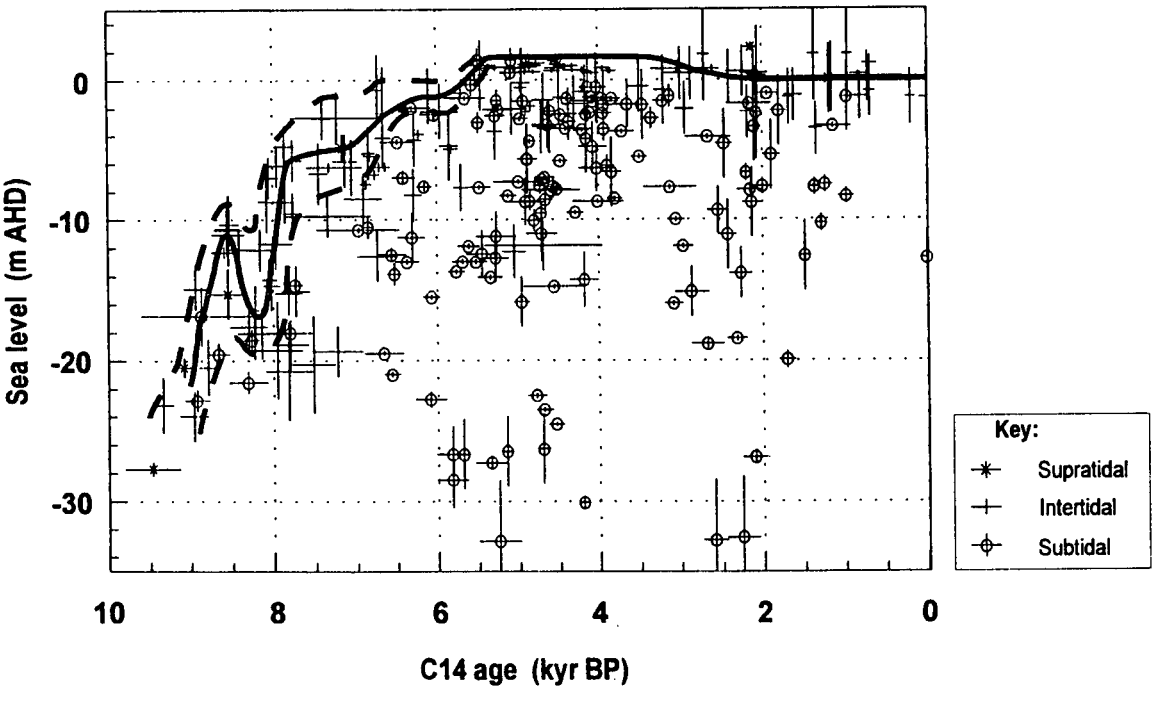


Figure 3. Sea levels for the last 9 ky B.P. with suggested sea level curve, and upper and lower envelope. All points are shown with error bars. Most data from subtidal sea-level indicators are from dated corals, and indicate sea levels significantly beneath those indicated by shelf and coastal sediments. (From Larcombe and others 1995).

The occurrence of coastal turbid-zone coral reefs in many environments where a suitably hard stable substrate is present, e.g. innermost Halifax Bay (Done 1982; Larcombe and Woolfe submitted) suggests that, at least for the late Holocene, supply of coral larvae has not been a limiting factor.

A number of sea-level curves have depicted sea level as passing through its modern level at 6.5–5.5 ky B.P., rising towards a mid-Holocene highstand (Belperio 1979; Chappell and others 1983; Hopley 1983a,b; Thom and Roy 1983; Grindrod and Rhodes 1984; Carter and others 1986; Crowley and others 1990; Lambeck and Nakada 1990), and most data points towards the younger end of this range. The mid-Holocene sea level peaked at 1–2 m above present levels at ca. 5700 (Chappell and others 1982, 1983; Hopley 1983). Geophysical modelling studies have also predicted a similar peak elevation for the northern Great Barrier Reef and Townsville area (Nakiboglu and others 1983; Lambeck and Nakada 1990).

The nature of the post-highstand fall is equivocal. Using data from coral micro-atolls, Chappell and others (1983) suggested that sea-level on the inner-shelf near Townsville fell linearly by ca. 1 m after 6 ky B.P., and that there were no secondary oscillations in sea-level between 6 and 0 ky B.P. More recently, Beaman and others, (1994) presented evidence from fossil oyster beds that the peak in sea-level was maintained for at least the period 5.2–3.7 ky B.P. In the nearby Gulf of Carpentaria, sea-level has probably fallen by 1–2 m in the last 4000 years (Chappell and others 1992; Woodroffe and Chappell 1993) and an extended period of peak sea-level is also supported by Flood and Frankel (1989) who inferred sea-levels in northern New South Wales at ca. 1 m above present at 3420 ky B.P., and possibly until as recently as 1780 ky B.P. Despite uncertainty on the precise nature of the sea-level fall, it's effects are clear in the morphology and age structure of many reefs, particularly on the inner shelf. Most, if not all, of the fringing reefs from the central and northern Great Barrier Reef have a degraded reef flat (including fossil microatolls) with prolific modern coral growth confined to the seaward edge and upper reef slope (Chappell and others 1983; Johnson and Risk 1986; Johnson and Carter 1987). In addition a few inner-shelf reefs have only reached sea level in the last 3000 years , whereas some mid- and outer-shelf reefs, growing from deeper foundations, have not yet reached sea level.

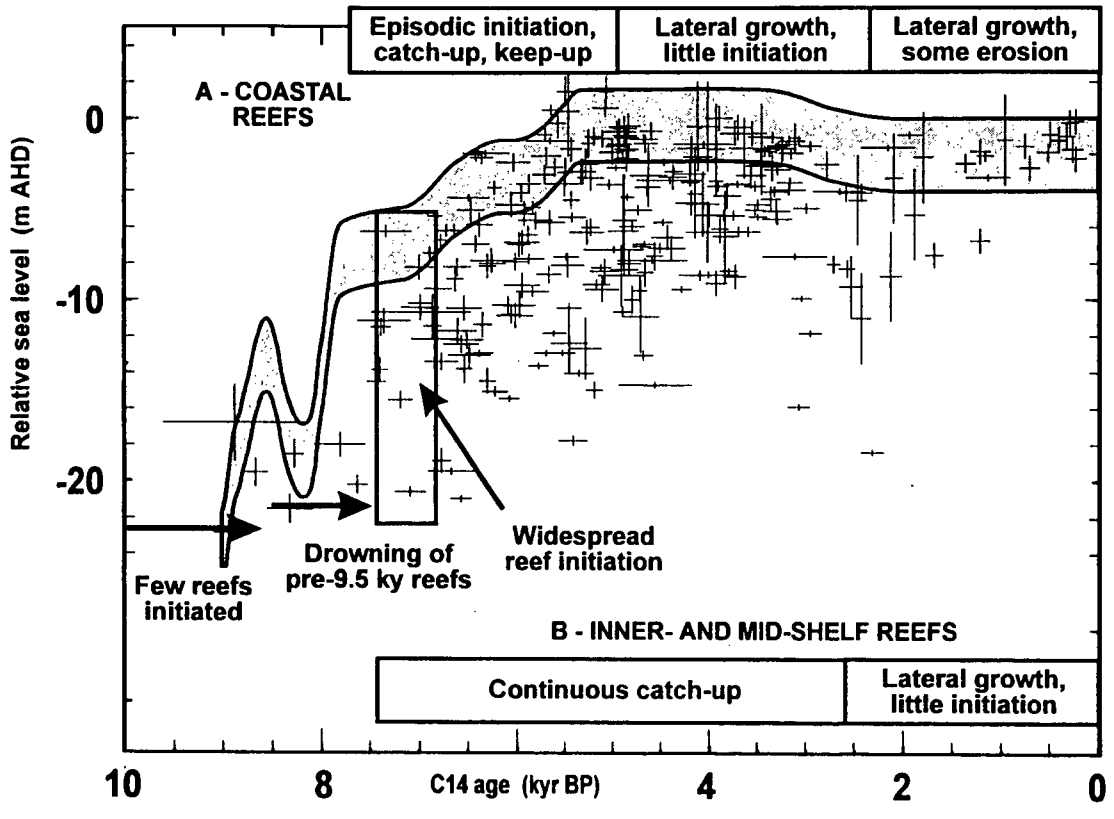


Figure 4. Sample elevations and radiocarbon ages (with error bars) of coral data from the central Great Barrier Reef shelf, superimposed upon the sea-level curve of Larcombe and others (1995). Note that, for the depth range -5 m to -17 m, there are no corals dated older than 7.5 ky B.P., although many radiocarbon dates are available. However, later on, towards the Holocene highstand, some sampled corals clearly occupied shallow water environments. This leads to an interpretation of contrasting growth phases for coastal reefs (A) compared to inner- and mid-shelf reefs (B). (Modified from Larcombe and Woolfe, submitted).

Our interpretation of the Holocene sea-level record operates at the limits of resolution. Changes in sea level may have occurred over periods of time similar to the magnitude of the dating errors, and many of the sea-level indicators commonly used have a significant vertical range in the sea level they represent. Although there is a strong basic understanding of the Holocene development of the Great Barrier Reef, the full complexity of sea-level changes and of the nature of transgressive shelf sediment bodies, together with their implications for reef development, may not be revealed for some time to come.

Modern sediment dispersal

Maxwell (1968) identified three main belts of terrigenous to carbonate-dominated sediments for the Great Barrier Reef: the terrigenous material nearshore, the carbonate sediment around the main reef tract and a middle area of intermediate composition. This pattern was later formalised by Belperio (1983) into a definition combining sediment type and topography , emphasising the clear separation of terrigenous sediments nearshore from reefal and shelf carbonates offshore (figure 5)

	water depth	carbonate content
Inner Shelf	0–20 m	>30%
Mid Shelf	20–40 m	30–80%
Outer Shelf	40–80	>80%

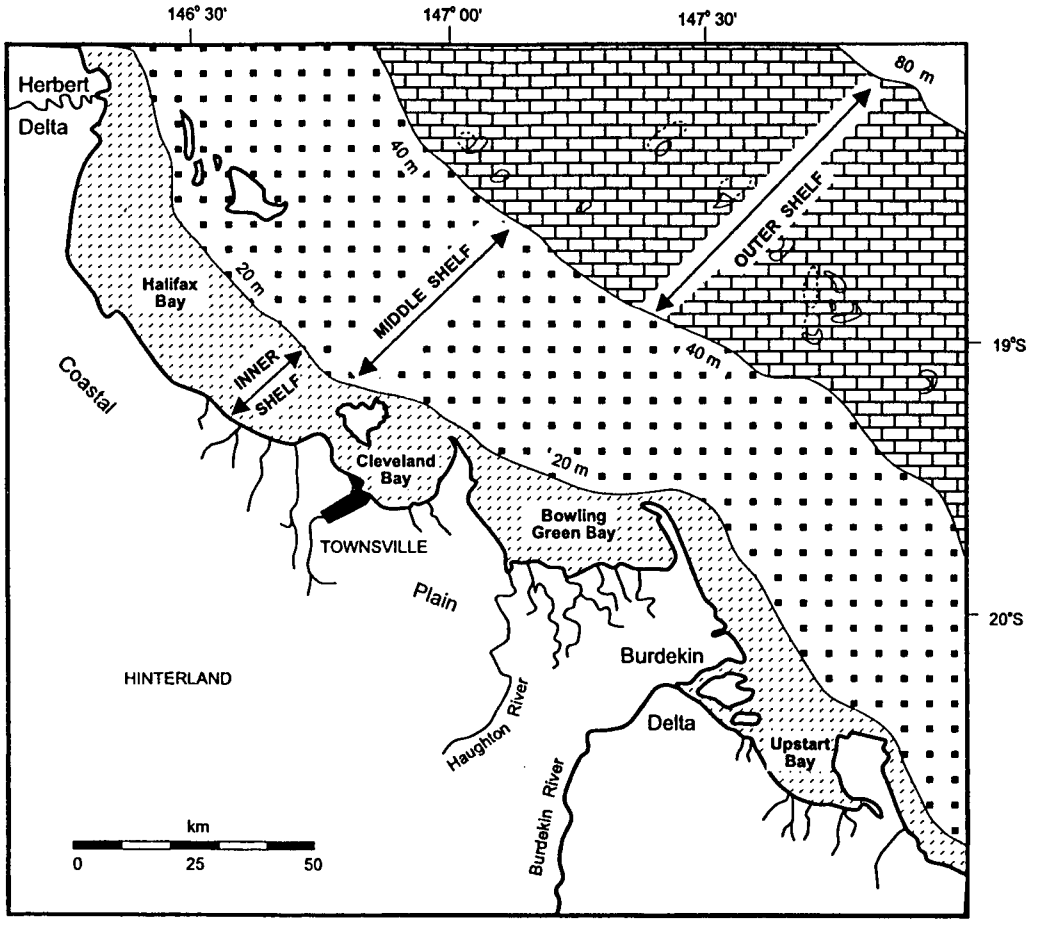


Figure 5. General nature of terrigenous-carbonate transition across the continental shelf off Townsville, showing inner shelf region (to 20 m water depth) of terrigenous sediment (<30% carbonate), midshelf (20–40 m) and outer shelf (40–80 m) of carbonate dominated sediments (>80% carbonate). After Belperio (1983) and Larcombe and Carter (in prep).

Post-glacial sediment deposited on the pre-Holocene surface is generally very thin (<2.5 m), and over many areas of the middle shelf, the pre-Holocene surface crops out on the sea floor (Orme and others 1978; Johnson and Searle 1984; Johnson and others 1986).

However, the thickest post-glacial deposits are on the middle shelf associated with incisions and transgressive prodelta lobe deposits (Johnson and others 1982). Depositional progradation has generated extensive marine coastal deposits along the length of the Queensland coastline, with greatest volumetric accumulations close to major rivers and in northward facing embayments, protected from the prevailing SE wind and wave systems (Belperio 1978, 1983; Johnson and others 1986; Way 1987; Carter and others 1993).

The Cape Tribulation studies show that terrigenous sediment on the inner shelf is contained against the coast, and drilling confirmed the reef matrix is very terrigenous (Johnson and Carter 1989; Partain and Hopley 1989). These studies supported the results of the Fantome Reef drilling program which showed in essence that the fringing reef there is based on a mud foundation , and presumably has grown for the past 5000 years in a muddy situation (Johnson and Risk 1986).

The reef matrix in these fringing reefs is very different to that in the main shelf reefs where carbonate contents were almost 100%, based on the older surface sampling by Maxwell (1968) and Orme and Flood (1978). The deeper samples recovered from Britomart and Davies Reefs (e.g. Johnson, Cuff and Rhodes 1984) confirmed this view – these reefs have formed free of terrigenous influx. In contrast there was some evidence from further north off Cooktown that sediment from the Endeavour River reached Boulder Reef, admittedly where the reef tract is much closer to shore (Davies and Hughes 1983).

The oceanographic data collected after the 1981 Burdekin flood by Wolanski and van Senden (1983) showed clearly that low salinity water containing the turbid plume was held close to the coast. A similar pattern was measured off the Johnstone River catchment after floods associated with Cyclone Winifred in 1986. Turbid water was noted well offshore from ships and reported from planes. However the concentration of the particulate matter in the water was extremely low (Dye unpubl. data), and there was debate at the time as to the proportion of suspended mud compared to phytoplankton bloom. Further there was evidence of resuspension of shelf sediment from the storm waves associated with the cyclone.

Stable carbon isotope studies showed terrestrial organic materials on the shelf both before and after the floods following Cyclone Winifred reached only about 15 km offshore, a distance similar to the general distribution of inner shelf mud deposits (Gagan, Sandstrom and Chivas 1986).

The general pattern which has emerged is that terrigenous influx is high around many inner shelf fringing reefs, though these have coral communities which are adapted to high water turbidities (Done 1982). Very little terrigenous sediment reaches the reef tract 30–50 km offshore.

How much sediment are the rivers putting into the Great Barrier Reef lagoon? Belperio (1983) estimated the Burdekin sediment discharge was 3.0 Mt washload mud, 0.45 Mt bedload sand/gravel and 0.9 Mt solute load. These figures are very dependent on the years measured and particularly on the discharge rating curves used, especially since the periodic large events are so important. Pringle (1986) also surveyed the problem. A more recent QDPI study (Moss and others 1993) estimates that present yields of suspended sediment, N and P are some 4–5 times pre-development levels. Onshore estimates of soil loss show similar drastic rises following clearing and poor soil conservation practices, especially on cane land (Neil and Yu in review).

High-resolution sediment mapping of the Great Barrier Reef lagoon

Grain size distributions are the sedimentary response to the processes of transport, resuspension, deposition, mixing and sediment modification by biota and chemical processes. From a physical sedimentology stand point, one of the more significant advances in recent years has resulted from a new generation of laser particle size analysers, which produce grain size profiles across the sand–mud range, giving estimates of the settling size rather than the absolute size derived from sieving techniques. Typically, sediment samples for most wave- or current-worked environments are found to be multimodal (even after the removal of carbonate by dissolution), and consequently traditional moment-type measures cannot adequately describe the grain size distribution of most shelf sediment (figure 6).

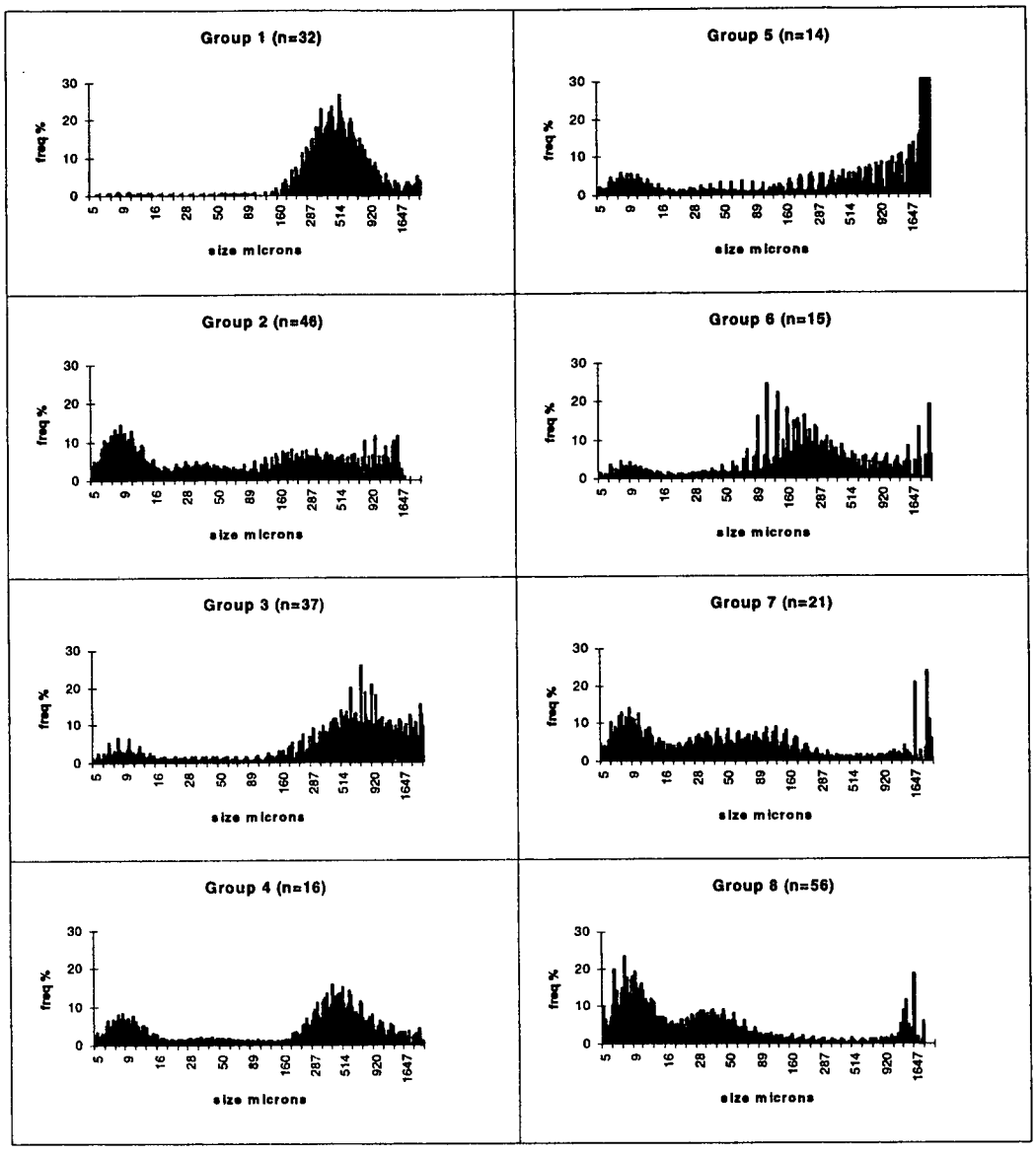


Figure 6. Graphical plots of Entropy grouped data from series of 200 shelf and coastal grab sampled sediments collected off Burdekin River area. In all cases the number in parenthesis is the sample population for that group, group 1 having the highest population of 63 and group 4 the lowest with 11.

For example, in the area near the Burdekin delta, eight discrete facies were derived by Entropy analysis of grain size data following the method of Woolfe and Michibayashi (1995) (figure 7). The groups represent discrete sedimentary facies which formed in response to different sedimentary processes. Detailed patterns of sediment character emerge, and emphasise for instance, very poor sorting of inner shelf bay fill facies e.g. Group 2. Further, the sediments infilling Bowling Green Bay and Upstart Bay have an asymmetric size distribution, the finest sediments dominating in the lee of headlands, protected from waves generated by the SE winds. Sediments become increasingly sandy with increased exposure to waves. For example, in Bowling Green Bay, Group 2 dominates on the exposed western side, and grades into nearshore, well-sorted unimodal medium sands of Group 1 (mode at 430 microns). This well-sorted medium sand facies is also prevalent along the eastern edge of Cape Bowling Green, and forms a modern sand bar within Bowling Green Bay extending from the mouth of Barratta Creek. Such detailed maps of sediment facies now need to be integrated with measurements of the physical processes operating, both the prevailing background processes and the periodic major perturbations induced by cyclones and floods.

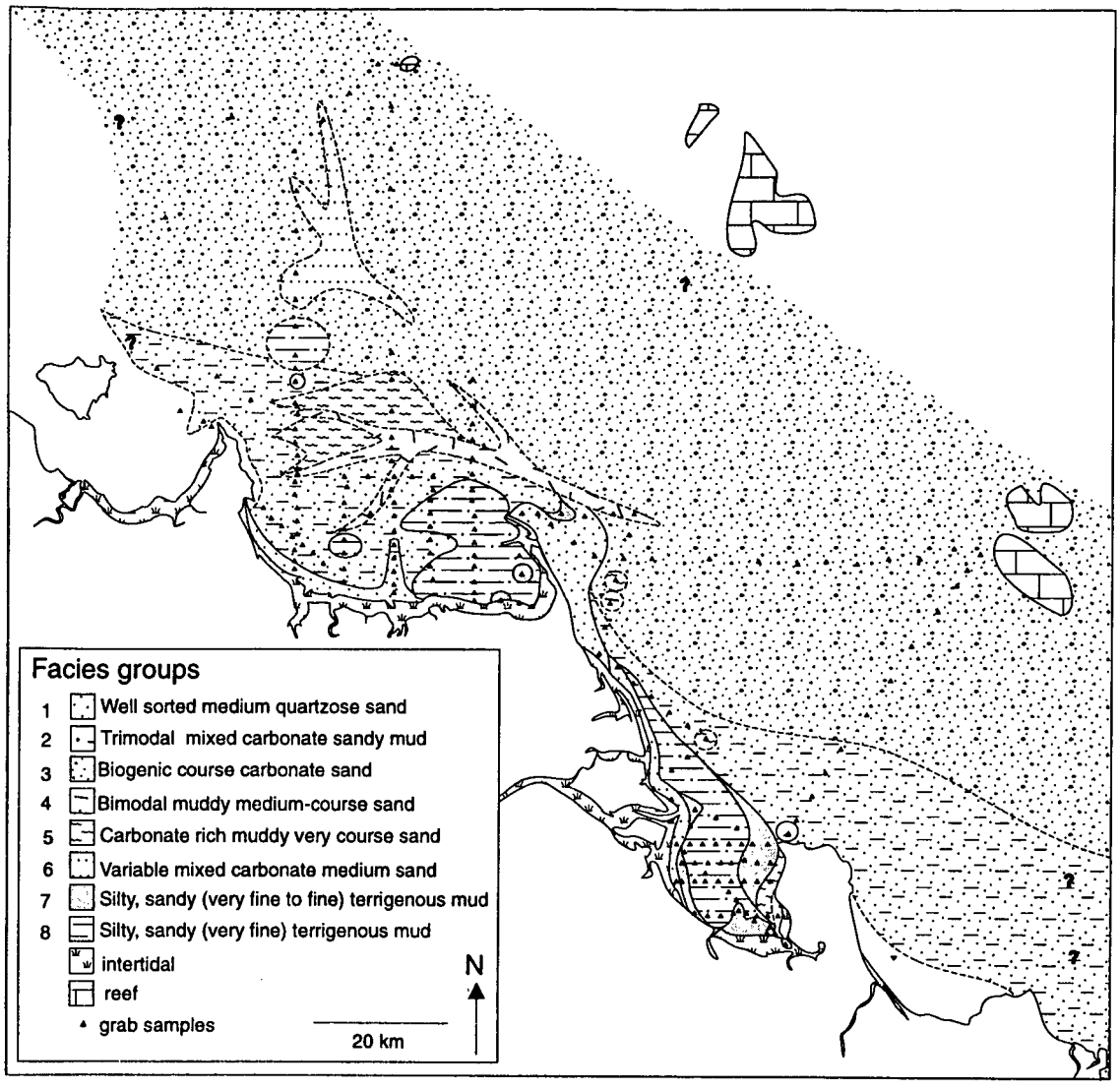


Figure 7. Distribution of sediment facies derived from Entropy analysis of laser-settling grain size analysis of seabed sediments off the Burdekin delta area. Note the distinct facies which are probably due to the combination of a range of processes: sediment input, wave and current reworking, bioturbation, and the balance between prevailing and periodic events.

Physical processes affecting sediment transport in the Great Barrier Reef lagoon

In the last two decades, work has been done by many researchers into the water circulation in the Great Barrier Reef region, and this has been extensively reviewed by Wolanski (1994). Much of this work has been motivated by biological applications especially that of larval and coral spawn dispersal. In contrast, apart from recent studies on the inner shelf, either related to the potential effects of dredging and the sediment dynamic regimes of shore-attached and fringing coral reefs (Parnell 1988; Larcombe and others 1995; Larcombe and Woolfe submitted) there have been few studies of sediment dynamics in the mid- and outer-shelf regions. In the following section, we summarise the results of recent studies of sediment transport in inshore waters, around fringing reefs, and in mangrove systems.

Sediment transport in inshore waters and near fringing reefs

Larcombe and others (1995) studied the suspended sediment concentrations (SSC) in Cleveland Bay, using data from self-cleaning nephelometers developed by Ridd and Larcombe (1994), wave gauges and current meters. This three month study indicated that high SSC concentrations (over 100 mg/l) can exist for many days during rough weather events in Cleveland Bay. The amplitude of long period waves (> 7 second) is by far the most

important factor causing high SSC. This study concluded that shorter period waves which are often of a much higher amplitude than the longer period waves have a smaller affect on SSC in water greater than 10 m deep. Calculations of bottom stresses induced by both waves and tidal current (Lou 1996) confirmed that higher bottom stresses were associated with long period waves. Tidal currents, even during spring tides, have minimal affect on SSC.

SSC concentration on the shallow fringing reefs of Magnetic Island, Rattlesnake Island and Paluma Shoals (Larcombe and others 1995; Costen 1996), indicate that SSC exceeding 10 mg/l exists for up to 20% of the time, with apparently no ill effect on the coral communities. Larcombe et al. (1995) caution against relying too heavily on SSC data taken manually because it is almost impossible to take data under the rough conditions when high SSC levels occur.

Wave stress calculations by Orpin and Ridd (in review) indicate that stresses of greater than 1 N/m2 are associated with rough weather during S.E. trade winds, when high SSC are observed in the water column. These stresses extend from the coast to water depths of 20 m, indicating that fine sediment deposited on the outer part of the inner shelf may be resuspended over many days in each year. It does not require major cyclonic events to mobilise this sediment. Orpin and Ridd (in review) have proposed that a net onshore flux of sediment may exist when sediment, suspended in deep but unsheltered areas of the shelf, is transported back towards the coast by tidal and wind-driven currents. The orientation of the coast line in the central Great Barrier Reef region is such that many areas of decreased wave activity exist (Cleveland Bay, Bowling Green Bay, southern Halifax Bay), in which such material may accumulate.

Sediment transport in mangrove systems

Mangrove systems, comprising tidal channels, mangrove swamps and associated salt flats, play a complex role in the nearshore sediment budget. In brief, they provide a major coastal site of fine-grained sediment accumulation, but sand may be either accumulated or actively discharged onto the inner shelf. Preliminary fieldwork (Larcombe and Ridd 1995, 1996; Bryce in prep.) and assessment of the literature (e.g. Wolanski and others 1992), suggests that for many estuarine mangrove creeks, other things being equal, sediment transport under dry season conditions depends on the relative areas of intertidal mangrove swamp and tidal channels.

A relatively large area of mangrove swamp is likely to produce weak currents through swamps, and a net landward flux of suspended sediment. Fast ebb currents in the creeks produce net seaward flux of sand. The mangrove system may thus progressively accumulate fine sediment, and simultaneously discharge bedload sediment seaward in the creeks. This model is hydrodynamically consistent with both independent field measurements (Wolanski and others 1980) and hydrodynamic models (e.g. Fry and Aubrey 1990). Thus, ebb tidal currents may be dominant in many mangrove creeks (Wolanski and others, 1980, 1990; Woodroffe 1985; Wolanski and Ridd 1986), which will direct bedload transport of coarse-grained material (sand) towards the creek mouth. Gordon Creek and Cocoa Creek near Townsville are examples of such systems (Larcombe and Ridd 1995, 1996; Bryce in prep.)

In contrast, fine-grained suspended material which is mixed into the surface layers of the water column by turbulent tidal currents may enter mangrove swamps and settle out during slack water at high tide. Because tidal currents in the swamps are almost always well below that required for resuspension of deposited sediment, material deposited on the flats is likely to accumulate there in the long-term. Furukawa and Wolanski (in press) have shown that, in a mangrove swamp close to Cairns Airport, suspended sediment concentrations (SSCs) on the ebb tide were less than 20% of the peak flood tide SSCs. Further, that rates of sediment accumulation in the mangrove swamps decreased exponentially with distance from the creek. It is therefore likely that fine-grained sediment accumulation in mangroves is enhanced during the trade-wind season, because high concentrations of sediment are placed in suspension by waves on the inner shelf, and then may be transported into the mangrove systems by tidal currents.

There are virtually no data for sediment transport, especially of bedload, in wet season conditions. However, work in the Normanby River (Bryce and others 1996 ;Bryce in prep.) indicates that bedload transport is directed landward by the tides during the dry season, and

that wet season floods are almost certainly insufficient to transport riverine sand out of the estuary. The sand is thus trapped in the estuary in the long-term (decades to centuries, and possibly longer). This may also be the case for other coastal plain estuaries. The long-term fate of sandy sediment on the tropical Great Barrier Reef coast is thus dependent upon interactions between the riverine sediment supply to the estuaries, the nature of the estuarine systems under dry and wet season conditions, and the form of coastal plain in which the estuary is located.

Concluding comment

The Great Barrier Reef lagoon represents a paradigm of contrasting sedimentary environments: one of the worlds largest coral reef provinces lies immediately adjacent to tropical rivers capable of delivering significant quantities of terrigenous sediment. However these influxes are normally confined to a 2–3 month period over the summer wet season. There is considerable interest in the scientific community about the magnitude of the sediment fluxes in the Great Barrier Reef lagoon (e.g. Larcombe and Woolfe 1995). Cross-shelf sediment fluxes are of particular interest. There are many mechanisms by which sediment can be transported, both along and across the shelf, but virtually no published data exist on the magnitudes of these sediment fluxes.

Contrary the evidence suggested by coastal geomorphology (abundant spits, bars, tombolos and cheniers), the Great Barrier Reef shelf receives relatively little terrestrial input with sediment delivery rates to the coast orders of magnitude lower than for most other continental margins. Sediment moving northwards within the shallow offshore area is trapped in north-facing embayments and these areas are the likely long-term repositories of anthropogenically-sourced sediment and contaminants. Detailed sediment mapping is revealing patterns which await integration with measurements of the physical processes to properly understand the mechanisms of sediment and pollutant dispersal. The visually conspicuous, muddy plumes produced by flooding from the coastal rivers, introduce only very minor amounts of sediment to the mid- and outer-shelf areas and appear not to pose a 'sediment threat' to the main reef tract.

There is a clear need for more studies measuring SSC, water current and wave parameters in the Great Barrier Reef region. All studies have so far been confined to relatively shallow water, mainly close to Townsville and there is almost no data of SSC from self-recording instruments from water depths greater than 15 m.

Cyclones are often cited as being important phenomena affecting sediment transport in the Great Barrier Reef region (Gagan and others 1990; Carter and others 1996,) however no process data have been collected which measure SSC concentration profiles during these extreme events. It has been suggested that resuspension of material by cyclones is a possible mechanism by which sediment can be moved to sensitive reef areas. However until measurements are made this will remain speculation.

ACKNOWLEDGMENTS

The papers summarised here have all depended on work by numerous students and technical staff over the past 15 years and we acknowledge our debt to these workers. We thank Bob Henderson and David Hopley for providing helpful comments on the manuscript. Richard Purdon produced the figures.

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Organism level response of corals to increased nutrient concentrations

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ABSTRACT

The Proceedings of the Great Barrier Reef Conference held in 1983 contained three papers that were directly or indirectly related to nutrients. Since that time community awareness to the potential problems of land-based impact on coral reefs and the contribution of nutrients in that process has received wide-spread publicity. However real this may be in the Great Barrier Reef region the potential threat has stimulated a surge in scientific research on a wide range of areas directly related to this problem.

This presentation will of necessity concentrate on research directed at understanding the influence of increased concentrations of inorganic nitrogen and phosphorus on corals and to a lesser degree data from our laboratory on giant clams. While the concern of management is the need to understand the effect of these nutrients on corals and their consequences for the reef. Many of the scientists active in this field are driven by their desire to understand the relationship between the symbiotic partners in corals. A knowledge of this relationship is essential to our understanding of how corals will respond to eutrophication. The goals of management and basic science are not incompatible in that observing the response of the coral and its dinoflagellate symbiont to increased nutrient concentrations can provide valuable data to both.

Approaches to the problem have varied tremendously. Papers are still being written documenting the eutrophication of Kaneohe Bay. However much of our current understanding stems from small scale manipulative experiments on individual coral colonies or nubbins. More recently collaborative efforts using large scale manipulative experiments have been conducted to address aspects of this problem. These include the workshop held in Hawaii in 1991 and the ENCORE project conducted on One Tree Island between 1993 and 1996.

A review of the possible causes and consequences of outbreaks of the crown-of-thorns starfish (*Acanthaster planci*) on the Great Barrier Reef – an Australian perspective

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ABSTRACT

Outbreaks of the crown-of-thorns starfish (*Acanthaster planci*) are responsible for the greatest documented ecological impact on the Great Barrier Reef. Establishing their causes and consequences is critical to the effective management of the Great Barrier Reef Marine Park. In particular, the possible role of human activities in controlling or exacerbating outbreaks, will determine whether or not management intervention on large scales is ecologically and philosophically appropriate. Targeted scientific research as well as monitoring of the dynamics of starfish populations on the Great Barrier Reef are essential for providing the necessary information upon which effective management can be based.

Over the last decade, a coordinated program of multidisciplinary scientific research has led to significant advances in our understanding of some aspects of the outbreak phenomenon on the Great Barrier Reef. Since 1985, the Crown-of-Thorns Starfish Research Committee (COTSREC) has been advising reef managers on scientific issues relevant to managing the phenomenon. The COTSREC program's main aim of establishing the causes and consequences of the outbreaks has focused investigations on the two main hypotheses implicating human activities – the role of nutrients derived from terrestrial sources, and on the effects of commercial exploitation of some of the natural predators of the starfish. Despite a considerable research effort, the question of outbreak causation remains unresolved. This paper reviews the evidence for and against the 'naturalness' of the observed phenomenon and discusses current management strategies that attempt to take uncertainty and risk into account.

INTRODUCTION

Recent history of *Acanthaster* outbreaks on the Great Barrier Reef

Twice in the last 35 years, major outbreaks of the crown-of-thorns starfish (COTS, *Acanthaster planci)* on the Great Barrier Reef have apparently originated on reefs in the Cairns Section (14°30'S – 17°52'S) of the Great Barrier Reef Marine Park (GBRMP) (Kenchington 1977; Moran et al. 1992). Outbreaking populations during the first (1962–1976) and second (1979–1991) episode were initially recorded on Green Island Reef off Cairns (16°46'S) with a number of surrounding reefs also being affected at about the same time (Moran 1986). Dedicated surveys of starfish populations were initiated only several years later, when the outbreaks had already progressed from their suggested geographic origin (Dight et al. 1990a,b; Moran et al. 1992). Recently, the initial stages of, what is now believed to be a third major outbreak episode, have been detected (Engelhardt and Lassig, in review) on reefs in the Cairns Section.

From the limited information available on the two earlier episodes, it appears that the overall patterns and characteristics of these events were very similar. Both apparently originated somewhere north of Green Island (Dight et al. 1990a; Moran et al. 1992), spread predominantly to the south over the next decade or so before waning at about latitude 21°S (Reichelt et al. 1990; Moran et al. 1992). While outbreak patterns appear to be consistent, there are no reliable comparative data to assess the relative extent or severity of these events. A variety of survey techniques including manta tows (Moran et al. 1989) and timed swim searches (Pearson and Endean 1969; Kenchington 1976) were used in these earlier surveys. Reefs were occasionally confused and published locations were at times ambiguous. Some survey data were aggregated into such broad categories as to defy meaningful ecological

interpretation. A lack of consistent definitions of what constitutes an outbreak further compounds the confusion.

Because monitoring programs were not in place before the two previous outbreak episodes, there remains a considerable lack of information on COTS population dynamics before, during and after large-scale outbreaks (Birkeland and Lucas 1990). Recent fine-scale surveys (Engelhardt et al. in press; Engelhardt and Lassig in review) have, for the first time, provided data on age structures of starfish population on a number of mid-shelf reefs in the suspected source area of previous outbreaks. With this information it has been possible to reliably 'hindcast' recent recruitment events in the study area and to make limited projections on likely future population changes. At even finer scales, detailed studies of COTS population dynamics on particular reefs are required to provide information on critical parameters such as rates of recruitment, migration and mortality. A combination of the various scales of population information is critical in improving our understanding of the causes of starfish outbreaks.

Over recent decades, the COTS phenomenon on the Great Barrier Reef has stimulated considerable public and scientific debate (Moran 1986). Generally, attention has been focused on the potential causes and consequences of the outbreaks and, in particular, the possible role of human activities in causing or exacerbating these events. From a management perspective it is imperative to determine whether or not there is a connection between human activities impacting on the Great Barrier Reef and the occurrence of COTS outbreaks. If such a connection exists, management agencies will have a responsibility to attempt to regulate those activities or at least ameliorate their effects. The following sections provide a critical review of the available evidence for and against the 'naturalness' of the COTS phenomenon on the Great Barrier Reef.

The ecological consequences of *Acanthaster* outbreaks

Broad-scale effects (Great Barrier Reef-wide)

Annual broad-scale surveys using the manta tow technique have established that, during the second Great Barrier Reef-wide episode (1979–1991), some 17±4% of reefs were affected to various degrees by outbreaks (Moran et al. 1992). During this period, starfish activity was found to be concentrated largely within the central third of the Great Barrier Reef, from about the Lizard Island area (14o40'S) in the north to reefs south of Townsville (20o30'S). Analysis of regional patterns of coral recovery following starfish outbreaks have reinforced the suggested pattern of outbreak progression interpreted from broad-scale survey results. Done et al. (1992) showed that recovery of hard coral populations on impacted reefs in the Central Section of the Great Barrier Reef lagged behind recovery of reefs to the north in terms of both coral composition, per cent live cover and colony size. Their conceptual model of a southward moving front of coral recovery some years after *A. planci* outbreaks appears to hold true for fast (i.e. *Acropora* spp.) as well as slow growing species (i.e. massive *Porites* spp).

Fine-scale effects (individual reef scale)

Impacts on individual reefs have also been found to be highly variable. During the second outbreak episode (1979–1991) approximately 57% of reefs with outbreaks had experienced moderate to high coral mortality (approx. 30 to >50%) over at least one third of their perimeters. On average, these outbreaks produced a 3.4-fold increase in the levels of dead coral cover (Moran et al. 1992). A preliminary comparison affected reefs from the first two outbreak episodes revealed that some 35 reefs had experienced outbreaks during successive episodes. The average time between the two episodes on these reefs was 14.68 years (Moran et al. 1992), which is consistent with earlier research that showed reef recovery (at least in terms of coral cover) may take from 12–15 years (Moran 1986). Consistent with their identified regional patterns of recovery, Done et al. (1992) were also able to demonstrate that local-scale recovery patterns on reefs where prolonged outbreaks had occurred, also followed as a wave like progression along the path of the outbreaking population of starfish. However, recovery processes on individual reefs were found to be highly variable, resulting in a typically patchy pattern of recovery on affected reefs.

Ayling and Ayling (1989) described a major impact of *A. planci* on coral communities on two Central Section reefs, with starfish densities of 200–260 per hectare recorded at the peak of the outbreaks. At both reefs, density peaks were relatively short-lived, with starfish

numbers dropping to <10 per hectare within 9 months. Mean per cent live coral cover during this period dropped from 30–50% cover at John Brewer Reef and 15–30% cover at Lodestone Reef to about 6.8% and <2% respectively. Recent follow-up studies on Central Section reefs affected during the 1980s have shown that, on many reefs, per cent live coral cover has now recovered to at least pre-outbreak conditions. For example, life coral cover in some parts of Lodestone Reef (18o42'S) is now as high as 70–80% (Williams, pers. comm.).

Monitoring of coral communities on Green Island Reef since 1986 has provided a unique data set on detailed recovery patterns following a major outbreak in 1979–80. By late 1990 coral cover in many previously affected areas had recovered to an extent that widespread spatial competition among established hard corals was again occurring in some areas (Fisk 1992). The maximum hard coral cover recorded was 41% at one site, with average hard coral cover across all sampling sites estimated at about 17.5%. Arborescent and plate *Acropora* spp. dominated the recovering community at all scales of investigation (spat, juvenile and adult colonies). Throughout the late 1980s only low numbers of *A. planci* were recorded at Green Island (Fisk 1990, 1992). Follow up surveys in early 1993 detected large reductions in coral cover (over 30% reductions in some sites), significant reductions in the frequencies of arborescent and plate *Acropora* spp., and a significant increase in dead standing coral skeletons (Fisk 1993). Fisk attributed these changes to a number of different sources of disturbance, including a major cyclone, localised predation by *A. planci* and *Drupella* spp. as well as the effects of black band disease. Fisk's study has highlighted the possible synergism between a number of stresses to corals that may influence theoretical recovery trajectories.

The typically patchy and highly variable nature of outbreak patterns and recovery processes suggests that the same reefs or sites may not necessarily be affected every time an outbreak cycle occurs. The question of outbreak patchiness is particularly critical to understanding the long-term effects of COTS outbreaks on massive coral communities.

Effects on massive coral communities

While massive corals are not the preferred prey of COTS (Moran 1986; Done 1987), they may suffer high rates of mortality during major outbreaks (Done 1987, 1988). A study of *A. planci* induced mortality rates on massive *Porites* spp. on 5 central Great Barrier Reef reefs affected during the second outbreak episode, showed that substantial parts of these communities had suffered significant mortality (Done 1988). Potentially, massive corals may play a significant role in understanding the long-term effects of outbreaks and have been used as circumstantial evidence to implicate human activities in outbreak causality (Endean and Cameron 1985). This interpretation is based on the argument that because massive coral species such as *Porites* spp. have very slow growth rates (ca. 1 cm per year, Isdale 1983) large colonies would take decades to centuries to be replaced after death (Potts et al. 1985; Done and Potts 1992). Because of this slow growth, reefs could not sustain outbreaks at the recent frequency of 15–17 years without rapid degradation in, and possibly loss of, massive coral communities. This suggested effect is regarded by some (Cameron et al. 1991) as *prima facie* evidence of increased outbreak frequency (or indeed novelty of outbreaks) in recent times. However, in some cases (Cameron et al. 1991) circumstantial evidence for the apparent inability of massive coral communities to cope with 15–20 year outbreak return periods was based on surveys of reefs affected by severe outbreaks only. Measurements of the effects of outbreaks of different intensities on massive coral communities have recently provided some evidence that appears to conflict with the above extrapolations. In a study comparing reefs affected by *A. planci* outbreaks to varying degrees with non-impacted reefs, DeVantier (1994) showed that significant reductions in species richness and abundance of massive corals would occur only under severe outbreak conditions (>200 COTS per hectare). On reefs unaffected by COTS outbreaks, DeVantier (1994) observed that massive corals had little or no injury (generally <1/3 of their surface areas) despite the impact of cyclones, bleaching and coral diseases. Size-structures of most coral taxa on unaffected reefs were broad and dominated by adult colonies (>20 cm diameter). Predation at densities of <100 starfish per hectare also had relatively little effect on massive coral assemblages when compared with other types of corals. Done (1987) simulated resilience of massive *Porites* communities under various outbreak frequencies. In the case of a 15–17 year return period, as observed on the Great Barrier Reef, he concluded that individual communities could remain viable if a particular set of criteria was met. However, his simulations suggest that relatively high rates of survivorship of both juvenile

and adult colonies are required to maintain the existing population structure, again highlighting the pivotal role of outbreak intensity.

Effects on reef fish communities

Although the effects of COTS outbreaks on coral communities are relatively well documented, there is surprisingly little information on the repercussions of *A. planci* induced changes for other types of reef biota. Intuitively, the influence of substantial coral mortality should flow through affected reef systems to produce marked downstream changes in community structures and trophodynamic relationships. Research to date has focused on numerical responses in fish communities and has yielded conflicting results. Inconsistencies between research results may be closely related to the size of the study area. For example, changes in reef fish communities on small scales, such as bommies within reefs, tended to be significant (Sano et al. 1987). However, at larger, reef scales Ayling and Ayling (1989) found no significant differences in the abundance and size distribution of coral trout (*Plectropomus* spp.) between outbreak affected and unaffected reefs. In contrast, butterflyfishes (Fam. Chaetodontidae), many of which are obligate corallivores, have shown dramatic responses following COTS outbreaks, with decreases of up to 80% having been recorded (Williams 1986; Ayling and Ayling 1989). There are also indications that small planktivorous pomacentrids may suffer a significant drop in abundance following outbreaks (Williams, pers. comm.), possibly due to loss of suitable shelter (typically arborescent and plate *Acropora* spp.). In a study of possible trophodynamic responses of roving herbivorous fishes on COTS affected reefs, Hart (1996) found no evidence of a post-outbreak response at reef scales. Despite a significant increase in the availability of potential food resources (i.e. turf algae) there were no statistically significant differences in the abundance, biomass, growth and feeding rates of a roving herbivorous fish (*Acanthurus nigrofuscus*) on impacted and non-impacted coral reefs. The researcher concluded that roving herbivorous reef fish were generally not food limited.

The possible causes of *Acanthaster planci* outbreaks

It has generally been acknowledged that outbreaks of *A. planci* may be caused by a multiplicity of factors, and that these may differ in both space and time. While some researchers believe that outbreaks may be an entirely natural phenomenon related to biological or physical features, others firmly believe that primary mechanisms involving human activities are implicated in outbreak causation. Recent research on the Great Barrier Reef has focused largely on the most commonly referred to hypotheses, the natural causes hypotheses, the 'terrestrial run-off hypothesis' (Birkeland 1982) and the 'predator removal hypothesis' (Endean 1969).

Geological perspectives

Geological studies have attempted to produce a time series of past outbreak events on the Great Barrier Reef to assess the novelty of recent outbreaks or their possible exacerbation since European settlement. Analysis of COTS skeletal elements retained in reefal sediments led researchers to conclude that large (outbreaking) populations of *A. planci* were not a recent phenomenon, but have occurred on the Great Barrier Reef for the past 3000 to 7000 years (Walbran et al. 1989; Henderson 1990). Furthermore, they suggest that, in terms of both spatial extent and intensity, there was no evidence that recent outbreaks differed from those indicated in the geological past. However, the geologists had to acknowledge that individual past outbreaks could not be identified because of the inaccuracies of available dating techniques (Carbon14 Accelerator Mass Spectrometry) and the ongoing disturbance of sedimental stratigraphy due to bioturbation by some infauna (Walbran et al. 1989). While the geologists were confident of their conclusions, some biologists disagreed with the interpretation of results as a reliable demonstration of the antiquity of outbreaks on the Great Barrier Reef (Keesing et al. 1992). Their criticism was based on the uncertainties associated with a number of vital assumptions the geologists had made. These included that (i) the majority of starfish from outbreak populations remain and die on the host reef, (ii) that reefs which have had recent COTS outbreaks can be discriminated from non-outbreaking ones by the abundance of skeletal elements in reefal sediments, (iii) that outbreaks will significantly increase the number of skeletal elements above normal background levels; and (iv) that the age of individual skeletal elements can be predicted from the age of their surrounding sediment or their depth in the sediment pile. Keesing et al. (1992) suggested that further significant progress in a sedimentological approach to assessing outbreak novelty would require investigations into alternative dating techniques,

positive location of sites with minimal bioturbation and sites where accumulation of skeletal elements might occur, as well as behavioural studies to determine where COTS die at the end of outbreaks. The validity of the geologists' assumptions has not been tested to date, leaving the question of the past history of COTS outbreaks on the Great Barrier Reef largely unresolved.

Natural causes hypotheses

Aspects of the reproductive and larval biology of *Acanthaster planci*

Characteristics of the reproductive biology of COTS have been linked to the species potential to undergo radical population changes. Babcock and Mundy (1993) have argued that outbreak causation may be directly related to the high potential of *A. planci* to produce massive numbers of offspring under favourable conditions. Observations of spawning behaviour combined with studies of gametogenic cycles in *Acanthaster* populations strongly indicate that spawning activity in the central Great Barrier Reef peaks in early December (Babcock and Mundy 1993). The identified summer spawning peak is consistent with other observations from the Great Barrier Reef (Birkeland and Lucas 1990; Gladstone 1992) and elsewhere in the Indo-Pacific (Birkeland and Lucas 1990). The exact timing of reproductive events is, however, not predictable, and spawnings have been observed both day and night, and at various stages of the tide and times of the month. Babcock and Mundy (1993) observed spawnings until late January, however, relatively fewer starfish participated in these later events. Laboratory studies showed that eggs spawned after December had reduced levels of fertilisation, and embryos were markedly less likely to develop successfully. Fertilisation success depends not only on the synchrony in spawning times, but also on the spatial distribution of COTS within reef habitats. In situ fertilisation rates measured by Babcock (1992) and Babcock and Mundy (1993) were the highest measured for any of the invertebrates observed, with 60–70% fertilisation where male and female starfish were separated by approximately 10m. Measurable fertilisation still occurred when spawning animals were separated by up to 100m. These results led Babcock and Mundy (1993) to conclude that COTS outbreaks may be initiated from a relatively small population of COTS through spawning synchrony and aggregative behaviour. Recently, Benzie and Dixon (1994) confirmed these results. Using data on in situ gamete concentrations and laboratory-measured fertilisation rates, they explained the observed high fertilising ability of *A. planci* by the fact that starfish gametes age relatively slowly with sperm maintaining high fertilising capacity even under highly diluted conditions.

While fertilisation success is clearly an important part of the overall reproductive equation, the number of larvae eventually settling onto reefs is affected by a variety of other factors. Temperature has been suggested as one key factor controlling COTS larval development (Lucas 1973). Analysing a 30-year data set of sea surface temperatures recorded along the Great Barrier Reef, Black (1992) showed that the optimum temperature for larval survival of 28°C (Lucas 1973) occurred at around latitude 16°S, which has been suggested as the most likely initial epicentre of COTS outbreaks (Dight et al. 1990a; Moran et al. 1992). This spatial coincidence, however, needs to be interpreted cautiously. Firstly, Black's analysis did not take horizontal and vertical small-scale variations in temperature into consideration. Secondly, Lucas' results indicate that while the optimum temperature is around 28°C, larval development can successfully occur over a range of approximately 24–30°C. It is, therefore, more appropriate to assume that water temperature in most parts of the Cairns Section during the spawning season of COTS is generally suitable for larval development. Lucas (1973) also found a strong interaction of temperature with salinity. Optimal larval development occurred under laboratory conditions of relatively low salinity (30 ppt) and relatively high temperature (28°C). The 'larval recruitment hypothesis' subsequently proposed by Lucas (1982) states that small variations of key parameters such as temperature and salinity may have significant effects on larval development and recruitment success. This implies that outbreaks may be initiated by naturally occurring climatic events.

Large-scale variations in sea surface temperature are a key feature of ocean-scale phenomena associated with the El Niño-Southern Oscillation (ENSO) system. A preliminary analysis of recorded COTS outbreaks from throughout the Indo-Pacific region led Zann (1996) to suggest that outbreaks may be positively correlated with phase shifts in the ENSO system. In his study, outbreaks appeared to be "...remarkably coincident in very widely separated areas in two oceans, closely corresponding to ENSO phase shifts". However, the identified correlations are likely to be subject to substantial biases and estimation errors. For

many records used, the likely year of recruitment of the observed outbreaking populations had to be estimated from purely anecdotal accounts of starfish size-frequency distributions and the timing of the first appearance of the outbreaks.

The population dynamics of *Acanthaster planci*

Because neither of the previously recorded outbreak episodes on the Great Barrier Reef were anticipated or planned for, there is a dearth of information on the dynamics of COTS populations leading up to these events. Consequently, there continues to be some uncertainty whether or not the observed outbreaks resulted from a single extraordinarily good year of recruitment or followed from a series of good recruitment years.

Kenchington (1977) attempted to determine inter-annual variations in COTS recruitment using size-frequency distributions of outbreak populations of *A. planci*. Suggested year classes were determined based on the modes recorded in these populations. This method, however, may not be reliable, as starfish size is highly susceptible to the quantity and quality of their available diet. A population of *A. planci* on Davies Reef (18°49'S) in the central Great Barrier Reef showed some drastic responses to the depletion of food resources that occurred during an active outbreak. Stump (1994) recorded a decrease in the mean starfish body size following a profound decline in coral resources. Apparently to maintain a higher short-term reproductive output, female starfish drew more heavily on their body reserves causing resorption of soft body wall and skeletal tissues, resulting in a reduced lifespan. Stump (1994) concluded that the reproductive success of *A. planci* and its ability to undergo sudden population explosions may be directly related to the flexible allocation of resources to the functions of growth, somatic maintenance and reproduction in response to changing environmental conditions. The development of this strategy also implies that periodic outbreaks of *A. planci* may occur under natural conditions.

Field studies involving mark/recapture exercises, collection of morphometric data and analysis of *A. planci* growth rates have convincingly shown that annual pigment bands deposited in aboral spine ossicles can be used to reliably determine age in sexually mature *A. planci* (Stump and Lucas 1990; Stump 1994). Recent fine-scale surveys in the Cairns Section (14°30'S– 17°30'S) have applied this ageing technique to describe population age structures within outbreaking populations of *A. planci*. These age determinations have demonstrated that starfish numbers have increased virtually simultaneously on mid-shelf reefs covering nearly three degrees of latitude (Engelhardt and Lassig in press). In addition, the analyses have shown that current outbreaks have resulted from a series of consecutive recruitment events, and not from a single unusually successful event.

Crown-of-thorns starfish and water quality parameters

Birkeland (1982) proposed the 'terrestrial run-off hypothesis', stating that primary COTS outbreaks were caused by heavy terrestrial run-off increasing nutrient inputs into reef waters. He suggested that higher levels of nutrients subsequently increased larval food supplies, in turn resulting in mass settlement of starfish larvae. The underlying premise is that COTS larval growth and survival are food limited under 'normal' conditions. A number of critical questions need to be addressed to assess the suggested links between water quality parameters and COTS outbreak on the Great Barrier Reef.

1. Have human activities, such as coastal development and river catchment modifications, increased nutrient inputs into Great Barrier Reef waters over the last 50 or so years?

Recent research (Moss et al. 1992) indicates that there have been 3–5fold increases in sediment and nutrient exports from Queensland coastal catchments since European settlement. Hence, it is highly probable that nutrient loadings in some parts the Great Barrier Reef, at least in the short-term, have also increased through these activities. However, there is only limited data to substantiate recent claims (Bell and Elmetri 1995) that nutrient levels have become chronically elevated and that large-scale eutrophication is occurring in Great Barrier Reef lagoon waters. In a review, Furnas (1996) showed that regional, time-averaged nutrient characteristics in the Cairns to Cooktown region were not significantly different to those found elsewhere in Great Barrier Reef shelf waters. Typically, average depth-weighted chlorophyll *a* concentrations were determined at 0.36–0.48 g l^{-1}, with markedly lower levels recorded under low rainfall and run-off conditions. These estimates are close to but below the apparent critical level required for COTS larval development (approx. 0.5 g l^{-1}, Lucas 1982; Okaji 1996). Several recent studies (Furnas 1996; Furnas and Brodie in press;

Brodie et al. in press) have now concluded that there is no evidence for widespread eutrophication of shelf waters in the Great Barrier Reef region from anthropogenic sources. While human activities such as modifications of river catchments, intensive agriculture and coastal development may enhance nutrient inputs into reef waters, similar inputs may occur naturally as a result of nutrient upwellings and cyclonic activity (Brodie 1992). The importance of periodic natural influxes of nutrients has been demonstrated by Furnas et al. (1995), who showed that, at a shelf-scale, significant amounts of nutrients (i.e. nitrates) may be contributed by upwelling. However, no such shelfbreak events have been recorded in the Cooktown region of the Great Barrier Reef Marine Park (Furnas 1996).

2. Do these increased nutrient levels (and their effects on food availability) extend to mid-shelf waters at times when larvae are likely to be present ?

Because *A. planci* populations most commonly occur on mid-shelf reefs (Moran et al. 1992), it has often been assumed that most recruitment events on the Great Barrier Reef would occur in relative isolation from terrestrial influences. Monitoring of river plumes has, however, confirmed the occasional extension of coastal influences to mid-shelf regions in parts of the Great Barrier Reef (Brodie and Furnas, in press). Available evidence suggests that rainfall, current strength and direction as well as prevailing winds strongly affect the cross-shelf extent of these plumes. The timing and frequency of major run-off events are unpredictable, as are COTS spawning events. As a result, it has not been possible to reliably match the spatial and temporal occurrence of river plumes with COTS larval clouds. However, a major river run-off event in the Cairns to Cooktown region that coincided with the reproductive season of *A. planci* in the summer of 1990/91 has been tentatively linked to current outbreaks in this region (Furnas 1996). During a persistent monsoonal rain depression (December '90 to March '91) that was associated with tropical cyclone 'Joy', researchers recorded widespread plumes of low salinity water coupled with high nutrient levels and higher than usual chlorophyll *a* concentrations. During this period (which persisted for more than a month) chlorophyll concentrations peaked at above the suggested threshold level for COTS larval development of 0.5 $\mu g\ l^{-1}$.

3. Do periodic nutrient increases in Great Barrier Reef waters result in increased food supplies for COTS larvae and, if so, does this increased food supply result in significantly higher rates of larval survival, shortening of larval life (which may translate into higher survival through shorter exposure to predation in the plankton) or greater settlement success of larvae?

In a series of laboratory rearing experiments, Okaji (1996) was able to confirm Lucas' (1973) earlier work that had shown that *A. planci* larvae obtained a significant proportion of their nutrition from relatively large phytoplankton (>2μm). Larvae reared in 2 μm-filtered natural seawater consistently failed to develop and metamorphose. While larvae showed some growth and modest survival in unfiltered natural seawater, their development was significantly slower than for larvae that were reared in nutrient enriched seawater. Okaji's experiments suggest that COTS larvae exhibit their optimal development and growth rates at phytoplankton concentrations of around 0.75 – 0.80μg chl. *a* l^{-1}. Chlorophyll concentrations of this level are uncommon in Great Barrier Reef waters. If the ambient concentration of chlorophyll *a* is used as the sole index of larval food availability, Okaji's findings would suggest that COTS larvae are indeed food-limited under natural environmental conditions, lending some support to Birkeland's hypothesis. Okaji's findings are opposed to earlier studies by Olson (1987) who concluded that under normal nutrient conditions, COTS larvae were unlikely to be food limited. Experimental investigations using in situ rearing chambers similar to the ones previously used by Olson demonstrated that COTS larvae would indeed grow and develop normally under the apparently natural food regime offered inside the experimental chambers (Okaji 1996). However, he considered these results unreliable, as chlorophyll *a* levels inside the rearing chambers were subsequently found to be elevated. Insufficient flushing of water, algal fouling and contamination during handling of chambers were blamed for the unreliable nature of earlier results.

Bell and Elmetri (1995) have suggested that, over the last 65 years, phytoplankton communities in the Great Barrier Reef lagoon have undergone a shift from the original domination by both centric and pennate diatoms (Marshall 1933) to communities that are now dominated by pennate diatoms and small flagellates. However, it is important to note

that the highest concentrations of large diatoms (> 20μm) recorded in surface waters generally occurred between the months of April and July, that is outside the reproductive period of *A. planci*. Similarly, abundances of small flagellates (< 20μm) also showed pronounced peaks in abundance at times when COTS larvae are not found in reef waters. Size fractionation analysis by Furnas (1996) established that phytoplankton biomass in Great Barrier Reef shelf waters is typically dominated by picoplankton cells (< 2μm) which are largely unsuitable for COTS larval nutrition. Typically, 40 to 80% of the measured biomass was made up of these smaller size fractions.

Total available larval food levels are likely to be above those indicated by chlorophyll concentrations alone. However, laboratory and field investigations to determine the likelihood of COTS larvae deriving significant parts of their nutrition from alternative sources, such as bacteria or dissolved organic matter, have failed to demonstrate any significant energetic contributions to the overall nutrition and development of COTS larvae. Ayukai and Hoegh-Guldberg (1992) found that heterotrophic bacteria (<0.8μm fraction) were not ingested by larvae. However, larvae were able to ingest two strains of photosynthetic cyanobacteria (approx. 1–2μm in diameter). Their results indicate that COTS larvae do not actively ingest bacteria, and although they may ingest photosynthetic picoplankton (< 2μm) both these potential sources of nutrition are unlikely to make a significant contribution to their development. Hoegh-Guldberg (1994) showed that *A. planci* larvae were capable of actively taking up dissolved free amino acids (DFAA) such as alanine, glutamic acid and arginine through transepidermic processes. He determined that threshold concentrations of DFAA required to meet larval metabolic expenditure were in the order of 1.8μM for bipinnaria and 4.7μM for the brachiolaria stage. Infrequent sampling by Ayukai et al. (1993) had previously shown that ambient DFAA concentrations in Great Barrier Reef waters were typically well below the compensatory threshold levels suggested by Hoegh-Guldberg (1994). However, Ayukai et al. (1993) initial data set did not resolve the key question of variabilities in ambient DFAA concentrations during the summer spawning period of *A. planci*. More recently, in situ monitoring of Cairns Section shelf waters showed that DFAA concentrations during the starfish's summer spawning season are typically below 0.1 μM (Ayukai et al. 1996). Despite the occurrence of a tropical cyclone and a subsequent major run-off event, there was no significant difference in ambient DFAA concentrations between flood and non-flood periods (0.111 $\pm$ 0.047μM and 0.109 $\pm$ 0.041μM respectively). This led the researchers to conclude that the contribution of DFAA to the nutrition of COTS larvae is unlikely to be significant. Their conclusion is further supported by the work of Okaji (1996) who estimated active larval uptake of the neutral amino acid alanine at a variety of background concentrations (0.148 – 0.465μM). Generally, larvae were only able to obtain a small fraction of their metabolic demand from DFAA sources at ambient concentrations. The overall contribution of DFAA to larval nutrition would be expected to be within a range of 10% (Hoegh-Guldberg 1994) to 13% (Okaji 1996) of the required uptake.

Large quantities of nutrients contained in terrestrial run-off have been shown to lead to short-term increases in phytoplankton densities only (Relevante and Gilmartin 1982; Brodie and Mitchell 1992), with blooms recorded in the Cairns to Cooktown area typically lasting between 3 and 5 days (Brodie, pers. comm.). Further research is needed to determine whether or not such short-term increases in nutrient levels in Great Barrier Reef waters can positively affect the abundance of phytoplankton species that are required for COTS larval development. Monitoring of size-fractionated chlorophyll concentrations in the suspected source area of COTS outbreaks should be continued to assess the probability of COTS larvae encountering such favourable conditions. The relative contribution of non-particulate organic matter such as detritus (i.e marine snow) and associated microbial populations to successful larval development also remains to be investigated. The key to more fully understanding the role of water quality and associated parameters lies in assessing the full nutritional spectrum that is available to COTS larvae. Available data on chlorophyll concentrations in Great Barrier Reef waters alone are not suggestive of a close link between COTS outbreaks and water quality parameters. However, the gaps outlined above would need to be addressed before more definitive statements about their possible role in outbreak causality can be made.

The role of predation

An answer to the question of whether or not human exploitation of the natural predators of *A. planci* has caused or exacerbated recent outbreaks on the Great Barrier Reef requires the resolution of three primary questions:

1. What are the predators of *A. planci* that may have been affected by fishing or collecting?
2. Have these activities caused a significant decline in the abundance of these predators?
3. Has this reduction caused or exacerbated starfish outbreaks?

Research has approached the testing of the 'predator removal hypothesis' (Endean 1969) from a variety of angles.

1. Surveys of anecdotal information on the identity of COTS predators and the incidence of predation.

Marine BioLogic (1991), using a questionnaire survey of marine scientists, obtained records of in situ observations of predation events on *A. planci*. The giant triton shell, *Charonia tritonis*, was the most commonly observed predator, accounting for 39 predation events. Maori wrasse, *Cheilinus undulatus*, were responsible for 17 events, lethrinid fishes for 13 events and toadfish for a further 11 events. Four other predators each accounted for a single event. The apparent rarity of observed predation events, particularly for fish predators, highlighted the impracticality of using direct observation as a means of measuring predation in the field. Although giant tritons (*C. tritonis*) were the most frequently observed predator of *A. planci*, they are relatively slow in consuming their prey, providing more opportunity for observations. Average consumption rates of *C. tritonis* have been found to be in the order of one starfish per week (Chesher 1969; Pearson and Endean 1969). Furthermore, feeding by *C. tritonis* may not necessarily be fatal to the starfish. Chesher (1969) showed that starfish may only be partially eaten and survive to regenerate lost arms. Experiments removing arms from starfish have shown that, while effects of damage are variable, minor damage causes little mortality in the short term. While minor damage is not usually fatal, it may cause a reduction in gonad development by around 10% (Sweatman 1995b) implying that sub-lethal damage may lower reproductive output of *A. planci* populations. Views on the significance of *C. tritonis* as a known predator remain diametrically opposed. Current population densities are largely unknown because of the cryptic nature of the species and its apparent rareness. The impact of collecting tritons from the Great Barrier Reef (prior to the banning of this activity in 1969) on shell populations is also unknown. The identified lack of information on key parameters combined with an inability to obtain sufficient numbers of *C. tritonis* for quantitative studies remains the main obstacle in improving our understanding of its role as a natural predator of *A. planci*.

2. Analysis of fish catch records to assess possible effects of fishing or collecting on putative COTS predators.

Analysis of Queensland Fish Board landings, records from charter operations and recreational spearfishing competitions to address the question of fishing pressure on putative COTS predators proved fruitless because of inadequate and often confused record keeping (Steven 1988). Reporting systems had changed over the 25 year period, taxonomy and common names of fish were inconsistent and no statistics were included to allow for a meaningful assessment of fishing effort. The lack of confirmed predator identities further limited the value of this study in understanding the effects of fishing on COTS predators. However, catch data (Craik and Fallows 1979) obtained from both commercial and recreational anglers show that reef-based fishing activities target mainly coral trout species (*Plectropomus* spp.), lethrinid species and, to a lesser degree, the Maori wrasse (*C. undulatus*). Given that all coral trouts are piscivores (Choat 1968), and hence are unlikely to affect starfish numbers, the most likely commercially exploited fish predators of *A. planci* are lethrinids and wrasses (Sweatman 1995a). Walker (1978) showed that the two most commonly caught lethrinids on the Great Barrier Reef, *Lethrinus miniatus* and *Lethrinus nebulosus* differed markedly in their feeding preferences and habitat selection when foraging for their invertebrate prey. *L. nebulosus* was typically associated with sandy bottom habitats inside reef lagoons and inter-reefal areas, again making it an unlikely predator of

juvenile and adult *A. planci*. In contrast, *L. miniatus* was shown to forage for food in coral rubble areas, a suitable habitat for juvenile *A. planci*. Consequently, recent predation studies have focused on the role of *L. miniatus* as a possible factor in controlling starfish outbreaks.

3. Feeding trials and gut content analysis to positively establish predators of COTS.

Positive identification of commercially exploited COTS predators is fundamental to addressing their role in starfish population dynamics. Experimental investigations where small juvenile COTS were presented to fish predators in the field indicated that lethrinids will eat juvenile starfish but they are not a preferred food (Sweatman 1995a). When juvenile *A. planci* were offered to lethrinids in aquaria no starfish were eaten. When juvenile *A. planci* were offered to lethrinids in the field, two species did eat some of them. However, this occurred in a minority of cases and in no instance were all the available individuals consumed. Generally, lethrinids were described as unenthusiastic predators of juvenile *A. planci*. Although other feeding trials have demonstrated that a variety of fish species, including lethrinids, will eat large juvenile and adult COTS under artificial conditions, extrapolation of the results to natural conditions is debatable (Sweatman 1995b).

A concerted fishing effort targeting *L. miniatus* within a short distance of high densities of adult COTS found no evidence that this species did prey on adult starfish. None of the 95 gut samples analysed contained any COTS fragments. However, on statistical grounds, Sweatman (in press) was unable to fully exclude the possibility of significant predation occurring. Estimates of predation rates from gut samples are imprecise because they are themselves products of several estimates (predator estimates, prey numbers), leading to a propagation of errors. Variation in gut fullness with time of capture suggested that *L. miniatus* do feed after dusk and so their feeding does coincide with times when juvenile *A. planci* would be out feeding on coral and hence accessible to predators.

4. Comparisons of putative predator densities on reefs that have been affected by outbreaks with densities on reefs that haven't.

Modelling of theoretical predation scenarios led Ormond et al. (1990) to conclude that fish predator densities of approximately 5–20 per 2000 m^2 of reef front would be sufficient to prevent outbreaks, providing larval recruitment events were not exceptionally high (assumed maximum settlement rate of 2 x 104 starfish). According to Ormond et al. (1990), predator densities sufficient to prevent outbreaks were found on Red Sea reefs and on sampled Great Barrier Reef reefs that had apparently not been affected by outbreaks. Lower predator densities were recorded on sampled Great Barrier Reef reefs that had experienced outbreaks. However, it appears likely that several confounding factors may have affected their comparisons. Pronounced differences in reef morphology and associated habitat characteristics may have confounded predator density estimates. Typically, reefs sampled in the northern Red Sea form a narrow fringe adjacent to a dry land mass. Consequently, reef-associated biota have only a limited area of suitable habitat available to them. The resulting concentration of biota combined with the generally clear waters in this part of the Red Sea greatly improve the chances of obtaining relatively accurate estimates of lethrinid densities. In contrast, most of the reefs sampled on the Great Barrier Reef were mid-shelf reefs characterised by highly variable reef morphologies and water clarity likely to have resulted in a different set of circumstances for observations of lethrinid fishes.

5. Experimental determinations of in situ predation rates on juvenile and adult starfish.

Because of their small size and less well developed spinal armour, juvenile *A. planci* are likely to be more vulnerable to predation than adult starfish. Placement of reared juvenile starfish in the field under a variety of experimental conditions has demonstrated that early post-settlement starfish experience high rates of mortality mainly due to predation by meiofauna including crabs, shrimp and fish (Keesing and Halford 1992a,b; Keesing 1993). In situ predation rates were strongly size-dependent, decreasing from 7.8% per day for newly settled starfish (0.5–1 mm diameter) to 2.5% per day at 3 mm and 0.8% per day at 13 mm (about 6 months of age). Estimated densities of these potential invertebrate predators of *A. planci* indicate that there is likely to be very high predation pressure on small *A. planci* in the field. It is important to note that none of the identified invertebrate predators are commercially exploited on the Great Barrier Reef. Juvenile *A. planci* reared in the laboratory on different coral prey species grew at vastly different rates. Starfish reared on

Acropora and *Stylophora* grew at the rate of 10–12 mm per month compared to just 0.1 mm per month in those feeding on *Porites* or coralline algae. The combination of results from predation and feeding observations indicates that COTS must settle in areas of abundant food of the favoured type to grow fast and survive the early onslaught of meiofaunal predators (Keesing 1993). Starfish that settle in areas where food availability is poor can be expected to grow slowly, thus prolonging the time spent at a small size vulnerable to predation. Based on these figures, Keesing and Halford (1992a) concluded that mortality during the first year of life following settlement is likely to account for the most important influence on eventual starfish population size.

A predator exclusion experiment found little evidence to support the hypothesis that commercially exploited fishes are important predators of juvenile *A. planci* (Sweatman 1995a). In a trial of predation effects on caged and uncaged starfish, predation rates on juvenile starfish (15–79 mm diameter) were lower (0.34% individuals per day) than those required by models (McCallum 1994) if population regulation by predators is to be achieved. However, the average mortality rate from predation in the first year may come close to McCallum's critical predation rate. To confirm these results, experimental manipulations of juveniles in the field need to be repeated on reefs subject to differing fishing pressures.

6. Modelling the effects of predation on COTS populations.

While mathematical models have been hampered by a lack of critical information on putative predators and life history characteristics of *A. planci*, they have provided some useful insights into possible causal mechanisms of outbreaks. Because of a lack of critical information on parameters such as larval survivorship, settlement rates as well as predator feeding rates and feeding behaviour, mathematical modelling has been unable to reliably establish a minimum predation level that would prevent outbreaks. However, McCallum (1991) suggested that a predatory mortality rate of 1.5% per day could prevent outbreaks. The estimated predator density to regulate COTS populations predicted by Ormond et al. (1990) is 2–10 times higher than that estimated by McCallum to have a substantial impact on COTS populations. This disparity highlights the need for additional information on key parameters to more realistically scope model assumptions.

McCallum's models correctly assume that all potential predators of *A. planci* are generalist feeders that have a typically wide range of alternative prey items. Furthermore, these predators also have reproductive rates slower than *A. planci*, thus they are unlikely to exhibit a rapid numerical response to increases in prey density. However, a functional (behavioural) response may be important. McCallum (1987) suggested that the dynamics of *A. planci* populations previously observed on the Great Barrier Reef – generally low starfish abundance with sudden and unpredictable outbreaks could be produced by the removal of a non-specialist predator showing a Type III (accelerating) functional response attacking the post-settlement stages of its prey. Squire (pers. comm., reported in Marine BioLogic (1991) noted several occurrences of *A. planci* remains in the stomachs of maori wrasse (*C. undulatus*) fished from northern Great Barrier Reef reefs where starfish were rare. The suggestion is that this species (which is targeted by commercial and recreational fishers) was actively searching for COTS when the starfish was rare, following the type III functional response. A recent expansion in the international live fish trade to Asia have resulted in increased fishing pressures on *C. undulatus* on the Great Barrier Reef. Given the suggested importance of this species as a controlling agent of COTS, fishing effects should be monitored closely.

As previously noted, mechanistic approaches trying to model actual biological processes rely heavily on accurate information for each of the model parameters. As there is little information on the identity, functional and numerical responses of the predators of juvenile *A. planci*, modelling has been unable to provide accurate predictions. Hence, mathematical models of this type should be regarded as 'pre-experimentation models' only. Their aims are to identify possible mechanistic patterns and to generate useful, testable directions for targeted research. Significant progress in this area of research will not come through further modelling exercises based on often inadequate data sets but rather through controlled experimental investigations into key components of the various model predictions.

While the view that over-collection or over-fishing of COTS predators has caused or exacerbated outbreaks has been strongly advocated by some proponents, support from research remains scant. With few exceptions (Ormond et al. 1990), the great majority of studies implicating human-induced removal of predators in outbreak causation are modelling rather than field studies (Bradbury and Antonelli 1990; Bradbury et al. 1990). Some more recent studies (Seymour and Bradbury 1992, 1994) now suggest that patterns of *A. planci* outbreaks observed on the Great Barrier Reef are not only consistent with the effects of predator removal, but are also leading to long-term degradation of the Great Barrier Reef ecosystem. While most of the suggested evidence is purely circumstantial, those concerns should not be ignored and, consequently, concerted efforts aimed at improving the accuracy of key model parameters should be initiated.

Managing the crown-of-thorns starfish issue

Understanding the causes of COTS outbreaks on the Great Barrier Reef is critical to the effective management of the Great Barrier Reef Marine Park. Under both the Great Barrier Reef Marine Park Act (1975) and World Heritage Properties Conservation Act (1983), the Great Barrier Reef Marine Park Authority (GBRMPA) has a number of obligations, not the least of which is the maintenance of the functional integrity of the Great Barrier Reef ecosystem. As previously outlined, the COTS phenomenon has the potential to severely compromise some of these obligations. A precautionary approach involving strategically directed monitoring, research and management activities is required to ensure that any possible long term deleterious effects of COTS outbreaks (should they occur) can be identified and appropriate responses be initiated. Currently, the Authority's policy with regard to COTS outbreaks is not to interfere with starfish populations on a large scale unless it can be shown that outbreaks are caused or exacerbated by human activity. In the absence of adequate proof to establish the suggested causal links, there is no justification for attempting large-scale controls of what could be an entirely natural cycle. The current policy on controls of *A. planci* states that:
"Broadscale control of crown-of-thorns starfish is not to be attempted in the Great Barrier Reef Marine Park unless human activity is proven to cause or exacerbate outbreaks, or unless any future outbreaks are much more extensive and intensive than the two that have been observed.

Local control of crown-of-thorns starfish (by any method involving treatment of individual starfish) must be consistent with zoning plan provisions and should be consistent with management plan provisions.

Recognising the potentially high risks associated with biological and chemical control measures in complex coral reef environments, research into biological and chemical control of crown-of-thorns starfish should not be supported other than in identifying potential agents whose application is consistent with the two policies above.

In the event of a causal relationship between human activity and crown-of-thorns starfish outbreaks being established, the Authority should use all its powers and influence to regulate that activity to minimise the effects of that activity on crown-of-thorns starfish populations, and should also seek to minimise the effects of outbreaks."

Marine Park Authority Meeting, June 1994 – MPA 148 (12)

The policy is based on sound risk-benefit principles (Kelleher 1993) and, appropriately, treats *A. planci* as a naturally occurring reef inhabitant. Under the policy, local-scale controls of COTS may be permitted in areas important to tourism or science. Local-scale controls using injection of toxic substances have been shown to be effective in protecting small areas of reef. Recent research has identified sodium bisulphate or 'Dry Acid' as an effective, environmentally acceptable agent for locally controlling COTS. The compound is biodegradable and does not affect other reef biota. The injection technique has been described in a published manual (Lassig 1995) and is currently being used by Great Barrier Reef tourism operations on some COTS affected reefs. A study underway on outbreaking reefs in the Cairns Section (Fisk 1996) is assessing the cost-effectiveness of a number of different strategies for applying this technique in the field.

Conclusions

Recent research into the COTS phenomenon has highlighted the inherent complexities of this issue. To date, scientific studies into the most commonly suggested possible causes of the outbreaks have been unable to produce adequate evidence implicating human activities in this periodic phenomenon. However, these studies have provided insights into a possible multiplicity of causes and have also identified remaining gaps in our knowledge.

A. planci outbreaks are responsible for the greatest, documented ecological impact on the Great Barrier Reef ecosystem. If human activities are implicated in causing or exacerbating outbreaks, many other management challenges may fade into relative insignificance. Both ongoing monitoring and targeted research into the causes of outbreaks are essential for providing the necessary short and long term information upon which effective management can be based. In the absence of satisfactory evidence implicating human activities in the causation of starfish outbreaks, the GBRMPA's policy of limited intervention remains a logical and realistic approach to managing this issue. With a third major outbreak episode now underway on the Great Barrier Reef, Reef managers will have to weigh up the risks associated with (i) the remaining uncertainties about the ultimate causes of the outbreaks, as well as (ii) the effectiveness of current management actions in maintaining ecosystem functionality. The quality and magnitude of ecological data that is now becoming available will, for the first time, allow a more formal evaluation of the various management options in a risk assessment framework. The potential threat posed by the COTS phenomenon to maintaining the Great Barrier Reef ecosystem requires a concerted effort to ensure that management can make informed and correct decisions based on reliable scientific information.

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Physical oceanography

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ABSTRACT

The water currents are important because they determine where water-borne particles will travel to. Particles of interest include natural ones: such as coral eggs and fish larvae; as well as pollutants such as dredge spoils, mud, pesticides and nutrients from farm run-off and sewage treatment plants. Cases of great practical importance are described, namely the impact of land use, reef recruitment of corals and fish larvae, and global change.

We have modelled the dominant hydrodynamics of the central Great Barrier Reef continental shelf, calibrating our models against our extensive tidal and current data. The currents (both speed and direction) show variability at all scales and are complex. These currents are also three-dimensional. This complexity in the currents causes patchiness in the transport of the water-borne particles.

The Burdekin River in flood generates a lens of brackish water floating over high salinity, oceanic water, and typically travels northward along the coast. Risk assessment analysis using the model results is needed to evaluate the impact of land use on the Great Barrier Reef. Further, the fate of pollutants, such as pesticides and heavy metals in river discharges is linked to chemical processes between these contaminants and the cohesive sediments. Enhanced flocculation around marine snow flocs and mangrove vegetation detritus lessens the direct impact on coral reefs.

Hydrodynamic models were merged with a huge historical data base collected over the last 10 years on coral and fish larvae around coral reefs. The results suggest that the recruitment of coral and fish larvae depends on advection from further upstream. On arrival, reef fish larvae aggregate in hydrodynamic shadow zones around coral reefs. Reef fish recruitment is controlled by both the water currents and the larval behaviour.

Introduction – large-scale oceanography of the Great Barrier Reef

The oceanography of the Great Barrier Reef is complex due to its large expanse along the shelf waters of north-east Australia (see a review in Wolanski 1994). The movement of water through the matrix and coastal lagoon is mostly controlled by the combined forcing of the tides, the wind, the Coral Sea currents and occasional river floods. Long-term field studies of the water flows in this region show fluctuations over short and long time scales. Locally, the currents are observed to be highly influenced by the steering and blocking effects of the reefs themselves. Numerical models, using spatial scales which incorporate the influence of the topography of the reefs, have proven to be successful in describing the complex water flows of the region (King 1995)

This paper examines the use of oceanography in multi-disciplinary studies of important environmental problems, namely the effects of land use, reef recruitment and global change. The paper also demonstrates the usefulness of data and model visualisation as a means to effect better communication between scientists and resource managers.

Methods – data and model visualisation: technological advances

As part of the AIMS–IBM project 'Coral Reefs and Mangroves: Modeling and Management' at Australian Institute of Marine Science, we have acquired significant computational and visualisation resources to further scientific research. Visualisation is carried out routinely

using IBM Data Explorer - DX. Visualisation offers a valuable platform for marine scientist for:

modelling flows in complex bathymetry (coral reefs and mangroves)
merging and interpreting physical–chemical–biological data sets with the goal of demonstrating the key processes
by the above technique enable an interaction between oceanographers, chemists and biologists
presentation of the output to marine resources managers

Computer visualisation offers a way for physicists, chemists and biologists to merge their data sets from point measurements of currents, concentration of larvae of shrimp, fish and corals, and chemical matters (e.g. hydrocarbons and mud). Both the merging of the physical and biological data sets and animation of the data are necessary because the data are patchy in time and in space and practically un-assailable using standard statistical techniques. The use of visualisation has led to breakthroughs in the scientific interpretation of data showing patchiness and great spatial and temporal variability, namely in being able to understand which are the dominant physical, chemical and biological process that must be taken into account in models. For an environmental manager, visualisation makes modelling a practical option because with it model predictions are easy to obtain, customable and simple to interpret.

Turbid river plumes

The Burdekin River drains an area of 130 000 km^2 of north Queensland and has the largest recorded mean annual flow for the Queensland Coast, 9.7 x 109 m^3. The river mouth is located between Cape Upstart to the south and Cape Bowling Green to the north (see figure 1). The run-off is highly variable, limited to a few floods (1–3 per year) from January to March.

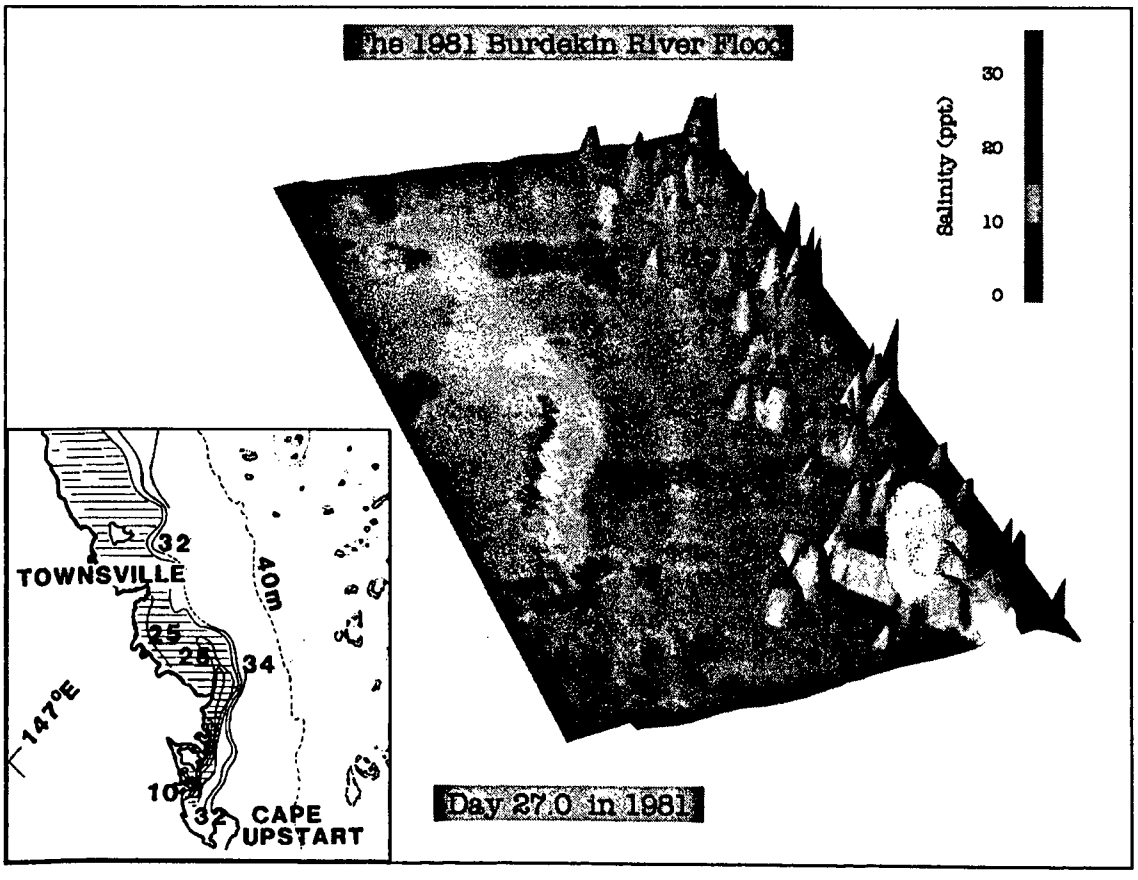


Figure 1. Predicted surface salinity distribution in the Great Barrier Reef during the Burdekin River flood on 27 January 1981. The inset shows the observed distribution for comparison.

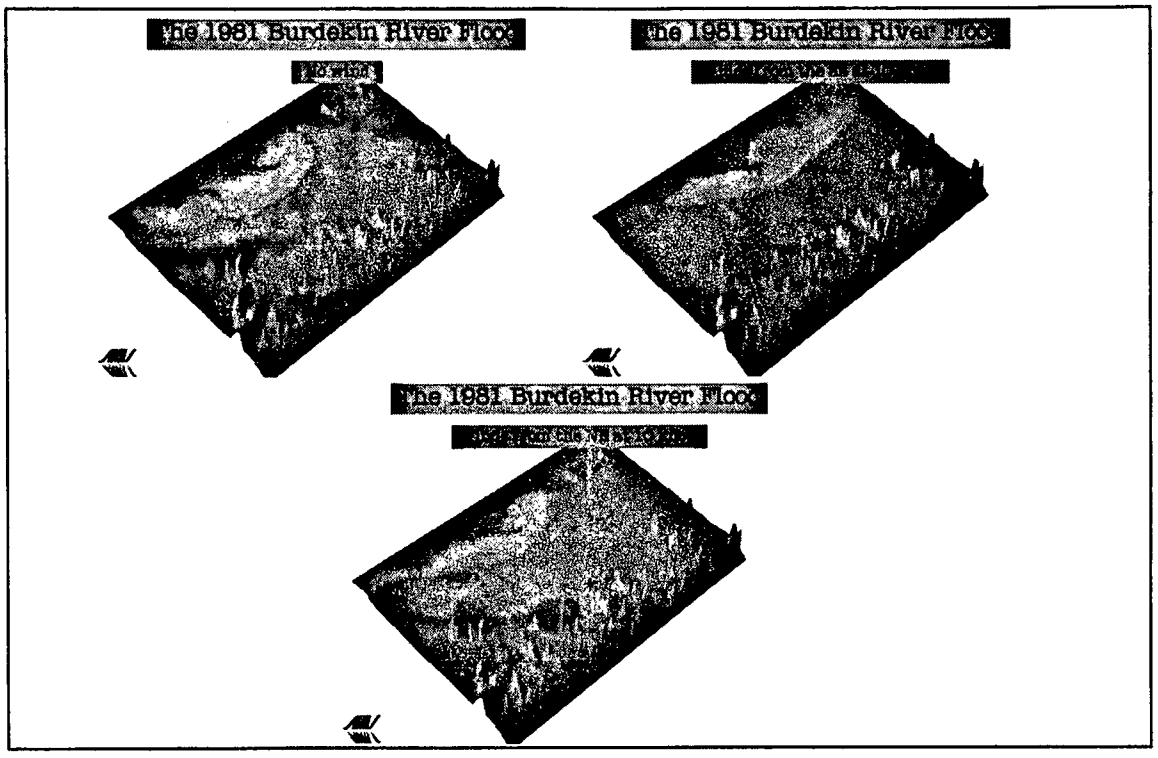


Figure 2. Comparison of surface salinity distribution using identical river discharges, but 3 typical wind patterns: no wind, 10 knot SE wind and 10 knot NE wind.

Our work involved setting up and verifying a 3-d hydrodynamic model incorporating the plume dynamics of the Burdekin River in flood. We have verified the model against the historical data of Wolanski and Van Senden (1983) for the 1981 flood (see figure 1), the only flood event for which an extensive river plume data set exists. The peak discharge of the flood in 1981 was over 12 000 tonne of water per second, and the river delivered a total of 7.5 billion tonne of freshwater into the Great Barrier Reef lagoon over a 3 week period. Figure 1 shows a snapshot of the predicted plume forcing the model with actual river discharge and wind data (King and Spagnol 1996). Given that the data were collected over a 2 day period, there is a very good agreement between the observed and predicted salinity distribution (figure 1). Comparisons at other times also show that the model is consistently reproducing the observations (see the animations).

Initial sensitivity analysis on the model runs show that the main driving influence on the fate of the plume water is the volume of the river discharge and the local wind forcing. Thus each year, one would expect different plume trajectories depending on the time-varying nature of both the wind and the rainfall/catchment (figure 2). Ultimately a risk assessment approach is required using 25 years of available wind and river discharge data, to quantify the likely impacts of the river floods on the Great Barrier Reef.

Studies of the intrusion of the Fly River plume into Torres Strait waters (Ayukai and Wolanski 1996) provide an insight into the likely impacts of river plumes on coral reefs in the Great Barrier Reef itself. During flow reversal process, the mixing between 'old' and 'new' plume waters result in the formation of coherent, low salinity patches. Silt is not carried by the river plume, only the clay is; however pollutants are mostly attached to the clay particles. The fate of this clay is strongly dependent on the interaction between physics and biology (figure 3). In the estuary the fine sediment is flocculated forming small (mean diameter about 30 m) flocs of fine sediment loosely bound by organic matter and containing very few plankton and their remains. Progressive dilution of riverine sediment with reefal, calcareous sediment west of Torres Strait changed the structure of the flocs. In coastal waters when a plankton bloom is present in the Fly River plume, the plankton removes the nutrients from river run-off and created huge (diameter typically several hundreds of m) marine snow flocs. The flocs were composed of colonies of dead plankton, faecal pellets and macroscopic aggregates of apparently biological origin. The riverine fine sediments were found attached to or embedded in these flocs. This high biological activity apparently

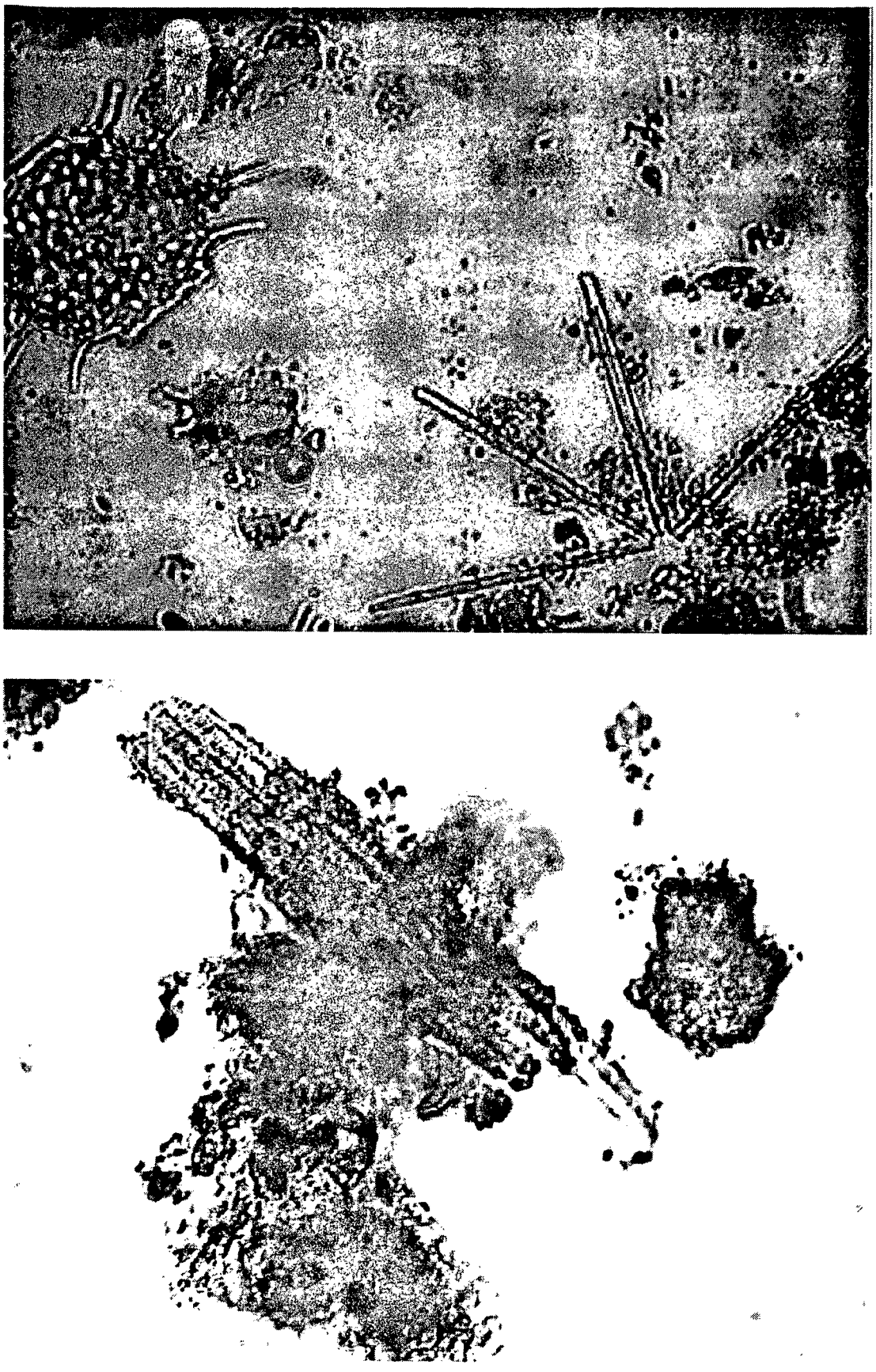


Figure 3. Microphotographs from coastal waters near Hinchinbrook Island showing: (top) macro-floc from aggregation around plankton detritus and (bottom) macro-floc from aggregation around vegetation detritus. The flocs are about 300 μm in diameter.

functioned as a barrier limiting the offshore transport of fine sediment. This effect is likely to occur also for the Great Barrier Reef though it has not been investigated before. A similar effect we found recently in Hinchinbrook Channel (figure 3) where biologically enhanced flocculation occurs on marine snow at neap tides and mangrove vegetation detritus at spring tides. For the Fly River plume some metals, e.g. particulate Fe, may be a conservative that can be used to study the fate of riverine sediment carried by river plumes.

Hence the impact of land-use on the Great Barrier Reef is related to the transient fate of the flood plume waters and its suspended sediment and is also linked to estuarine filtering processes. In particular, the fate of pollutants such as pesticides and heavy metals is linked to chemical processes between these contaminants and the cohesive sediment, and to the sediment particle sorting by size.

Reef recruitment

Flows around coral reefs are complex (figure 4) and include eddies, convergence and divergence zones, tidal jets and stagnation zones. These flows are three-dimensional and are biologically important because they determine the aggregation zones of plankton and coral eggs at sea. By comparing with data from the field and from models, we have discovered that the vertical circulation is controlled by viscous walls formed by the intense turbulence in the vortex sheets shed by separation points. This is sub-grid scale phenomenon that needs to be parameterised explicitly in 3-D models(Wolanski et al. 1996). These processes vary in time and in space.

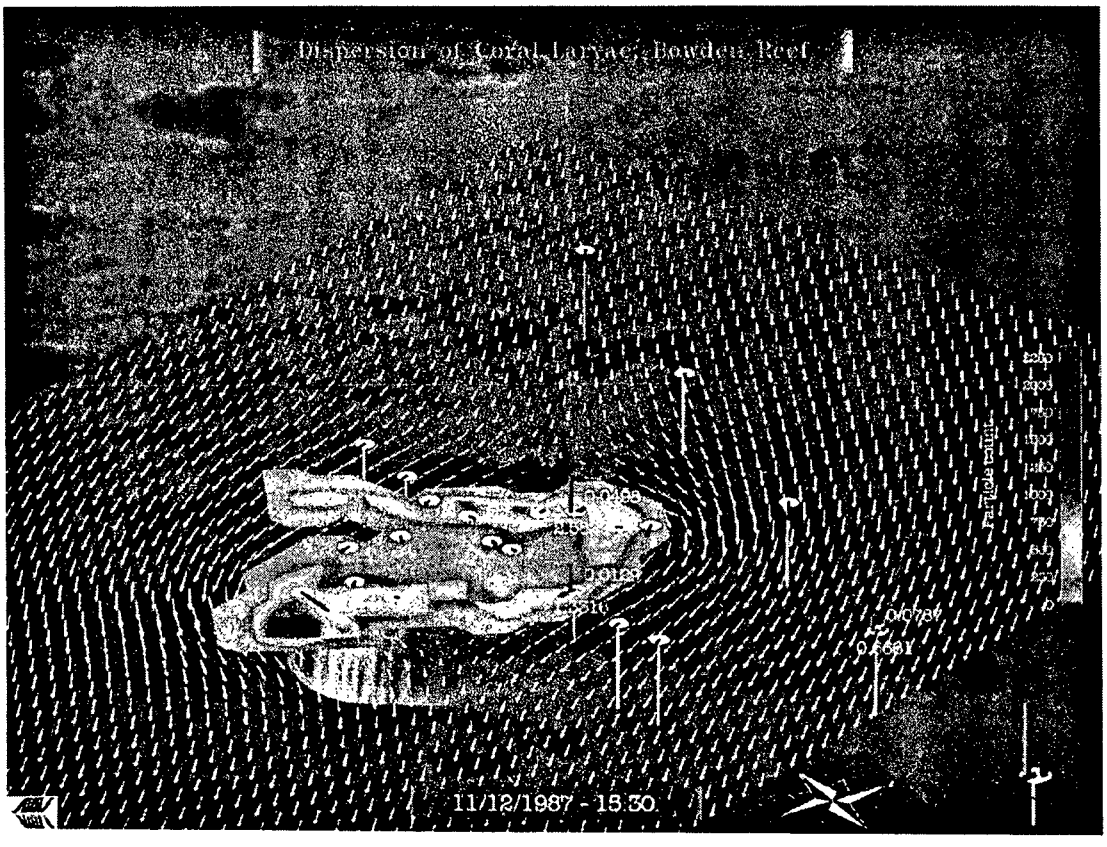


Figure 4. Predicted current (arrows) distribution around Bowden Reef, Great Barrier Reef, at 1530 h on 11 December 1987, together with the predicted distribution (plume) of coral larvae concentration following mass coral spawning. The white pins represent collection sites and the colour bars over the white pins represent observed coral larvae concentrations at the surface (right) and at 6 m depth (left).

In collaboration with biologists, principally Drs J. Oliver and P. Doherty, we have used DX to explore a huge historical data base collected over the last 10 years on coral and fish larvae around coral reefs. We have used these data to calibrate numerical models of the

flushing of coral larvae from the reefs where they were spawned (figure 4). We found that reef recruitment depends on advection of coral larvae from further upstream (see the animations).

The same methodology for modelling the fate of coral larvae was applied to fish larvae on coral reefs. Visualising the data revealed that the fish larvae were not initially resident around a particular coral reef, instead they arrived from upstream with the water currents. On arrival, reef fish larvae aggregated in hydrodynamic shadow zones around coral reefs. We were successful in modelling reef recruitment of fish taking into account both the water currents and the larval fish behaviour (figure 5). This has important management implications. Indeed in most marine systems, pelagic marine fish larvae are at the mercy of fluctuating, dispersing water currents, with little relationship resulting between the adult stock population and larvae recruitment, the majority of the larvae die at sea. However for the Great Barrier Reef, we demonstrated that the opposite is true, namely a high level of coral reef fish recruitment occurs in hydrodynamic shadow zones. We also show that recruitment is controlled by both the water currents and the larval behaviour. The strong link between recruitment and adult stock suggest that fish stocks in the Great Barrier Reef may be particularly susceptible to over-fishing.

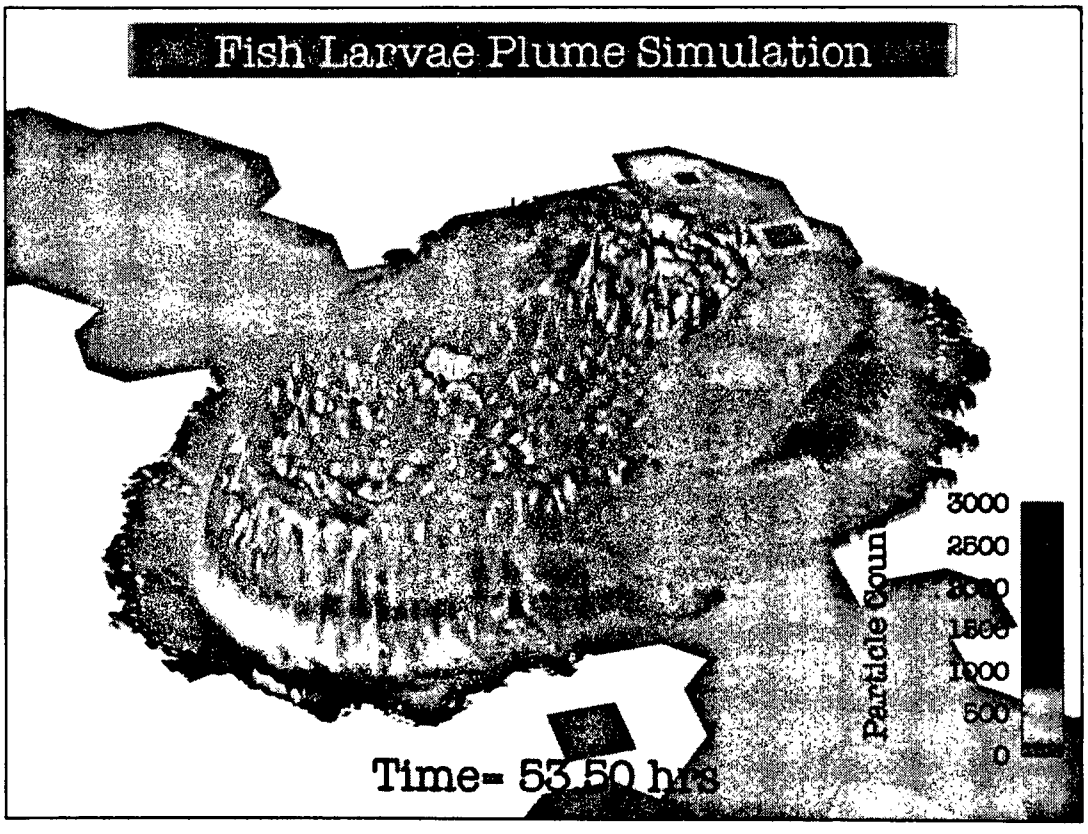


Figure 5. Predicted distribution of damselfish around Bowden Reef taking into account currents and fish behaviour

Implications of global change

Assuming that global change will be so rapid that the biological system will be faced with a sudden change in the physical forcing, we have developed three scenarios and proposed models of possible oceanographic effects of global change on coral reefs. We predicted that sheltered lagoonal reefs will suffer from an increased residence time of pollutants and a decrease of the upwelling of oceanic nutrients. Also, we predict that changes in wave dynamics over a leeward coral reef following a rise in sea level will modify coral zonation. Finally we predict that global change may increase the recruitment of fish and coral larvae as can be seen by browsing on the Internet at URL address http://ibm590.aims.gov.au.

ACKNOWLEDGMENTS

This study was supported by the Australian Institute of Marine Science, the IBM International Foundation and the CRC Reef Research Centre.

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ADDITIONAL SESSION

Management-science links

Chair: Helene Marsh

Rapporteur: Dianne Brien

•

Catchment management links to the Great Barrier Reef
Chris Robson
(presented by D Begbie)

•

Effects of sugarcane growing on the environment
H Bonanno
(presented by I Ballantyne)

•

The marine tourism initiative towards use management in the Great Barrier Reef
E Green

•

Fisheries management in the Great Barrier Reef region
J Tanzer*, M Elmer and T Healy

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Catchment management links to the Great Barrier Reef

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General Manager, Water and Catchment Management, Resource Management, Department of Natural Resources, GPO Box 2454, Brisbane Qld 4001

ABSTRACT

Considerable concerns have been raised about the perceived impacts of river catchments discharging onto the lagoon and other areas of the Great Barrier Reef. This paper summarises programs and activities led or facilitated by the Queensland Department of Natural Resources in addressing these concerns. These programs are aimed at changing the management of these catchments to minimise impacts on the coastal marine and reefal environments. Under the Integrated Catchment Management Initiative, catchment coordinating committees are operating in all the wet tropics catchments and in several of the larger basins (Fitzroy and Burnett) that discharge into the Great Barrier Reef World Heritage Area.

Investigations to date have highlighted possible impacts from agriculture, and in localised areas, urban development, on the estuarine and inshore reefal areas. However, the picture is far from clear. Impacts appear to be very episodic and linked to periods of high rainfall and high discharge rates from coastal rivers and streams. Examples of research activities to better understand catchments processes are outlined in the paper.

Voluntary programs like integrated catchment management, landcare and property management planning are contributing to improved management of catchments, however many of these changes will not be evident for many years. Regulatory instruments either adopted by industries (for example codes of practice) or imposed through local and state governments are also having positive effects. While there is evidence that the significant changes that have occurred in the catchments of the reef have had some effects on the reef itself, there is a notable lack of information on the extent and nature of these impacts. Until better information is available, catchment managers can for the time being only take a best bet approach to changing management systems to ameliorate and minimise these impacts.

1.0 INTRODUCTION

The value of the Great Barrier Reef has long been acknowledged at State, Commonwealth and international levels. As the lead agency for natural resource management in Queensland, the Department of Natural Resources acknowledges the significant role it can play in maintaining and enhancing the values of the reef.

The Department of Natural Resources has the responsibility of supporting the economic growth of Queensland through the sustainable use, development and management of land, water, and native vegetation resources, while protecting the rights and interests of both the individual and the community (Department of Natural Resources 1996).

The Department delivers its responsibilities through seven Programs (Attachment 1). The Department's efforts in the sustainable use of land, forest and water resources and catchment management are delivered through its Resource Management Program (see Box). This program draws together the government's role in planning and managing the use of land, water and native vegetation, as well as the management of pest plants and pest animals and the use of certain government lands (Department of Natural Resources 1996).

The Department does not have management responsibility for any part of the Great Barrier Reef itself. However the delivery of its lead agency services and statutory responsibilities can have a significant influence and impact on river catchments and the quality and quantity of

water discharged into the waters of the reef. These services and responsibilities include:

- management of water resources, riverine integrity, native forests and Crown land;
- the lead role in the development, promotion, and implementation of integrated catchment management;
- research assessment and monitoring of the condition and trend of land and water resources and setting guidelines or standards for the use of those resources; and
- overseeing implementation of best management practices for those resources.

A plan showing the catchments that drain into the waters of the Great Barrier Reef is attached (Attachment 2). The following outlines some of the Department's services and responsibilities that can ultimately have a significant influence on the condition of the Great Barrier Reef.

The Resource Management Program goals are:

- *To have available quality information for decision making, at all levels, on the sustainable use and management of the State's natural resources.*
- *To increase understanding of natural resource processes and the impacts of resource use and management.*
- *To ensure the allocation of the State's natural resources is sustainable.*
- *To ensure Queensland's natural resources are used and managed responsibly, sustainably, productively, equitably and safely.*

2.0 Catchment impacts on the Reef – what do we know?

The variety of land-based inputs which may threaten the health and stability of the lagoon and reef, can be categorised into three groups – sediments, nutrients and poisons (heavy metals and other toxins). The export of these materials from the land is influenced by rainfall, soil type, land cover and land use (Furnas and Brodie 1995). The change in land use patterns on Queensland's east coast, has not only made available more material for transport, due to inputs such as fertiliser and pesticides, but increased the rate at which they are lost from the land, since vegetation cover has been reduced.

The fate of contaminated materials entering the Great Barrier Reef Lagoon is still not well understood (Finlayson and Silburn 1995).

2.1 Sediments

Much of the change in land use in the catchments contributing to the Great Barrier Reef lagoon has involved both a reduction in vegetation cover and increased soil disturbance through cultivation, grazing, infrastructure development, roading and urban uses. This has resulted in higher rates of erosion and ultimately a greater sediment load in creeks, rivers and estuaries. Changes in catchment hydrology and use have also promoted changes to river morphology with river bank erosion contributing greatly to total bed load.

It is estimated there has been a total increase by 261% in the sediment in streams draining to the reef (Creighton et al 1996). This is possibly an underestimate of aggregate changes since European settlement. Grazing, particularly exacerbated by annual and prolonged drought conditions, contributes similar increases to that from cropping (Neil 1995).

It is suggested that up to 80% of eroded sediment stays within local drainage lines (Prove and Hicks 1991) and is then progressively reworked during major events. Highest sediment loads occur after storm events, when sediments previously trapped in drainage lines are reworked and transported downstream (Brodie and Furnas 1991) in addition to the transport off paddock through to the Lagoon of finer particles such as clays. The majority of river sediments are deposited in the near shore zone of the Great Barrier Lagoon and estuaries (Prove and Hicks 1991). Coarse particles are deposited closer to the shore while finer particles may reach up to 15 km offshore and during major events are observed in colloidal suspension on the Barrier Reef proper.

2.2 Nutrients

Agricultural, residential and industrial land uses across catchments all contribute nutrients to river systems. The three nutrients of major concern are carbon, nitrogen and phosphorus. Carbon is mostly connected with point discharges from sewage plants, sugar mills and abattoirs (Hunter and Rayment 1990). Carbon is readily quantified and data available suggest that carbon does not pose a threat in comparison to nitrogen and phosphorus.

The addition of nitrogen and phosphorus as fertilisers has increased with the expansion of agricultural lands and rate of increase in nutrient export from fertilisers is likely to be in the same order of magnitude as the increase in sediment load.

Moss and Rayment et al. (1993) estimated that there have been substantial increases in the quantity of nitrogen and phosphorus in waters from rivers discharging into reef waters since European settlement. While a proportion of this is from intensive agricultural activity and wastewater disposal, the largest total contributions are from the extensive grazing lands of the larger catchments – Burdekin and Fitzroy.

2.3 Heavy metals and other toxins

There is a large variety of potentially harmful materials which find their way from catchments to the Great Barrier Reef Lagoon – for example, pesticides, weedicides and heavy metals. In many cases such materials are sprayed or added to vegetation or the top layer of soil, leaving them extremely vulnerable to erosion in surface run-off.

Heavy metals are added to soil in fertilisers. Copper and zinc are added to the land intentionally as essential plant nutrients. The other important heavy metal, Cadmium, is not a plant nutrient, but is present in many phosphate fertilisers (Hunter and Rayment 1991)

In the Great Barrier Reef at present, heavy metals and other miscellaneous toxins are considered to be well below dangerous levels and therefore, thought to be insignificant (Hunter and Rayment 1991). There appears to be no real impact of heavy metals from catchments on the reef.

3.0 Catchment management and action

The Department of Natural Resources (and previously as the Department of Primary Industries) has sought to foster effective catchment management in priority areas like the wet tropics. This is being achieved using education; community, government and industry involvement and implementation of works and changed management practices.

Community involvement in catchment management and rehabilitation relies upon:

- development, promotion and acceptance of locally appropriate management practices by community based forums such as Catchment Coordinating Committees;
- lead agencies and groups such as Local Governments, River Trusts, Catchment Coordinating Committees and Landcare groups actively promoting particular management techniques through demonstration and works projects, and through enforcement; and
- peer influencing by individuals or groups

Through a range of extension and awareness mechanisms, the Queensland community have become increasingly aware of the multiple values of their catchment and river systems, the inter-related nature of these values, and the need for reduced downstream effects on the Great Barrier Reef.

3.1 Integrated Catchment Management process

Integrated Catchment Management aims to integrate the management of land, water, vegetation and other biological resources on a catchment basis to achieve the sustainable and balanced use of these resources (Queensland Government 1991). Integrated Catchment Management involves the community and government working together through Catchment

Coordinating Committees to develop and implement strategies for the better management of catchments.

The importance of catchment management to the long term health of the Great Barrier Reef has been recognised since the start of the Queensland Government's Integrated Catchment Management Program. The Great Barrier Reef Marine Park Authority was a foundation member of the State Catchment Management Coordinating Committee (CMCC), which oversees catchment management activities conducted under the auspices of ICM, and has also been an active participant in the Downstream Effects of Agricultural Practices sub-committee of the CMCC.

There are Catchment Coordinating Committees in the Mossman/Daintree Rivers, Barron, Russell/Mulgrave, Johnstone, Tully/Murray, Herbert, Pioneer, Fitzroy and Burnett catchments, all of which discharge into the Great Barrier Reef lagoon. These Committees are active in producing and then implementing Catchment Management Strategies that identify significant catchment issues and propose preferred ways of addressing these issues. Catchment strategies have been prepared by Committees in the Johnstone (Johnstone River Catchment Coordinating Committee 1994) Pioneer (Pioneer Integrated Catchment Management Association 1995) Russell Mulgrave and Herbert with a draft Strategy currently under review for the Fitzroy.

Catchment strategies have focused on the land vegetation and riverine based activities affecting the catchment. The extent to which they address potential concerns with the reef varies according to the information available on impacts and the nature of the changes needed to ameliorate these impacts.

Most actions to address in-catchment concerns have an impact on the quality and quantity of river discharges. For example soil erosion and stream bank erosion in the upper Pioneer river catchment are two issues targeted by the Pioneer Integrated Catchment Management Association. While the impact of sediment from the Pioneer on the reef is not quantified, by treating the causes of these problems, the benefits will flow on to the lagoon and reef.

Interest in catchment management has stimulated a range of monitoring, research and development projects in these catchments to improve understanding of the issues and to be able to better design strategies to reduce their impact. Over $1.7M of State funds has also been made available to Catchment groups who have prepared Catchment Management Strategies to implement on-the-ground works tackling key problems. Examples of works undertaken include:

- River rehabilitation and bank erosion control;
- Dairy effluent management systems;
- Riparian land revegetation and rehabilitation; and
- Provision of nursery infrastructure to support rehabilitation programs.

It is anticipated that as ICM grows to cover the remaining catchments discharging into the Great Barrier Reef lagoon, and Catchment Strategies are implemented over time, substantial reductions in land use impacts from catchments will occur.

3.2 Landcare action and property management planning

A third of the Landcare groups in the State are located in the catchments of rivers draining to the Great Barrier Reef lagoon. Groups of local landholders and other interested people comprise these Landcare groups. While their interests and activities vary, they are all working on improving the sustainable use of land and water resources in their area, generally on a farm by farm basis. A survey of issues of concern to Landcare groups in the region showed that 25% – 30% of groups felt water quality decline was a concern while 30% –33% identified timber clearing as a concern (Curtis et al. 1994). A range of activities, from weed control to property management planning and water quality monitoring form the key interests of these groups and all contribute to the lessening of impacts of land use upon the catchments and their receiving waters – the Great Barrier Reef Lagoon.

Action

The ability of Landcare to make rapid major changes in the catchments is determined largely by the availability of funds to carry out the necessary works. Generally funding for Landcare provided under the National Landcare Program has been restricted to planning, education, investigation and awareness building type activities. Where Catchment Coordinating Committees have endorsed catchment management strategies, some State ICM funding for on-ground works is being provided to groups to carry out strategic work consistent with the strategy.

Property management planning

Property management planning, a joint activity of the Departments of Primary Industries and Natural Resources, aims to help individual landholders improve their management skills, including their use of land, water and vegetation resources. It provides and has been used as a platform for the introduction of voluntary codes of practice for the beef, horticulture, dairying and sugarcane industries in the Wet Tropics.

Currently there are property management planning centres operating at Mareeba, South Johnstone, Ayr, Mackay and Rockhampton in the catchments of the Great Barrier Reef.

Whilst much has and is being done, much remains to be done in the field of improved farming systems. Research and development and most importantly demonstration of improved farming systems is required in all industries to foster voluntary adoption of improved techniques. To support these community based initiatives, a number of research and investigative projects have been conducted.

Green Cane Trash Blanketing Benefits the Reef

> *From a 'new technology' perspective, the most significant gains have been in the management of sugarcane, where under green cane trash blanketing, soil losses can be reduced from 47–505 t/ha.year to <15 t/ha.year (Prove et al. 1995). In 1994, 58 % of the cane harvested in the catchments of the Great Barrier Reef was green although the proportion varied from 1% to 98%, the highest proportion was in the Herbert river catchment. By 1996 virtually all the cane harvested in the Wet Tropics was harvested green and with in excess of 50% harvested green in Mackay Whitsunday..*

3.3 Waterwatch

Waterwatch is a community-based water quality monitoring program which encourages widespread community participation in monitoring the riparian and instream condition of our waterways (rivers, lakes, groundwaters and estuaries). This often results in community groups taking on-ground remedial action to address identified issues. Resources such as the Waterwatch Queensland Technical Manual are available to Waterwatch groups and a collaborative approach to dealing with issues is encouraged. Through an ethical approach the program helps to instil a sense of ownership by the whole community of catchment management issues.

Waterwatch programs in the Far North and the Mackay district help to create an awareness of the significance of water quality issues in catchments that can have serious impacts on the Great Barrier Reef. The data produced has been used as a basis for discussion and planning at community meetings to develop and implement local strategies to address water quality issues. In Far North Queensland a full time Waterwatch coordinator, employed by the Department of Natural Resources, works with 12 community groups across seven catchments in assessing the condition of their local waterways. Approximately 200 volunteers are involved in the program which examines the biological and chemical parameters at over 130 sites. Quality Control procedures ensure the reliability of the data collected. In Mackay, a part-time Waterwatch coordinator employed by the Pioneer ICM group (using funds from the national Waterwatch Community Grants program), works with 4 community monitoring groups and coordinates an education program within the local schools. Catchment reports which have been prepared using the Waterwatch data provide valuable community input into local strategies addressing water quality issues.

3.4 Partnerships

All of this community activity relies upon close partnerships of community groups (such as Landcare groups and Catchment Coordinating Committees) and Commonwealth, State and Local authorities. It is important that they are consistent and focused in their approach to catchment management, providing both the technical base and the catalysts for community action. The foreshadowed change in focus of the National Landcare Program should provide the opportunity for additional funding of these essential activities of catchment management and repair with their flow-on benefits for the Great Barrier Reef Lagoon.

4.0 Department of Natural Resources activities

The Department of Natural Resources has and continues to undertake a wide range of activities relevant to the quality and quantity of catchment run-off. Several of the more significant activities are:

4.1 Research

With commencement of the Integrated Catchment Management (ICM) initiative in Queensland, the need to provide technical support for communities, particularly in 'pilot' catchments was recognised. Priorities included the assessment of in-stream and riparian condition, links between land use and water quality, and the extent to which pesticides and heavy metals were impacting on the aquatic environment. For example, a detailed water quality monitoring network was established at multiple sites in the Johnstone River Catchment, North Queensland (Hunter 1992), while a desk-top assessment was made of the 'State of Queensland rivers' (Department of Primary Industries 1993). A DEAP Technical Sub-committee of Queensland's Catchment Management Coordinating Committee was formed to provide strategic advice and to develop action plans on priority issues and challenges listed in the DEAP Strategic Plan 1995–1998. Some of the research and monitoring initiatives undertaken in recent years that are linked to the Great Barrier Reef and its Lagoon are summarised in the paper in table 1.

4.2 Water monitoring

The Department is responsible for monitoring water quality and quantity in non-tidal streams, storages and groundwater systems and undertakes this via networks of monitoring stations.

4.2.1 Streamflow

Streamflow is measured on a continuous basis at some 460 automatic streamgauging stations in Queensland. Of these, some 254 streamgauging stations are located within the catchments that drain to the Great Barrier Reef and its Lagoon.

Each station uses modern solid state logging equipment which has replaced the electromechanical recorders of the past. Apart from greater reliability and flexibility in use the new equipment enables a range of parameters to be measured concurrently as well as the use of telemetry to provide for remote interrogation of stations from anywhere in the State. Some 80% of stations are currently connected to telemetry. Rainfall (210 sites) and climate data (10 sites) are also measured which augments data collected by the Bureau of Meteorology. The streamflow data (some 20 000 station years of information) is stored on comprehensive databases located in 8 district offices in the State..

4.2.2 Sediment measurement

More recently a program has been implemented to measure sediment loads in streams. Both suspended sediment and bed load is measured. A methodology and procedure has been developed and a program designed to obtain measurements in some 14 priority catchments which include the Mulgrave, Russell, Tully, Herbert, Black, Don, Fitzroy and Isaac Rivers. Useful measurements have been carried out in some 8 streams over the last 2 to 3 years.

4.2.3 Groundwater

Groundwater levels are monitored regularly at around 4000 subartesian monitoring bores in Queensland and at a further 280 artesian bores. Of the catchments draining to the Great

Barrier Reef, significant monitoring bore networks exist in the Mackay, Bowen, and Lower Burdekin areas.

The data, which has been collected over many decades, is stored on a purpose designed database accessible in most of the Department's district offices.

Table 1. Selected research and monitoring activities undertaken in Queensland to support Integrated Catchment Management

Project	Comment
Monitoring nutrients – Coastal Rivers (1991–1996)	Focus on surface waters of Johnstone Catchment, Nth Qld.
Pesticide and toxic heavy metal monitoring in aquatic fauna, North Qld coastal rivers	Commenced 1991. Less detections at lower concentrations than found in an earlier survey.
Inventory of fish resources / riverine condition assessment, Johnstone River Catchment.	Commenced 1991. Ratings made at 200 sites throughout the catchment, covering five zones.
Nutrient balances and transport, Johnstone River Catchment.	Project designed to measuring nutrient losses from sugarcane, banana, pasture and rainforest lands, and to devising fertiliser management strategies which minimised these losses.
Pesticide and fertiliser use audits..	Comprehensive audit of pesticides (insecticides, fungicides, herbicides) done for the Pumicestone Passage and Condamine-Balonne Catchments, and for the Qld Sugar Industry. Also historical fertiliser-use audits for coastal Qld, Condamine-Balonne and Border Rivers of Qld.
Nutrient control in irrigation drainage systems using artificial wetlands	Four constructed wetlands in Lower Burdekin Irrigation Area. Effectiveness of different wetland designs being evaluated.
Pesticides in cotton and sugar production systems.	Cotton system studied in Emerald Irrigation Area 1993–1996 as part of national program. Sugar studies about to commence in Bundaberg and Innisfail.
Heavy metal surveys.	Completed for Qld soils used for vegetable production; current for heavy metals in Qld canelands.
State of the Rivers Surveys – Qld	Current surveys and reports cover the Maroochy, Upper Condamine, Dawson, and Herbert River Systems.
Monitoring river health – macro-invertebrates.	State wide (Qld) survey as a component of a nation-wide strategy.
Sediment and nutrient losses from grazing lands	Action planning by DEAP Committee
Data-base on DEAP	PC based database of technical and user information on DEAP issues and findings.
Decision support.	Catchment-scale decision support models designed to benefit ICM and natural resource management. Work in Barron and Johnstone River Catchments is current.

Note: For details of the first three mentioned papers, see: 'Land Use Patterns and Nutrient Loading of the Great Barrier Reef Region' ed. D. Yellowlees (James Cook University of North Queensland, Townsville).

4.2.4 Water Quality

Chemical water quality has over several decades been sampled routinely but infrequently, at stream gauging stations and monitoring bores. The water quality data obtained have generally only been suitable for analysis of major ions because of the less than optimum sampling conditions and, in the case of streamflow, because the samples were taken mainly during low flow conditions.

In the last few years efforts have been made to direct greater priority to improving the comprehensiveness and quality of water quality monitoring in non-tidal streams, storages, and groundwater. This has included the design of ambient monitoring networks, the equipping of selected gauging stations and bores with conductivity, temperature and pH sensors to continuously monitor the status of streams and some aquifers and the monitoring of water quality in storages as well as routine field sampling. Specific measurement has also been undertaken in coastal aquifers to monitor the possibility of sea water intrusion. Separate water quality monitoring networks have been progressively designed in each of the major irrigation areas and projects.

Some 170 ambient surfacewater quality stations are monitored by DNR of which some 79 are in catchments adjacent to the Great Barrier Reef and its Lagoon. All the sites are at existing gauging stations to enable concentration and flux to be measured. Field sampling is carried out at each of the sites which are also equipped with continuous measuring probes and in some cases automatic samplers. The sites typically measure pH, temperature, major ions, nutrients, chlorophyll 'a' and metals. The program provides for the monitoring of pesticides or other parameters as required. As part of the manual sampling both water and mud samples are collected and analysed.

The data is stored on the Department's HYDSYS water quality database which is expected to be operational by March 1997. Both hard copy and electronic outputs will be available with the option of CD-ROM format being considered.

The Department of Environment also carries out an ambient water quality monitoring program of fresh and estuarine waters, although it generally focuses on estuarine waters.

A Water Quality Monitoring Steering Group with representatives from DNR, DoE, GBRMPA, Brisbane City Council and community groups was established about one year ago to provide a focus and facilitate the coordination of water quality monitoring in the State.

4.2.5 Monitoring River Health Initiative

The Department is also currently involved in the Monitoring River Health Initiative of the National River Health Program. This joint State/Commonwealth Initiative, which highlights the ecological role of rivers, is seeking to develop a standardised biological assessment scheme for evaluating river health based on macroinverterbrate community data.

The project commenced in Queensland in 1994 and involves monitoring of 200 reference and 20 monitoring sites in 27 major catchments (including those draining to the Reef). The biosampling process has been completed and currently a model is being constructed which will be used as a predictive tool to aid in decision making. The program has also proven useful in providing relevant information to the Water Allocation and Management Planning process and other related initiatives. The Commonwealth has recently extended the program for another year, and depending on the needs of the predictive model further continuance of the monitoring program will be considered.

4.3 Development of Guidelines for Works on Floodplains

The objective of these Guidelines developed for the Wet Tropics is to ensure coordinated development of agriculturally sustainable land, with minimal adverse impacts on the broader environment (both natural and existing developments). Equally important, the Guidelines provide a basis for a consistent approach by all agencies and community groups.

The Floodplain Guidelines are based upon 5 principles, as follows:

Principle 1: Consider Multiple Values and Uses of the Floodplain
Principle 2: Understand the Natural System, both hydrological and ecological components.
Principle 3: Evaluate and justify Land Development Proposals, both regionally and locally
Principle 4: Compile and Refer to a Catchment Plan
Principle 5: Maintain Key Natural Areas and Processes

The Principles ensure that development occurs in a rational and integrated fashion with priority given to maintaining and enhancing key natural areas and processes.

Implementation of the guidelines relies on action by Sugar Cane Assignment Committees, Shire Councils, Catchment Coordinating Committees, River Improvement Trusts, Drainage Boards, Landcare Groups and Industry Organisations. The Guidelines target these key industry bodies to assist in their decisions and projects and it was in partnership with these bodies that the Guidelines were developed.

The Guidelines have been finalised and will be printed and distributed to local governments, State departments, statutory bodies and interested organisations in the wet tropics.

4.4 River management

The Department plays an active role in assisting and facilitating riverine management. Two areas are riparian zone research and support for River Improvement Trusts.

Riparian Zone Research

In partnership with the Commonwealth's Land and Water Resource Research and Development Corporation (LWRRDC), the Department is undertaking applied research into a number of riparian zone issues. In the Johnstone River Catchment, the role of riparian vegetation in filtering out sediments and nutrients from entering the river system is being studied at a number of sites (Reference list attached). Early indications from this work are that the smaller first order drainage lines play a vital role in reducing inputs. These gullies and small streams are the major entry points for run-off and so logically are the best places to filter out undesirable sediments and chemicals. Mixes of grasses and woody vegetation in the riparian zone are being trialled to determine optimum arrangements for trapping sediments (in grasses), absorbing chemicals (by infiltration and then removal by larger vegetation) and providing ecological values (habitat, food sources, etc).

Also in the Johnstone, trials looking at the impact of shade on the growth of macrophytes (para grass) within drainage lines and streams indicate that the invasive grass can be controlled with shade (Reference list attached). Hence the re-establishment of riparian canopy cover will help to remove this pest weed which proliferates in drainage lines and reduces the flow-carrying capacity of the feature. The study also found that para grass provides very little energy to the riverine environment and so its removal will have virtually no impact on in-stream food webs.

These research projects are part of a national research and development program which has a goal 'to develop guidelines and demonstrate practices for the effective and economic management of riparian zones in order to help maintain and improve the condition and values of streams, wetlands, lakes, and their associated terrestrial ecosystems'. The function and values of riparian lands in stabilising stream banks, improving water quality and enhancing wildlife ecosystems are being analysed and communicated to industry, government agencies, community groups and landholders across Australia. Without this effort in developing effective design and management strategies for riparian lands, we will continue to rely only on empirical evidence and trial and error. In the short term, the program will act as a broker and disseminator of our current best practices and innovative management strategies.

River Improvement Trusts

River Improvement Trusts are statutory bodies charged with the management of the bed and banks of streams. Currently there are 11 Trusts in catchments draining into the Great Barrier Reef Lagoon. They are set up on a Shire basis and hence may be concerned with more than one river. Typically River Improvement Trusts carry out works that enhance or maintain the river flow and drainage function of rivers.

Concerns about the lack of longer term planning of Trust activities, led the Department to encourage and assist Trusts in the preparation of strategic river management plans. These plans were to take a long term view of the management of the rivers, their behaviour and

current issues, and recommend a plan of action for strategic works. Environmental and other impacts were to be considered in the recommended actions.

To date seven of the eleven Trusts have prepared Strategic Plans. These are the Mulgrave Shire, Cardwell Shire, Herbert, Burdekin, Pioneer, Upper Pioneer (Mirani Shire) and Proserpine (Proserpine and O'Connell Rivers). While receipt of a State Government subsidy on approved trust works (25%) is not dependent on the strategic plan, Trust plans can be used to support and justify funding applications. The Department generally given higher priority to those applications which are consistent with approved strategic river management plans.

Increasing scrutiny of the impact of river works and requirements for greater detail and planning in funding applications is moving Trusts toward works and activities that deliver benefits to the environment while enhancing the hydraulic function of rivers.

Trust work in stream bank stabilisation has highlighted attention on the substantial contribution of stream banks to suspended and bed load sediment. This continues to be a major component of Trusts work although `softer' engineering solutions are now being integrated with traditional techniques in stabilisation works.

4.5 Planning

4.5.1 Water Allocation and Management Planning

As outlined in the Council of Australia Government's Water Reform Agenda agreed to in February 1994, serious limitations and problems are emerging in certain parts of Australia as competition for scarce freshwater water resources increases and the need for environmental flows becomes recognised. In response the Department has established a Water Allocation and Management Planning (WAMP) framework. The planning framework (see figure 1) will provide a clearer and more integrated approach to the allocation of water resources on a catchment or water basin basis and will lead to greater certainty over entitlements for all water users (including the environment).

The identification and management of water for ecosystems, as environmental flows, will assist in the maintenance of water quality in-stream and provide for the discharge of needed fresh water into reef waters.

The preparation of Water Allocation and Management Plans (WAMP) is based on the best available ecological, economic and social data. Particular emphasis is placed on determining the nature of environmental flow requirements. Once finalised, WAMPs will become the water allocation policy for the plan area, so that the Department's decisions on the taking of water for consumptive uses and the management of flows for agreed environmental needs must not be inconsistent with the plan. Under the proposed Natural Resource Management legislation currently being considered, it is intended that following the completion of the planning process (figure 1) the WAMP for a catchment or basin would become a statutory plan.

Catchment Coordinating Committees assist in the WAMP process by advising on community and industry consultation efforts in the process. The community reference panel is an integral part of the WAMP process.

Currently WAMPs are being prepared for the Barron and Fitzroy River systems as well as several others in southern Queensland. WAMPs will be prepared in other river systems on a priority basis. It is planned that WAMPs will be prepared for the Burdekin and Pioneer River catchments in the near future, commencing next year. They require a major commitment of Departmental resources and the commitment of the community in the consultation process.

4.5.2 Planning and Environment assessment and coordination

The Department, through its Resource Management Program, has the lead agency role for coordinating the assessment of all water infrastructure and commercial forest operations and development proposals, and as appropriate to the particular operation or development proposal, either make recommendations to Government on the natural resource

sustainability of the proposal or make decisions under the relevant legislation. This is a growing area of activity for the Department which will need to be delivered in a timely and constructive manner. In relation to the Great Barrier Reef and its Lagoon, this role is of particular significance in the short to medium term in the Fitzroy, Pioneer, Burdekin, and Barron River catchments.

Figure 1 **WATER ALLOCATION AND MANAGEMENT PLANNING**

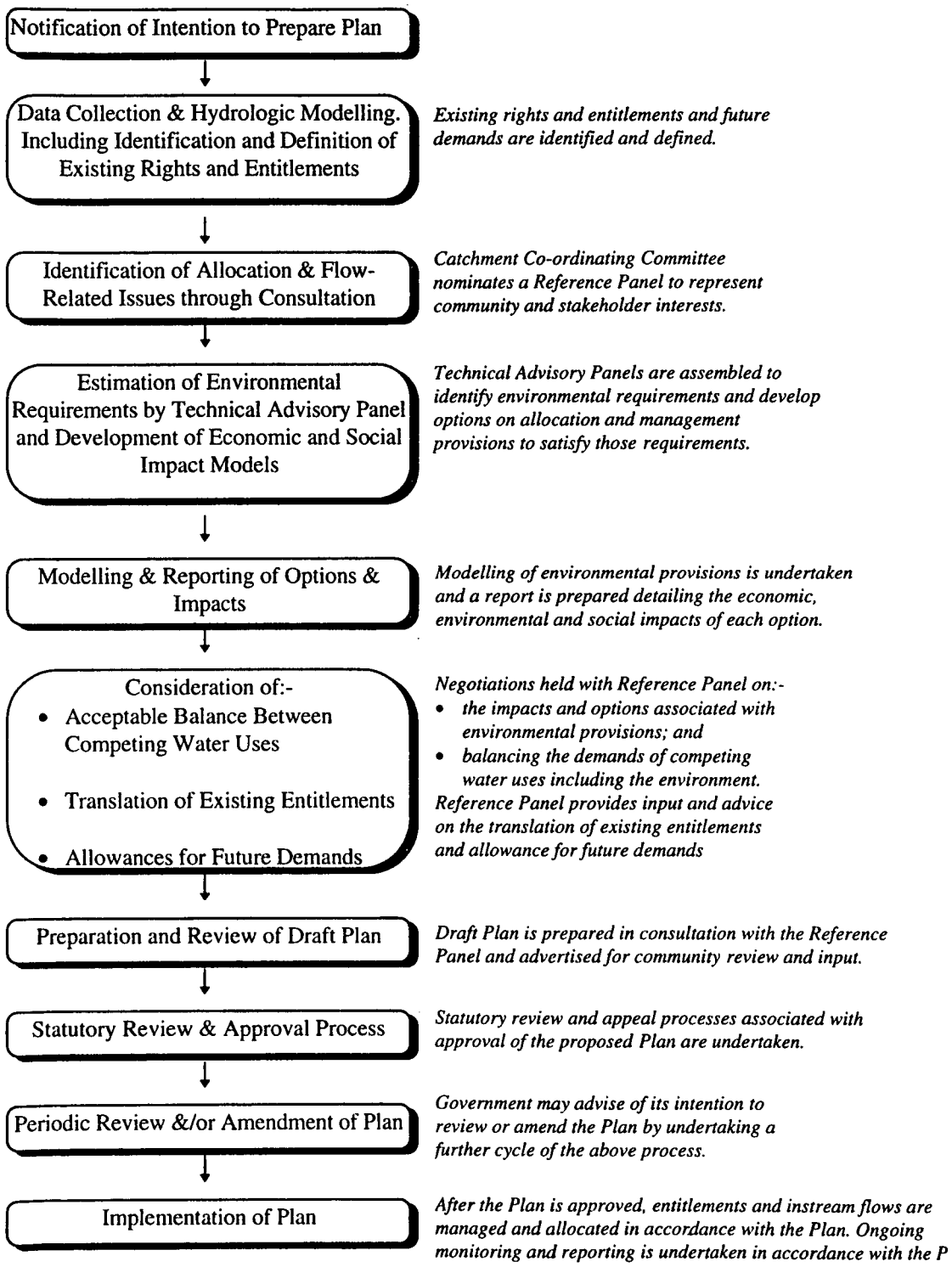


Figure 1. Water allocation and management planning

Further, as a referral agency for land use development applications lodged with local governments, the Department has a key role in identifying possible adverse impacts on the reef. Advice on land suitability, drainage (particularly acid sulphate soils), effects on surface and ground water and soil degradation is provided. The Department also plays a key role in providing information and advice for the preparation of planning schemes and development control plans by local governments when needed.

4.6 Management and regulation

4.6.1 Allocation and management

While the emphasis in catchment management in Queensland is on cooperative community and government action to protect and manage these important resources, enforcement provides a backup as a 'last resort' to ensure appropriate practices are undertaken by all.

For example the *Water Resource Act 1989* provides mechanisms to regulate and where necessary prosecute inappropriate actions in the following key areas:

- use, flow and control of water in watercourses, lakes and springs;
- extraction of quarry materials from watercourses and lakes;
- native vegetation, excavation and placement of fill in watercourses;
- use of groundwater in declared areas;

Regulation is achieved through licences and permits with conditions to ensure works are appropriate. Notices are issued to remove inappropriate works and rehabilitate areas affected by unauthorised works. Offence provisions provide for fines and removal of works to deter unauthorised works.

The Department is developing proposals for Natural Resource Management legislation to replace the *Water Resources Act 1989* and associated Acts. This legislation is proposed to provide for the allocation of the State's water and forest resources and for their on going sustainable management. It will also provide for a coordinated approach to resource management including the establishment of catchment coordinating committees, preparation of resource allocation and management plans, plans to deal with critical areas as well as regulatory provisions.

4.6.2 Water infrastructure projects

As already noted, it is the role of the Resource Management group of the Department to set the conditions under which a resource can be allocated and used by a developer/operator, and ensure appropriate codes of practice are developed and adopted. Developer/operators will also need to comply with specific environmental requirements as outlined in the *Environmental Protection Act* and *Nature Conservation Act* as administered by the Department of Environment.

Planning for new proposals require consideration on the need for and detail required in an Environmental Impact Assessment of the proposal. The Department's Resource Management group will be responsible for coordinating the terms of reference and ensuring input from other agencies and stakeholders is considered. Resource Management will also be required to specify resource management related constraints including the management and use of natural waterways and the installation and maintenance of licensable works.

Projects will require an Environmental Management Plan that addresses concerns raised in the impact assessment. Coordination and detailing the specification of monitoring required in the EMP as is the responsibility of Resource Management in DNR. This group is also charged with oversight of compliance with the monitoring program.

The lessons learned from the Sugar Industry Infrastructure Package have helped shape the current approach (see Box over page).

5.0 Concluding comments

The Department of Natural Resources, through a range of programs and initiatives is committed to ensuring the use of land, native vegetation and water resources in catchments does not adversely affect the values of the Great Barrier Reef.

The Department is able to make a significant contribution not only to knowledge about catchment processes and their impact on the reef, but also to the use and management of those catchments. The Department seeks to operate in a partnership approach with all stakeholders due to the complexity of the natural and man made systems to be managed.

Queensland Sugar Industry Infrastructure Package (SIIP). an example of responsible development

On 26 November 1993, the Federal and State Governments jointly announced the Queensland Sugar Industry Infrastructure Package.

Twelve projects were selected for funding under the Package, subject to more detailed environmental assessment and development of Environmental Management Plans. The approval is subject to conditions with respect to environmental planning approvals being met, industry sponsors being able to meet capital contribution requirements and institutional arrangements to form a local Water Board.

The total expenditure on these twelve projects will amount to approximately $117 million of which $38 million is being provided jointly by the State and the Commonwealth, $45 million from the sugar industry and a further $34 million from the State. Funding form the Package are only available until the 30 June 1997.

The Projects being funded by the Package include two (2) major water storages (Teemburra Dam near Mackay and Walla Weir near Bundaberg), and ten(10) projects for irrigation, water management (mainly drainage works), and cane transportation (mainly new tramway systems) in Babinda and Mulgrave areas, Tully area and Herbert River Valley, the Burdekin, Mackay region and Sarina, Bundaberg district and Hervey Bay.

The responsibility for administrating the Package rest with the Department of Natural Resources. A Review Committee of Industry and State and Federal Government representatives has been established to oversee the process of negotiation with project sponsors and proponents to achieve unconditional approval and implementation.

An Environmental Working Group for the Package (representative of Industry, State and Federal Government representatives) has also been established to deal with environmental planning issues relevant to the projects.

The objective of the environmental process for the successful projects is to ensure that the projects are ecologically sustainable, consistent with the best land management practice and comply with both the Commonwealth and State Environmental Legislation.

Formal Implementation and Administration Agreements will be prepared when final environmental approval is granted for each project. These Agreements will contain Environmental and Land Management Requirements (i.e. environmental protection measures, safeguards and cover all recommendation by the Department of Environment and the Commonwealth Environment Protection Agency) that need to be adopted during the construction and operation of the works.

NB: During the reviews of the SIIP projects comments are sought from a number of advisory bodies and emphasis has been given to the importance of water quality management so as to avoid degradation of the Great Barrier Reef Marine Park. Other matters that are being addressed in respect of SIIP irrigation projects include, the importance of ensuring that on farm work is adequately supervised: ensuring that drainage works are integrated; provision of adequate environmental flows; groundwater assessment and protection from contamination; and implementation of coordinated environmental planning processes in line with COAG Water Resources Policy reforms and ESD principles.

Catchment management is a partnership enterprise. This partnership is based upon an awareness of the multiple values of catchments, a commitment among agencies to work with the community and the implementation of a range of initiatives which engender individual

and community stewardship of natural resources. Much remains to be done. A commitment by all stakeholders to work together is essential.

While many of the gross impacts of changed land use in the catchments of the Great Barrier Reef have been identified and some quantified, there is still a lot unknown about the effects of land use changes and management on coastal and reefal communities. As this understanding grows catchment management guidelines and practices will move from a precautionary 'best bet' approach to a more solid information based approach.

Important land and water management initiatives are underway to address the issues of soil erosion, pasture management, vegetation rehabilitation, water management, and riverine management. More will be needed. Incentives for both government and private land and water managers need to be continued and further developed.

The 25 Year Strategic Plan for the Great Barrier Reef World Heritage Area recognises the need for careful management of the reef and those areas with significant impacts on the Area. While many of the direct uses of the reef have obvious and often significant impacts on the reef the long term and potentially more deleterious impacts of adverse catchment management practices and uses highlights the importance of achieving sustainable catchment management and use. Accordingly the three tiers of Government through their respective agencies must continue to work cooperatively and with the community for the long term sustainability of the Great Barrier Reef and its adjoining catchments.

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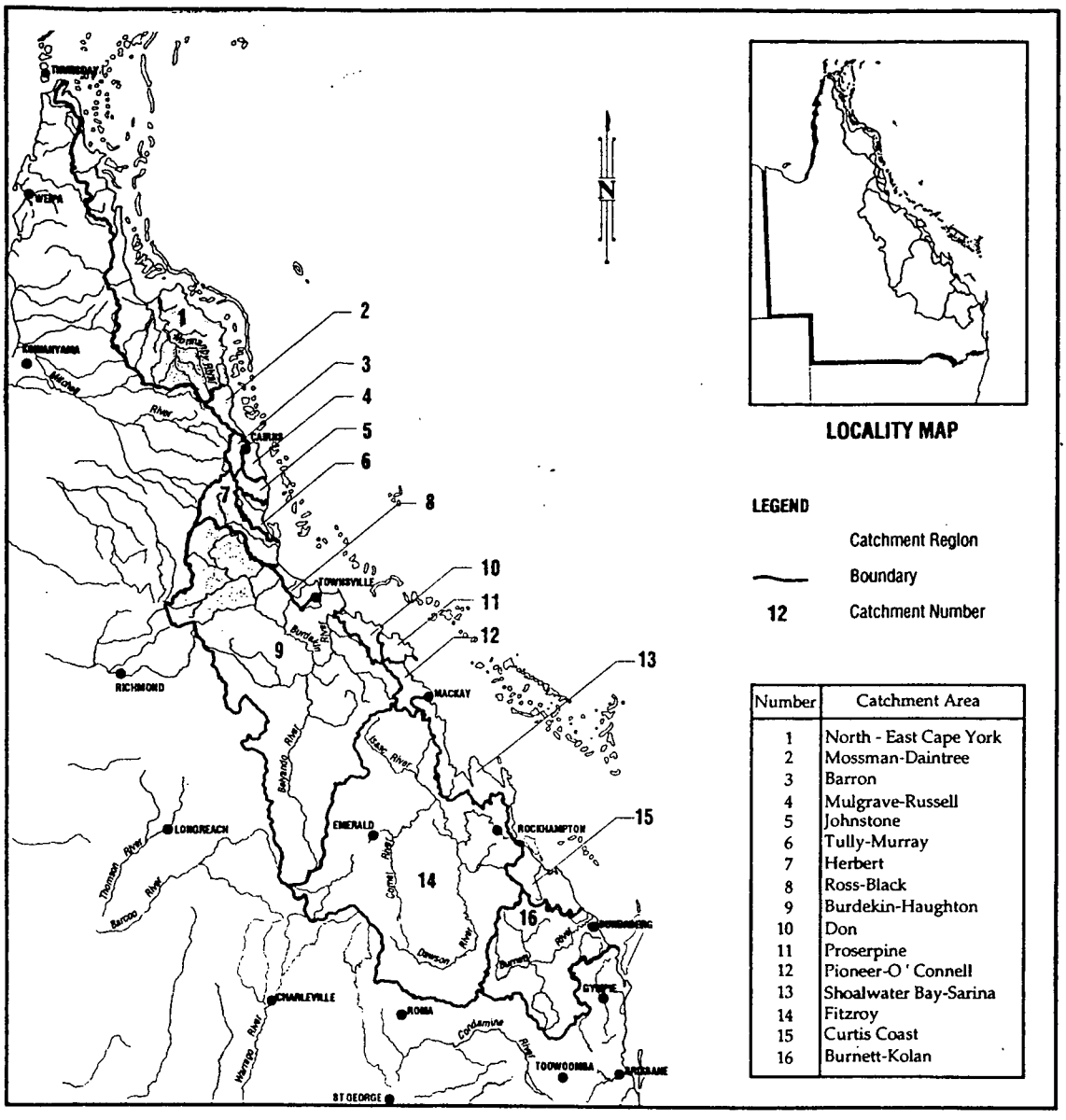
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PROGRAM STRUCTURE

PROGRAM	SUBPROGRAMS
LAND ADMINISTRATION	• Land Interests & Titling • Aboriginal & Torres Strait Islander Land Dealings • State Land Administration
RESOURCE MANAGEMENT	• Land Planning • Land Management • Land Protection • Water & Catchment Management • Forest Resources • Community Land Use
LAND INFORMATION	• Surveying & Mapping • Valuations • Land Information Management
REGIONAL INFRASTRUCTURE DEVELOPMENT	• Regional Infrastructure Planning • Water Industry Development • Water Infrastructure Development • Water Infrastructure Operation
CORPORATE MANAGEMENT	• Executive Services • Strategic Services • Business Services
LAND COURT & TRIBUNALS	• Land Court • Land Tribunals *(Please Note: DNR has no influence over the strategies or policies of the Land Court and Land Tribunals which plan and report independently. They are included here as their funding is allocated via the Department).*



Number	Catchment Area
1	North - East Cape York
2	Mossman-Daintree
3	Barron
4	Mulgrave-Russell
5	Johnstone
6	Tully-Murray
7	Herbert
8	Ross-Black
9	Burdekin-Haughton
10	Don
11	Proserpine
12	Pioneer-O ' Connell
13	Shoalwater Bay-Sarina
14	Fitzroy
15	Curtis Coast
16	Burnett-Kolan

Effects of sugarcane growing on the environment

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ABSTRACT

In recent years, the potential for environmental impact from primary production has caused increased public concern. Issues include land degradation through erosion, salinity, acidification or contamination, and deterioration of ground and surface water quality through excess nutrients, chemicals, salinity and soil run-off. Noise, air pollution and loss of habitat and species are also community concerns. There is an increasing awareness among farmers generally of the need to remain environmentally sustainable and economically viable.

As the peak body representing all cane growers, CANEGROWERS continues to play a leading role in environmental issues. Ways in which growers have responded positively to changing community expectations about the environment are outlined.

An independent environmental audit of canegrowing practices, commissioned by CANEGROWERS, marks the start of a new era in resource management for the industry. The results of the audit are discussed.

The audit will ensure that changing community expectations about the environment are taken into consideration as the industry moves away from the legacies of past practices which were not always sustainable in the long term.

With the benefit of hindsight and improved knowledge, farmers, scientists and governments now recognise that some commonly used practices are no longer appropriate. However, attitudes and practices which are deeply established in the national culture can not be changed overnight. It will take time and money.

The environment is not just an important issue for cane growers. It is of vital concern to all Australians and the whole community must play its part. If we as a nation want certain changes in the way things are done we must all be prepared to share the cost, not just those landholders who are closest to the problem.

Industry growth

From modest beginnings over 130 years ago, the Australian raw sugar industry has developed into one of the world's largest exporters and is now one of Australia's most important rural industries.

Earnings exceed that of all other crops except wheat and the sugar industry now has surpassed beef cattle as Queensland's biggest rural industry. It provides economic stability for many cities and towns, securing jobs and underpinning regional growth.

Income from the Queensland industry, which produces over 95% of Australia's raw sugar, exceeded $1.76 billion in 1995–96 with over $1.65 billion in exports. The Queensland Sugar Corporation was the State's second largest exporter.

Since 1988 the industry has undergone considerable deregulation, resulting in greatly increased production, both from existing canelands and new areas. Land assigned for canegrowing has increased by nearly 125 000 hectares or 35%.

Scarcity of ideal agricultural land has resulted in more marginal land being utilised. Although greater financial and physical inputs (such as irrigation) are needed to maintain overall productivity and profitability, improved technology has allowed these areas to be brought into production economically.

Environmental concerns

In recent years, the potential for environmental impact from primary production has caused increased public concern. Issues include land degradation through erosion, salinity, acidification or contamination, and deterioration of ground and surface water quality through excess nutrients, chemicals, salinity and soil run-off. Noise, air pollution and loss of habitat and species are also community concerns.

There is an increasing awareness among farmers generally of the need to remain environmentally sustainable as well as economically viable.

Environmental issues are particularly important to cane growers because their expanding industry is located close to large centres of population, coastal streams and the Great Barrier Reef. The canegrowing industry recognises that it must balance growth and productivity with responsible use of land and water.

The growers' organisation

As the peak body representing all cane growers, the CANEGROWERS organisation continues to play a leading role in environmental issues. It represents growers' interests on many diverse bodies at national, state and local level.

Ways in which growers have responded positively to changing community expectations about the environment include:

- commissioning of a comprehensive independent audit of how canegrowing practices affect the environment;
- development of voluntary guidelines for sustainable canegrowing;
- increasing involvement in Landcare and Integrated Catchment Management initiatives (in 1995 CANEGROWERS was awarded a State Landcare award for its 'significant contribution to raising awareness and understanding of land care').
- widespread adoption of green cane harvesting and trash blanketing (in 1995, green cane harvesting and trash blanketing exceeded 50% for the first time and in 1996 is expected to exceed 55% of the total crop);
- acceptance of the need for training for the safe use of agricultural chemicals (more than 70% of growers have completed voluntary accreditation courses).
- support for environmental initiatives such as the establishment of the Cooperative Research Centre for Sustainable Sugar Production.

Industry research

The sugar industry spends an estimated $38 million a year on R&D – about $1 a tonne of cane. An increasing amount focuses on environmentally related issues; CANEGROWERS strongly supports increased R&D funding for sustainability issues and initiatives.

Although sugar production is just one of many factors impacting on the environment, the industry has come under particular scrutiny over its possible effect on the coastal and marine environment.

Although the presence of nutrients, sediments, herbicides and pesticides in coastal waters is not disputed, the origins of these substances have not been clearly identified and their effect on the marine environment is not fully understood. The sugar industry is playing a leading role in a number of joint projects designed to provide more factual information on these matters.

Nutrient losses in integrated catchment management situations are being assessed in the Johnstone and Herbert River valleys. These studies are complemented by continuing projects to monitor pesticide residues in the sugar industry and to monitor nutrients and

pesticides in surface drainage water and soil in irrigated sugarcane. New industry research projects will capitalise on these monitoring projects through optimising nutrient management in sugar industry catchments, and examining pesticide transport in sugar production systems.

Environmental audit

A recently completed environmental audit of canegrowing practices will form the basis for an ongoing CANEGROWERS environmental management strategy and influence the drafting of guidelines for sustainable canegrowing and the development of an industry-wide environmental management plan.

In June 1995 CANEGROWERS commissioned Gutteridge Haskins & Davey to carry out the audit to assist growers to manage environmental impacts of their activities according to world recognised best practice.

The objectives were to:

- document how current canegrowing practices are impacting on the environment,
- measure the adoption of sustainable farming practices by ordinary cane farmers,
- identify attitudes and concerns in the broader community, and
- consider any actions which may be necessary to address those concerns and to ensure long-term sustainability.

The snapshot of the industry provided by the audit gives a reliable benchmark against which future progress can be measured.

The audit, which was confined to canegrowing practices (not sugar milling, refining or marketing), comprised two elements.

1. The audit team evaluated the perceptions and opinions of 180 stakeholders from all tiers of government, conservation groups, Landcare and Integrated Catchment Management Groups, research organisations, canegrowing and sugar milling organisations, recreational and commercial fishermen, community groups, small crop farmers, and Aboriginal groups.

2. The audit team visited 130 cane farms in all areas from Mossman to Beenleigh, interviewing the owners/managers and observing environmental management practices.

Responsiveness to change

The consultants believed there was a major need for further education and consultation by the industry with the various stakeholders to firstly understand the community's concerns and secondly to communicate the positive environmental management and pollution control incentives which the industry already practices.

Approximately 63% of the non-growers stakeholders who were interviewed considered that current environmental management practices of cane growers needed improvement. However, there were some areas in which the industry was performing very well, e.g. green cane harvesting and trash blanketing and chemical accreditation training.

The current level of environmental awareness in all regions was judged to be relatively low e.g. 23% of growers audited were not aware of industry codes of practice. Apart from some districts, there was a need for the industry to secure attitudinal changes amongst growers through better education processes and more effective transfer of technical information.

Generally the audit team found that growers would like to do 'the right thing' by the environment but they did not possess sufficient information or knowledge to do so. In some instances, cane growers are suffering the legacy of poor management practices in the past

when environmental regulation, community awareness and scientific information was not available.

Air emissions

Air emissions were rated as a low priority by 64% of all stakeholder respondents.

The move to trash blanketing which generally accompanies green cane harvesting was seen to provide a number of benefits: it slows weed growth, conserves moisture in the soil, recycles nutrient and organic matter and helps reduce soil erosion.

Although it was generally agreed that trash fires cause more problems than pre-harvest cane fires, the majority of stockholders regarded green harvesting (which in some areas requires burning of trash) as a better option from an environmental viewpoint.

The audit found that while aerial spraying was limited to only a few district and at certain times, it represented bad public relations for canegrowing. However, there was no factual evidence that the very limited 2,4-D aerial spraying was damaging other crops. Cane growers considered that perceived impact was causing more concern than actual damage.

Land management

As the industry expands, land management issues need to be considered to ensure productivity and profitability in conjunction with sustainable development.

The integrity of the assignment system was of concern to some stakeholders. A perception exists in the community that assignment boards act too quickly and that the potential for vertical expansion from existing land is not adequately assessed before granting additional assignment on new land.

Expansion on to marginal land was causing concern. The 'tenuous and fragile nature' of some soils is of concern to some stakeholders who believe that some growers are still planting cane on steep slopes thereby causing erosion and soil losses. Soil erosion was seen as a significant problem by 34% of the research community. Soil erosion was seen as a direct result of deforestation and degraded riparian zones.

The report considered that management practices should be developed and adopted by the industry to minimise soil erosion in creeks and drains and river banks and extension of management and protection practices for the riparian zones is required. Expansion into marginal low-lying areas should be restricted until full soil analysis is undertaken and the area's unimproved suitability for canegrowing is assessed.

The issue of farm expansion was seen by many stakeholders as having potentially high impact; 49% of respondents considered that clearing for expansion was a high priority issue and 56% considered riparian zones to be a high priority issue.

Although cane farming has thinned riparian corridors which are critical for river health, bank stability and fauna habitats, some growers were seen to be actively revegetating these corridors.

Conservation groups consider that the benefits of riparian zones are poorly understood by many farmers. Riparian damage was perceived to have a direct consequence on soil and river and creek erosion.

About 45% of stakeholders saw canegrowing as having a negative effect on fauna and flora in Queensland.

The report stated that the industry needs to increase education of growers about appropriate soil management and the inter-relationship of vegetation, soils, landforms, water, ecosystems and their interdependence.

Water management

About 65% of the audited growers practise some form of irrigation. The main water management issues perceived by stakeholders involved impoundment effects of waterways such as weirs, river crossings, creek diversions and barrages.

The report found that 49% of stakeholders believe that irrigation practices needed to be improved in areas where supplementary irrigation is practised. The report suggested that a water allocation review should be undertaken across the industry to assess the sustainability of canegrowing in areas totally reliant on supplementary water sources.

Drainage was regarded by 43% of all stakeholders as being of high concern, especially in the northern Wet Tropics and the Burdekin. Perceived major problems included the blocking off of creeks and straightening of water courses, exposure of acid sulfate soils, opening of marginal areas, and drainage of wetlands.

Waste management and chemicals

The audit team was impressed with the level of knowledge, storage and management of chemicals in the industry although better record keeping was needed. Location of some aboveground fuel storage tanks on farms represented a high risk of contamination of soil and water from accidental spills.

Local government authorities need to provide appropriate infrastructure to enable environmentally responsible disposal of chemical containers.

Generally, waste management on farms was considered to be responsible with on-farm dumps being a legacy of poor past practices which growers are trying to remedy.

Fertiliser management

The audit team did not assess that excessive rates of fertilisers were being used on cane farms although some stakeholders regarded growers as being 'risk averse' and hence inclined to over use nitrogen as a cure-all for poor seasons.

Fertiliser run-off was seen by stakeholders as a low to medium priority mainly because insufficient knowledge exists as to its off-farm impact.

Noise

Although noise from canegrowing practices was unlikely to become a major nuisance factor, the report suggested that a code of practice should be designed for harvesting contractors and mill transport vehicles to minimise noise impacts of proposed 24-hour harvesting.

Conclusion

The environmental audit of canegrowing practices marks the start of a new era in resource management for the industry. It will help ensure the industry's continued sustainability and ensure that changing community expectations about the environment are taken into consideration as we move away from the legacies of past practices which may not have been sustainable in the long term.

It gives a sound basis for ongoing strategic planning to improve industry attitudes and understanding of environmental issues and to translate that improved knowledge into practical sustainable practices at the farm level.

The canegrowing industry is only the second agricultural industry in Australia to commission an environmental audit of this type. We have taken the bold step of exposing our flank to the potentially damaging effect of an independent scrutiny on such a publicly sensitive issue because we are serious about doing the right thing in terms of best environmental practice.

As one of Australia's largest and fastest growing crop industries, we recognise that cane growers must be prepared to play a leading role in encouraging the universal adoption of ecologically sustainable methods.

With the benefit of hindsight and improved knowledge, farmers, scientists and governments now recognise that some commonly used practices, both in the city and in the Bush, are no longer appropriate. However, attitudes and practices which are deeply established in the national culture can not be changed overnight. It will take time and it will take money.

We believe that the environment is not just an important issue for cane growers, nor for the sugar industry. It is of vital concern to all Australians and the whole community must play its part. If we as a nation want certain changes in the way things are done we must all be prepared to share the cost, not just those landholders who are closest to the problem.

The marine tourism initiative towards use management in the Great Barrier Reef

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ABSTRACT

Reef Tourism 2005 is a Marine Tourism initiated project to develop a 10 year strategic plan for the ecological and economical sustainable development of the Marine Tourism Industry in the Cairns Section of the Great Barrier Reef World Heritage Area.

With the exponential growth of Marine Tourism in the late 1980s and early 1990s, management practices were forced into a largely experimental and reactive role in responding to Marine Tourism's changes and perceived impacts. This causes frustration, costly and time consuming delays for all involved and antagonism between the reef management agencies and the Marine Tourism Industry.

In 1995 the regional Marine Tourism Industry associations of the Cairns Section (Cairns, Port Douglas, Game Fisherman, Cod Hole and Upolu Cay Operators Associations) collectively and in partnership with the Far North Queensland Regional Development Network, the Great Barrier Reef Marine Park Authority, Queensland Department of Environment and Reef CRC set up this project to research the factors effecting long term sustainable use by Marine Tourism in the Great Barrier Reef and to develop recommendations which have endorsement from both Industry and reef management to preserve and protect the Industry's workplace and product, the Great Barrier Reef.

This paper presents an outline of the research and development process underway, the main issues facing the participants and the approaches to addressing these issues and emerging trends.

INTRODUCTION

The increasing world trend in reef visitation (to experience the reef environment) coupled with the degradation of coral reef outside the Great Barrier Reef provide an added incentive to produce viable outcomes and develop means of transferring this type of project to other Marine Tourism Industries, marine and social scientists and natural resource management agencies worldwide. The marine tourism industry (MTI) believe it is of vital importance for the users, regulatory bodies and the scientific community to participate together in the preservation and conservation of this finite resource.

The Reef Tourism 2005 Project

The full title of the project is Reef Tourism 2005 (RT 2005). The project aims for ecologically and economically sustainable development of marine tourism in the Great Barrier Reef World Heritage Area. The project participants are:

Cairns Marine Tourism Operators Association (CMTOA)
Douglas Shire Marine Tourism Operators Association (DMTOA)
Cairns Professional Game Fishing Association (CPGFA)
Cod Hole and Ribbon Reefs Operators Association (CHARROA)
Great Barrier Reef Marine Park Authority (GBRMPA)
Cooperative Research Centre - Reef Research (REEF CRC)
Queensland Department of Environment (QDE)
Regional Development Network of Far North Queensland (RDO)

The project participants are made up of the above associations who represent over 90% of the operators in the Cairns section. The industry part of the steering committee overseeing

the project, are representative of the large, medium and small operators to ensure all industry is part of the process. The marine tourism industry in the context of this project may be defined as vessels and planes licensed by the authority to conduct commercial activities within the Marine Park.

We have identified eight sub sections:

Day tours - provide day trips to reef destinations and may offer a variety of activities including:
- snorkelling;
- introductory or certified diving;
- organised/structured interpretation and education of reef and environment;
- glass bottom boat tour;
- some operators provide island transfers, departures are scheduled.

Day dive provides:
- day SCUBA diving trips to reef destinations;
- caters mainly for certified divers but often accommodates snorkellers;
- departures are scheduled.

Extended diver (one night or more) provides:
- extended SCUBA diving trips for divers (mainly certified) to various reef destinations (trip duration is usually between one and four nights);
- combined training course and extended dive for divers in training;
- departures are usually scheduled.

Extended non-dive provides:
- extended trips to various reef destinations (trips duration is usually between three and seven nights);
- departures usually scheduled for larger operators.

Island transfers provides:
- transfers from the adjacent mainland to islands.

Game fishing charter provides:
- 'Game' fishing trips (for pelagic species) for visitors for duration of one day or more;
- snorkelling and diving are also available;
- no scheduled departures.

General charter provides:
- available for a variety of activities including game fishing. 'mother shipping', diving and touring;
- boats chartered for various durations with no scheduled departures;
- grades of charter may vary from economy to luxury.

Other fishing charter provides:
- reef and estuary fishing trips for visitors;
- duration may be one day or up to twelve nights;
- no scheduled departures.

Day tours, day dive and extended dive carry about 70-85% of visitors to the reef and are mostly site-specific, while the other groups carry several hundred thousand visitors and are mostly roving operators.

Marine tourism and the composition of the marine tourism industry have undergone major changes since the last Great Barrier Reef Conference 13 years ago. The number of visitors has increased to over 1.7 million in 1995 and the experience most of the visitors seek now has more to do with interacting with the environment than taking part of it home with them. With the exponential growth of the marine tourism industry in the last decade, two ideologies have become apparent: one, the push to develop, fuelled by tourism and aided by population growth, has clashed with the other, which has aims of protection and conservation of the natural resource. This clash is being witnessed world-wide and is

certainly not unique to the Great Barrier Reef. For the operators of the marine tourism industry, this clash has manifested itself in what appears to be unnecessary red tape, causing costly delays and increasingly mixed signals as to the desirability of tourism being an accepted reasonable use of the marine park. This has resulted in the natural resource managers fending off a belligerent industry that need prompt, consistent decision making and security to enable long term business planning. On the other side of the fence management has been faced with the lack of substantive knowledge of marine tourism's impact on the reef environment and in some ways forced into a holding pattern, a situation that for a dynamic industry like marine tourism was unacceptable.

Industry's lack of understanding of the rationale behind many of the decisions made during the early 1990s by management and the need to understand the complexities and the implication of current decisions was one of the driving forces which led to the members of the above association approaching the Federal government, the management bodies and the Reef CRC to form the Reef Tourism Project.

The primary objectives of the project are:

- to identify the factors affecting the continued growth of the marine tourism industry;
- to ensure the ecologically sustainable development of the industry;
- to preserve and protect the industry's workplace and product, the Great Barrier Reef;
- to provide recommendations for the sustainable development and management which will have endorsement from both industry and regulatory authorities allowing for continued growth; and
- to assist the Marine Tourism Industry in achieving a greater degree of self regulation.

To achieve these objectives a number of research and development tasks have been undertaken. These tasks are designed to produce environmental, economic, social and management strategies which combine to give a strategy for the long term sustainable development and use of the Marine Park.

ENVIRONMENTAL

+

ECONOMIC

+

TRAINING

+

USE MANAGEMENT



2 YEAR, 5 YEAR AND 10 YEAR
STRATEGIC PLAN

Environmental strategy

The environmental strategy is made up of three tasks designed to identify factors that may degrade the environment, monitor these factors and take action to minimise them.

Task 10
Identify concerns and potential threats to the ecologically sustainable use of the Marine park by the marine tourism industry and develop contingency plans to address concerns.

Many allegations have been made about marine tourism's impact on the reef environment. The need to put these to a rigorous examination so both industry and management bodies can determine and prioritise negative impacts is seen as a cornerstone of industry's continuing use of the reef. In conjunction with the Authority, QDoE and the CRC, a study has been undertaken to identify and prioritise these impacts.

Task 11
Develop processes to provide ongoing monitoring systems for cost effective continuous evaluation of reef systems by industry.

Two monitoring programs are being trialled to achieve this aim. One in conjunction with James Cook University and the Reef CRC with the roving part of the fleet, involving transect monitoring of reefs and the other with GBRMPA involving site specific impact monitoring. Scientists, users and managers understand the need for cost effective, continuous monitoring of this finite resource, data collection, interpretation of the data and knowledge based decision making are the ingredients of successful marine park management. The science community has a challenge from the marine tourism industry. We are in the field every day, dive instructors spend sometimes most of their working day underwater in the Great Barrier Reef. Not only are they well placed to notices changes to their workplace, but also are well placed to collect data. Please become involved and teach us how to. The marine tourism industry on the Great Barrier Reef is the larges and fastest growing marine tourism industry in the world, we must get it right here. I am told that Australia is involved in teaching monitoring to many other countrys. If we are the smart country, we must make it work at home first, before we transfer to other locations.

Task 12
Develop and implement industry codes of practice based on agreed best practice principles.

A draft code of practice has been formulated, based around existing codes and best practice principles -- this is now under fine tuning amongst the industry. It serves two functions, one, to raise the awareness of the individual operators to impact minimisation and two, to unite the industry to the common goal of protection of the environment.

The economic strategy

The economics of the Great Barrier Reef and the marine tourism industry in the age of cost efficiency will be a major determining factor in the future development of the north Queensland.

Task 7
Structure and economics of the Marine Tourism Industry in the Cairns section of the Great Barrier Reef.

The need to quantify and position:

what the marine tourism industry represents in economic terms;

the ramifications on the economy by its development or decline;

the factors affecting its economic growth; these are fundamental to the planning of where the regional economy of north Queensland will be in the next century

The Coopers and Lybrand study (Task 7) is now available and show approximately 70% of visitors come to the far north primarily for a reef experience. The reef tourism industry generates over $600 million into the regional economy and is responsible for the employment of several thousand people directly and many more thousand indirectly. These facts alone place the Great Barrier Reef as the driving force of development in the regional economy and highlight the need to ensure sustainability.

Task 9
Develop a profile of marine tourism marketing and resource use.

Marketing bodies use the reef as an icon to draw visitors to the north, very successfully. The ATC, QTTC and regional marketing bodies and the individual operators market to the world the beauty and wonder of the reef. This is one of the tools we use for economic growth and is presently the main way of presenting world heritage area values to the world. To maintain the marine tourism industry edge in international competitiveness it is important that the product advertised matches the reality and as approximately 30% of visitors return for a second trip to the reef, James Cook University Tourism Department has been involved in a study of visitor expectation to ensure product reality matches those expectations. An interesting fact to come from that research shows that most visitors state as their second reason for visiting the reef is to learn more about the environment. Interestingly the first reason was for a cultural experience.

Training Strategy

Task 8
Identify industry training needs

Task 13
Develop training options

The Marine Tourism Industry employs several thousand staff in a wide range of fields. The need for staff who can produce a mixed drink, take a boat off a lee shore, book a foreign language group on the experience that will suit them and explain the complexity of the reef environment, calls for many skills. RT 2005 has been involved in the setting up of the GBRMPA Reef Interpretation course which many staff have already undertaken, an excellent example of industry management and science working together.

The Reef Tourism project, with the Reef CRC and the Maritime College of Australia are currently involved in the identification of training needs. This will be combined with the RT 2005 and the industry training and advisory board of Queensland's training option study to blend the needs to the options and produce training that will meet the needs of the industry, staff and the local job seekers during the next decade.

Use Management strategy

All of the previous research and development tasks are designed to raise industry competency and understanding to participate in the management process and to establish partnerships between regulatory bodies and users. The use management strategy is primarily based on looking at what has worked in management, what hasn't worked and why; creating the process to allow liaison and debate and then rolling up our sleeves and doing it.

Task 3
The need for industry to understand the rationale and goals behind the management bodies' decisions and have an understanding of the reasons for the success and failures of global reef management is crucial to the industry taking its place at the decision making table.

Scientific research and coral reef management literature is often difficult to obtain without specialist facilities. Most literature concerning the subject is written by academics and environmental managers for academics and managers. The Reef Tourism 2005 project commissioned this study so we in industry will not reinvent wheels and will have a clearer appreciation of impacts on reef systems. The report is now available from the Reef Tourism 2005 office but if any one would like a copy there is a small wait as we may be going into second print.

Task 4
With the complexity of issues surrounding reef management and the marine tourism industry we in industry had two choices - either draw the fleet in a circle or become involved. As the major users of the park in the 1990s, it is not only cost efficient to bring the marine tourism industry into the process from the beginning but also environmentally sensible as we are in the field and do have accumulated experience to offer the debate. The other main Great Barrier Reef industry, the fishing industry, has over 40 full time staff to

deal with these issues. The marine tourism industry has a full time staff of one, who has been our lobbyist, our coordinator, our liaison person and does a herculean job of it.

This is an issue that is the industry's, the need for a well resourced industry body, is crucial to our ability to successfully liaise with management. The representative structure of any group ebbs and floods, the marine tourism industry is no different. Management must take into account the nature of a diverse industry that drives boats not desks in all planning exercises. The far north Queensland operators are currently involved in formalising communication and liaison between industry and management on many levels. The Reef CRC and the marine tourism industry have an excellent working relationship and the structure should be a model for reef management agencies worldwide.

Task 6
The industry in the Cairns section has been actively involved in consultation and negotiation with the Marine Park during the whole of the mooring and anchoring plans, the new plans of management and a host of day to day issues, we do not always see eye to eye but it is expediting the decision making process which may be a world first. Many other reef management agencies have adopted the process of joint decision making; the fishing industry is enshrined in the legislative process; and somebody did say to me last month user pays, user says? This initiative is not a reaction to recent history but rather a need not only by industry but also management bodies and researchers at all levels to work to achieving our common goal. In the most cost efficient and expedient way.

CONCLUSIONS

RT 2005 has just passed its halfway mark. The lack of hard data in what is relatively a new industry has caused nominal delays and shows the need for continued work in the biological and social sciences if we are to get it right. Most of the research tasks are nearing completion and the development tasks are well underway. Many of the benefits and results are taking on a more permanent life than the project time scale.

The project will be producing a 2, 5 and 10 year strategic plan, this will have industry/management milestones, time frames and ongoing evaluation of the issues and requirements surrounding the ESD of the marine tourism industry. The development achievements and thirst for knowledge are a testament to the willingness of those involved in the project to donate their time and energy, which is all voluntary to the long term sustainability of the Great Barrier Reef.

Fisheries management in the Great Barrier Reef region

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ABSTRACT

The Great Barrier Reef is an important resource for commercial, recreational and indigenous fishing. Under the Offshore Constitutional Settlement between the Commonwealth and State Government responsibility for management is shared between both Governments. However, the great majority of fishing activities in terms of value and participants is managed by the Queensland Fisheries Management Authority on behalf of the Queensland Government.

The principal fisheries dependent on the reef are the line, trawl and collection (trochus and bêche-de-mer). Management of these fisheries is carried out under the *Queensland Fisheries Act 1994* which has as its objectives ensuring fisheries are used in an ecologically sustainable way, optimising benefits and ensuring fair access.

Management plans involving extensive public consultation are presently being prepared for the trawl and reef line fisheries. Expertise-based management advisory committees drive the management planning model which incorporates a three step process-discussion paper, draft management plans and statutory management plan.

Increasing use of fish stocks by recreational fishers, the growth of the charter fishing sector, increasing prices paid for the commercial catch together with a paucity of reliable data all present significant issues for fisheries management in the reef region.

It is most important fisheries management delivers outcomes that are in keeping with public expectations for the are given its significant conservation status. The Queensland Fisheries Management Authority works closely with the Great Barrier Reef Marine Park Authority in developing management arrangements.

INTRODUCTION

The management of fisheries in the Great Barrier Reef Marine Park and World Heritage Area involves a number of unique challenges and issues for management agencies and industry. The Queensland Fisheries Management Authority (QFMA) has responsibility for most of the fisheries in the area covered by the world heritage listing Queensland's most important commercial fishery – trawl – occurs throughout much of the area. Line fishing for tropical coral reef species and mackerels is also important commercially and further is a major recreational fishery. Inshore gill netting also takes place in the World Heritage Area as do several collection or harvest fisheries – trochus, bêche-de-mer, tropical rock lobster and aquarium fish.

Management plans are currently being developed for each of these fisheries based on objectives of ecological sustainability, optimum community benefits and fair access. The management planning model is dependent on extensive stakeholder and public consultation. Management Advisory Committees (MACs) advise the Authority (i.e. the QFMA) on development of these plans.

The next five years is going to be a critical period from a fisheries management perspective. There will be increasing demands during this time on the fisheries of the reef and these pressures will only continue to mount into the future. Management arrangements will need to anticipate these changes and ensure the statutory plans are capable of delivering on the public expectations of sustainable use in the context of a World Heritage Area.

Fisheries of the Reef area

Fisheries of the Reef area

Under the Offshore Constitutional Settlement (OCS) fisheries management is divided between the Commonwealth and State depending on species and location of the fishery. In terms of the reef fisheries most are managed by the Queensland Government through the QFMA. The Commonwealth manages the pelagic tuna and bill fish species which are utilised by both commercial and recreational fishers.

The principal fisheries in the reef area which come under Queensland jurisdiction are:

- Trawl – prawns and scallops
- Reef Line – includes the troll fisheries for mackerels
- Net – Estuarine and Inshore. (Occurs mainly outside the Great Barrier Reef Marine Park.)
- Harvest or collection fisheries – trochus, bêche-de-mer, aquarium fish, tropical rock lobster or crayfish.

All these fisheries are managed as limited entry regimes.

Trawl Fishery

The trawl fishery is a multi-species fishery, with participants targeting several species of prawns and saucer scallops with a range of other species taken incidentally. It is an exclusively commercial fishery. The major proportion of the Queensland catch is taken from within the Great Barrier Reef World Heritage area. Two areas are regarded as 'hot spots' within the area – the Townsville region and Princess Charlotte Bay. Over the last three seasons, Princess Charlotte Bay and the area north to Cape York has accounted for up to 30% of the landings.

Currently, 823 otter trawl boat licences authorise participation of vessels in the World Heritage area. There is no current scientific evidence to suggest biological overfishing of stocks targeted in the Queensland trawl industry. In other words, current exploitation levels are thought to be sustainable, although some sectors of industry have expressed concern for stocks of eastern king prawns and scallops and further work is required to clarify the situation for certain species and geographical areas.

The trawl sector in Queensland produces up to 10 000 tonnes of product with a value to fishers of approximately $150m per annum. The value of the prawn catch is approximately $100m per annum with scallops earning approximately $30m and various other species such as 'bugs' and finfish making up the remainder.

The average age of the trawl fleet is almost 20 years. A range of closures to trawling exist including those under the Great Barrier Reef Marine Park Authority (GBRMPA) zoning plans.

Major management issues for trawling in the World Heritage Area

The following issues are all discussed in detail in the trawl discussion paper soon to be released publicly by the QFMA.

By-catch

Prawn trawling in tropical waters is generally found to generate a higher rate of by-catch because of the diversity of species encountered compared with more temperate and sub tropical Australian waters. The reduction of non target species is considered to be desirable from the perspective of maintaining biodiversity and minimising waste Additionally, the washing up of discarded species on beaches causes concern amongst local communities along the coast.
Fish and turtle excluder devices are presently being trialled and evaluated for use on trawlers in Queensland waters.

Habitat management and consequences of trawling

A major study being carried out by CSIRO and the Queensland Department of Primary Industries (QDPI) is looking into the environmental effects of prawn trawling in the Far Northern Section of the Great Barrier Reef Marine Park. This study is being conducted over five years and is the most comprehensive yet to document the direct impacts of trawling. Understanding how areas of the reef are affected by trawling, if and how these areas may recover should they be closed to trawling or if different strategies for trawling were implemented is a critical issue for management.

Pollution

Run-off from adjacent catchments is of concern to the trawl industry especially with respect to prawns because of their dependence on seagrass and estuaries for significant parts of most species lifecycle.

Fishing effort and fishing capacity

The trawl fishery advisory body TRAWLMAC believes there is now too much effort in the fishery from an economic efficiency perspective and there is a need to reduce both effort and the number of vessels. Initial discussions will commence soon amongst the trawl operators on how this can be progressed.

Impact on biodiversity

Governments world-wide are moving to implement legislation and policies to maintain and conserve existing levels of biodiversity. Much of the impetus for these measures can be attributed to the United Nations Convention on Biological Diversity. Australia is a signatory to the Convention. Signatories are required to implement strategies for the individual elements of the Convention, which are:

- conservation of biodiversity;
- promotion of sustainable use of its components; and
- assurance of fair and equitable sharing of the benefits arising out of the utilisation of genetic resources.

Governments and resource management agencies around Australia are in the process of generating upgraded management arrangements which give effect to this convention.

The fishing industry has advocated that relevant government agencies recognise those measures that have been or are being implemented to meet convention obligations. Some of the existing fisheries management measures include:

- limited entry arrangements;
- seasonal and spatial closures;
- gear and apparatus restrictions; and
- research into the effects of fishing.

The QFMA endorses this view whilst recognising that any approach to biodiversity should emphasise the precautionary principle.

Endangered species

A number of species that occur in waters off the Queensland east coast are listed in the Commonwealth *Endangered Species Act 1992* and the Queensland *Nature Conservation Act 1992* as being endangered, threatened or rare. These species include the green, hawksbill, olive ridley, flatback, loggerhead and leatherback turtles; the saltwater crocodile; dugong; and the Irrawaddy River and Indo-Pacific humpback dolphins. The highest potential for interaction between these species and trawling occurs in the case of marine turtles, in particular green and loggerhead turtles.

In response to concerns that the population of loggerhead turtles was declining, a program to monitor turtle captures in the east coast otter trawl fishery was established in 1991. Based

on the sampling procedures associated with this program, researchers estimate that about 5000 (±1200) turtles are landed in trawl nets annually, of which between 1–6% die. These captures are not evenly distributed throughout the fishery's area of management. Most captures occur in shallow waters close to the coast or inshore feeding grounds such as Moreton Bay, where fishers are generally targeting banana and tiger prawns. Turtles are least frequently captured in offshore, deep-water fisheries, where fishers are targeting king prawns and scallops.

The Authority has acknowledged concern expressed about the potential for the accidental capture of sea turtles during trawling operations and has taken the advice of TRAWLMAC that the issue be addressed by a package of measures based on:

- a pre-determined level of bycatch (particularly turtle) reduction within prescribed periods, aiming at reduction in the trawl capture of turtles by 50% by the year 2000;
- the identification of critical areas and/or times for restricting trawling, unless TEDs are fitted to trawl nets;
- an educational program directed towards industry being well-informed on issues pertaining to endangered species;
- spatial restrictions to the use of trawl nets without TEDs fitted;
- seasonal closures to the use of trawl nets without TEDs fitted; and
- further development and utilisation of Codes of Practice that minimise the effects of trawling on endangered species.

The Discussion Paper on the Queensland Trawl Fishery to be released in December will advocate the widespread trialling of a range of turtle excluder devices in areas where the probability of turtle catches is appreciable. Critical areas include Moreton Bay and sites associated with the inshore tiger prawn fishery such as Princess Charlotte Bay and Repulse Bay.

Reef Line Fishery

Again this fishery extends throughout the Great Barrier Reef World Heritage Area except of course in those areas closed to line fishing under marine park zoning. The better known fishes are coral trout, red emperor, red throat sweetlip and the mackerels both 'Spaniards' and the lesser mackerels. These species are sought by commercial, recreational and indigenous sectors and are highly regarded for their eating qualities. They also form an important part of the reef visitor's experience, featuring in underwater viewing, diving and photography.

There are 251 licensed operations in the principal Great Barrier Reef Line Fishery with a further 1563 licence holders with much more limited commercial access to reef fish stocks.

Recreational fishing for tropical coral reef fish and mackerels has long been a popular pastime. Only limited information is available on the catch and the fishing effort.

To overcome this gap a comprehensive data collection system known as RFISH is being applied by the QFMA. Results from this system should begin to be available in a useful form for management in the near future.

Recent studies have estimated that 24 300 privately registered boats fish the Great Barrier Reef region annually, for a total catch weight between 3500 and 4300 tonnes.

Spear fishing also occurs in the region although once again data is limited in terms of catch and effort.

Various Aboriginal and Torres Strait Islander communities engage in community fishing for a commercial purpose, and community fishing permits have been issued to the chairpersons of various communities for that purpose. The number of active community permits has varied from year to year, depending on the level of commercial fishing activity by those communities each year.

Indigenous fishing for traditional or customary purposes is not curtailed by fisheries legislation in Queensland, although the Act provides for fishery management plans to be developed for those purposes in consultation with relevant parties.

Charter Fishing

This group of stakeholders represents a significant industry, with about 220 commercial tour operators working within the Great Barrier Reef. New permit-style management arrangements were recently introduced for this sector. The charter boat fleet operating in the Marine Park and Work Heritage area is larger than most other State's commercial fishing fleets in terms of vessels. Commercial charter fishing is an important part of the tourism and leisure industry dependent on the reef and is treated as a separate sector for the purposes of fisheries management.

Passive users, including underwater viewing, diving and photography interests, also have a stake in managing tropical coral reef fish. Information provided by GBRMPA shows that about 1.5 million people visit the Great Barrier Reef annually. These visitors participate in a variety of tourist activities, including snorkelling and diving. Only a small percentage, however, are involved in fishing activities.

Commercial and recreational fishers are limited to rod and line or handline apparatus limited to three lines with a maximum of six hooks attached to each.

The commercial fishery has been under a licence limitation scheme since 1984. The zoning arrangements in the Marine Park limit line fishing in certain areas such as Marine Park 'B' zones and in higher level protection zones. The commercial fishery has a freeze on tender boat licences. Other management measures include:

- recreational bag limits for 26 popular reef species;
- minimum and maximum size limits for 36 reef fish species affecting all resource users;
- specific arrangements for all charter boats involved in extended charters; and
- division of the commercial fishery into separate limited licence areas which in February 1995 were further subdivided with the amendment of OCS arrangements.

Major Management Issues for the Reef Line Fishery

Catch trends of Tropical Coral Reef Fish

Available data on both commercial and recreational catch trends reveal no long term trend such as a decline in catch and effort relationships over time. There is however evidence of a decline in the average weight of fish in certain areas where fishing has occurred over a sustained period.

Information about tropical coral reef fish stocks in insufficient to demonstrate whether present harvest levels are within the range of sustainable uses of species now fished. This is also true of the Spanish Mackerel and the various targeted shark species.
The proposed 'effects of fishing' experiment is designed to provide the require information in terms of reef fish populations. Results from this experiment will provide valuable input for REEFMAC in its task of providing management advice for this fishery.

As noted earlier the QFMA recently initiated a recreational data monitoring program (RFISH) to obtain recreational catch and effort data for the whole of Queensland.

The data available for management use is likely to improve considerably in the next 3 to 7 years.

Local area depletion

Evidence from a number of studies show that fishing pressure on the Great Barrier Reef has resulted in localised depletion of coral trout and red throat emperor in areas close to major population centres and or reefs open to fishing compared to adjacent protected reefs.

It may be that area specific management interventions are warranted in areas where severe depletion has occurred or is likely to occur. For example, seasonal closures may have a role to play in these circumstances. The question of the scale of an area to be managed is one requiring further consideration.

Resource allocation

As is the case with the estuarine and crab fisheries there is conflict between competing interests for access to reef fish stocks. This is most prevalent or intense conflict occurs with regard to reef areas close to major population centres such as Townsville, Cairns, Innisfail and Mackay.

There are a number of methods of determining access between competing interests such as zoning which is presently use by GBRMPA. To date there have not been any recreational or indigenous exclusive areas set aside in the World Heritage area under Fisheries Legislation. Bag limits apply to the most sought after or commonly caught species of reef fish. These bag limits will also be reviewed under the management planning process.

Latent Effort

Latent effort of excess fishing capacity is simply the gap between actual fishing effort applied by commercial, recreational and other resource users and their potential effort, if all were to fish to the limit of their capacity.

The reef fishery shows evidence of excess fishing capacity in both the commercial and recreational sectors. For the commercial sector the extent to which this effort is utilised depends very much on prices received and the costs involved. For the recreational fishery it comes down much more to lifestyle and on individual's leisure time.

Live Fish Industry

Over the last two years, commercial harvesting of live reef fish has emerged as a new use of reef stocks, in response to export market demand, principally from Hong Kong. Prices for live fish are considerably higher than for fillets or whole fish.

This fact presents both opportunities for commercial fishing and potential problems in terms of management given the level of latent effort in the commercial fleet. Already the trade has attracted considerable public concern and comment especially in relation to concentration of fishing effort and the targeting of undersized fish, especially coral trout.

To present concentrations of fishing effort particularly near community centres and to facilitate compliance, the QFMA has introduced a policy that:

(i) excludes the use of specialised fish transport vessels from the live fish trade, requiring operators to land their own catch; and

(ii) advised other agencies, with powers to approve 'at sea' structures, that the QFMA would not support the approval of fixed structures or other sea-based holding facilities to retain live captured reef fish.

Collection or Harvest Fisheries

The reef collection fisheries are aquarium fish, bêche-de-mer, coral and shell grit, trochus. The QFMA issues authorities to take to operators in these fisheries. There are 63 aquarium fish collectors authorised to operate, 33 coral and shell grit, 3 for shell collecting, 5 trochus and 19 bêche-de-mer. All these fisheries are exclusively commercial except for recreational shell collecting.
There are also 30 authorisations issued by the QFMA for the collection of crayfish (tropical rock lobster) from the tip of Cape York down to 14 S. South of this latitude the fishery is exclusively for recreational use.

Net Fishery (Estuarine and Inshore)

There are 1294 endorsements or authorisations for operators to use set gill nets for the east coast of Queensland much of which is covered by the Great Barrier Reef World Heritage Area. Principal species targeted are barramundi, salmon and mixed estuarine species.

The major issues associated with the use of this apparatus are those concerning the by catch of protected or endangered species such as turtle, dugongs and dolphins. There is also questions of resource allocation between the various sections which fish in these inshore and estuarine areas.
Doubtlessly the issue of dugong drowning is the most contentious matter facing this fishery at the present time. A number of measures are being considered by the Marine Park Authority and the Federal Government to address the decline in dugong. The industry is developing a code of practice to minimise the drawings of dugongs in gill nets

The Legislative Framework

Fisheries management for the State is carried out under the *Queensland Fisheries Act 1994* and the *Fisheries Regulation 1995.*

The legislation sets out the objectives for fisheries management and sets up the institutional arrangements including the functions and powers of the Authority.

The legislation stipulates that in determining management arrangements the QFMA must have regard to the principles of ecologically sustainable development.

'Ecologically Sustainable Development' is defined in the Act as developments -

(a) carried out in a way that maintains biodiversity and ecological processes on which fisheries resources depend; and
(b) that maintains and improves the total quality of present and future life.

A number of other Acts, made by the Queensland Government or Commonwealth Government, impact on the management and use of fish stocks in the reef area. For example, if product is to be exported, the *Commonwealth Wildlife and Protection (Regulation of Imports and Exports) Act 1982.*

The Great Barrier Reef Marine Park Act 1975 has significant impacts on managing and accessing fish stocks.

The Marine Park legislation, establishes the Great Barrier Reef Marine Park Authority (GBRMPA) which has significant responsibilities for ensuring the conservation of fish stocks, within the wider context of its responsibilities. Similar complementary legislation for Queensland's marine parks is contained in the *Marine Park Act 1982,* administered by the Queensland Department of Environment.

Development of Fisheries Management Plans for Reef Fisheries

Following its establishment in early 1995 the QFMA Board decided the development of management plans based on ESD principles for Queensland's major fisheries should be its priority and this should be pursued over the forthcoming five years. The approach which has been adopted to this task is based on the Management Advisory Committees or MACs for each fishery and estuarine public and interest group consultation.

The QFMA has established six MACs to advise on fisheries management These are:

- Tropical Finmac
- Trawlmac
- Reefmac
- Subtropical Finmac
- Crabmac
- Freshwatermac

Each of these committees have members from across a range of interest groups chosen for their expertise in various aspects of the fishery. Their role and purpose is to provide expert advice to the Board for each respective fishery including advice on the development of management plans. Members are chosen by the QFMA Board from commercial and recreational fishers, scientists, resource managers, environmentalists, seafood marketers and others as appropriate to the particular circumstances of the group. For example, Freshwatermac has a Local Government person because of the number of storages that are managed by local councils and REEFMAC has a member from the Great Barrier Reef Marine Park Authority.

The management planning process implemented by the QFMA has three (3) phases:

(i) Discussion paper
(ii) Draft Management Plan
(iii) Statutory Management Plan

Management plans are currently being developed for the Gulf of Carpentaria, Tropical Coral Reef, Trawl, Freshwater, Subtropical and Tropical Finfish fisheries.

The fishery discussion paper phase serves three (3) main purposes:

(i) As background and resource documents; collating information on the known state of the fishery including existing management interventions.
(ii) To put forward major issues to be addressed by management plan.
(iii) Stimulate as broad as possible public involvement in the plan.

The legislation does not stipulate there must be a discussion paper however it does state the need for a Draft Management Plan to be developed and released. These draft plans, like the discussion papers, are to be distributed widely. It is considered important they also contain an explanation of how proposals are arrived at.

The discussion paper seeks feedback and responses so that management can incorporate this information into the draft management plan. The two-way flow of information is further augmented by a series of public meetings that are conducted throughout the area impacting on the fishery.

Draft Management Plans are essentially statements of intent. The proposed management arrangements are set out and then another round of public consultation takes place.

Following this phase the QFMA Board agrees on a management plan for recommendation to the Minister and passage into statute. The Act requires that a Fishery Management Plan made by the QFMA must set out:

(a) a description of the fishery
(b) the known status of the fishery
(c) the objectives of the plan
(d) the measures by which objectives are to be achieved; and
(e) how the plan may be appealed or amended, including the consultation and other processes to be followed before amendment or appeal.

Obviously this management planning process cannot deliver 'quick-fixes'. It is however thorough in terms of allowing for public input and transparency. It is hoped these features will enhance the level of understanding and support especially from the broader community for the measures adopted.
Critical problems that arise requiring a more urgent response can be dealt with through the Board without having to proceed through the management planning process. For example, the Authority recently implemented a number of emergency measures to deal with bêche-de-mer overfishing in the Torres Strait.

The discussion paper for the Tropical Coral Reef Fishery was released in June 1996 and the Trawl discussion paper is due out in December. There have been over 450 written responses received on the former of these documents.

Conclusions and the future for the management of fisheries in the Great Barrier Reef Area

At the present there is not evidence of major declines in any of the major fisheries of the Reef. Whether this should be interpreted as the result of management interventions that have been in place or as a function of the large area of the Great Barrier Reef fisheries and the relatively low effort per unit area to date is a matter of conjecture and opinion.

What is certain is that the public concern regarding the operations of the trawl fishery is increasing. The industry is itself aware of this concern and scrutiny and through is taking steps to ensure the debate is informed and the operations of the fleet comes up to best environmental practice. The trawl operations in the world heritage area are the source of significant income and employment for regional coastal economies. The challenge for managers is to work with the industry and other agencies to develop a management plan which secures the future for the trawl sector by meeting the ecological standards expected by the public and allows for viable economic operations to continue. Having initially set the agreed standards of operations in a management plan; compliance through a quality assurance system is one possibility under consideration.The reef line fishery with its competing interests, commercial, recreational, indigenous and charter, directly involves many more people than do any of the other fisheries. The information available to managers on this fishery is not revealing a decline in catch rates for either the commercial or recreational fishers . However responses to the discussion paper for tropical reef species is indicating public perception is different. Many respondents are of the opinion there is decline . The reason for the difference could lie in the issue of local area depletion that occurs close to major population centres where the more easily accessed reefs receive relatively concentrated effort.

Basically more detailed data and information is required for management of this fishery. Logbook independent data is required for purposes of stock assessment and to evaluate the effect of fishing including the suitability of existing bag limits, size limits and closures.. The pressures are increasing on this fishery in terms of recreational effort as population increases along the Queensland coast. Moreover prices for these most sought after of eating fish are increasing steadily and so the incentive for commercial operators to increase there efforts is growing. The development of the live fish trade with Asian countries offers significant opportunities for fishers and exporters. It is already estimated to be worth around $30 million although the present ban on air transport using compressed oxygen cylinders has set the trade at least in the short term.

Certainly the objective has to be to avoid the bad practices that have plagued the live fish trade in other areas of the pacific . The problems and issues associated with the trade are being raised in the Tropical Coral Reef discussion paper with a view to putting forward appropriate management mechanisms .

The establishment of the Great Barrier Reef Marine Park and the listing of the Park and adjacent areas as World Heritage has considerably lifted the public's expectations and scrutiny of fisheries management in the area.

Fishing is an exploitive activity. If its management is in keeping with ESD principles then it should be possible for it to continue and complement the special conservation status of the Great Barrier Reef area.

The QFMA carries out management on behalf of the Queensland Government and in keeping with the OCS agreement with the Commonwealth In undertaking its responsibilities it relies heavily on the cooperation of other natural resource management agencies especially the GBRMPA. This relationship will need to strengthen in the challenging period ahead.

SESSION 5

People and the Reef

Chair: Peter Valentine

Rapporteur: Helene Marsh

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Keynote Paper: Science brokering and managing uncertainty
P Cullen

•

Science and tourism infrastructure on the Great Barrier Reef: learning from experience or just 'muddling through'?
G Inglis

•

Understanding Great Barrier Reef economics
S Driml*, T Hundloe and R Blamey

•

Understanding the tourist market
P Pearce*, G Moscardo and B Woods

•

Understanding visitors and use through social sciences research
M Fenton and D Benzaken
(abstract only, not presented)

•

Science brokering and managing uncertainty

Peter Cullen
CRC for Freshwater Ecology, University of Canberra ACT

ABSTRACT

Managing any natural resource is about managing uncertainty. Managers seek to make decisions that minimise risks to the resource itself, and to the various interests involved, especially the political ones. The interests involved all tend to believe that their interest is the most important and the benefits of that use exceed the costs. Often of course the benefits are captured by one group and the costs are borne by others.

Science can make a number of contributions to resource management. Its is important to understand what science is however. It is a means of discovering better and better approximations to the truth by establishing explanations and then subjecting them to critical tests. The best explanation, or hypothesis, is accepted as the working 'truth', although scientists would always expect a better answer may be found and the accepted answer will periodically be challenged.

Science in the natural resource area has particular challenges. These include how to select the best research questions to address, how to manage collaboration between the various specialists required to understand a complex natural system, how to integrate the knowledge that emerges from various studies to build system understanding and how to assure quality in the research.

Disagreement is fundamental to the advancement of science, yet causes havoc with resource manager and the public who do not understand this is how ideas compete for supremacy and are tested. Developing appropriate mechanisms for understanding and resolving such conflicts is a basic tool for both resource managers and for scientists, and one that most are poorly trained in.

INTRODUCTION

I start from a simple proposition. In managing natural resources, knowledge is better than ignorance. This seemingly simple proposition is in fact quite radical in the Australian and international context of resource management. Knowledge can come from experience or from the systematic development of knowledge that we know as science. Regardless of the source of the knowledge, the challenge is the intellectual interfaces between those who produce or act as custodians for knowledge, and the potential users of that knowledge. Brokering refers to the bringing together those with the knowledge with those who need the knowledge.

The public do not trust experts. Substantive experts in particular disciplines, or even process experts (managers?) are seen as often not understanding the particular problem, being sales promoters for some favoured technological fix, or just on the take for research funds. On the other hand in a crisis situation there is a symbolic value in carting some expert a long distance (the expertise increases exponentially with the distance) to give advice. If the advice is unpalatable it will be ignored or sabotaged. A recent toxic algal bloom led to warning signs being placed around a lake. These were removed by local residents concerned with the economic impact on the local tourist industry. That is public involvement in the nineties.

Managing any natural resource is about managing uncertainty. Managers seek to make decisions that minimise risks to the resource itself, and to the various interests concerned, especially the political ones. The challenge for resource managers and politicians is the setting of clear and useful objectives as to what the resource is meant to achieve for society. There is a great temptation to keep these objectives ambiguous, so as to maximise support

from the various interests. This can work well until a conflict arises, when the agency can be made to look indecisive and weak.

The interests involved all tend to believe that their interest is the most important and that their proposed use of the resource produces benefits that far exceed the costs. Often of course the benefits are captured by one group and the costs are borne by others. If the costs are to be borne by future generations and taxpayers, they may not even have a voice at the negotiating table.

Whilst resource managers aim to minimise uncertainty and risk for their political masters, they often have a very limited understanding of the risk Much of the risk is driven by climatic factors, and our length of record is relatively short, and the climate may well be changing anyway in ways we do not really understand. When you consider that runs of dry or wet years may last a decade, it becomes obvious why early settlers made so many poor decisions, for which we are still paying the costs in terms of land degradation.

Resource management has been partly driven by experienced managers in state agencies, and partly driven by land holders. Both of these groups had certain levels of expertise. This can be considered the technocratic model of resource management. The current fashion for community involvement introduces new players to the resource management arena - ones with great commitment, but at times little knowledge or experience, and also ones who may not have to pay any personal costs for poor decisions. This can be considered the democratic model of resource management, and the ways we can deliver technical input to this process are still being explored and developed. Landcare and its derivatives have demonstrated the power of community groups to provide an integrated approach to a problem and get solutions adopted. This has involved genuine public ownership of a problem and real public based decision making - not just an opportunity to participate or even be involved with some one else's decision making,

In this difficult arena it is easy to see why fashionable although simplistic solutions emerge that are widely adopted before they are seen to fail. Charismatic individuals promote these solutions which are adopted without the careful scrutiny of propositions we would expect in science.

The contribution of science

By science I refer to the thinking processes characterised by Karl Popper (1969) that requires a hypothesis (or a conjecture on how the system is likely to perform under some condition) and a rigorous test in an attempt to disprove the hypothesis. The goal is prediction through understanding. In order to achieve such understanding scientists must spend energy describing and cataloguing phenomena before they can establish and test hypotheses about causal relationships, which will lead to predictive models.

It is an interesting paradox that in technically complex resource management issues, with a heavy scientific involvement, that there is commonly little preparedness to accept any scientific view as a way forward. The situation can almost be caricatured that for every expert there is an equal and opposite expert.

Collingridge and Reeve (1986) argue that more knowledge does not necessarily advance rational policy making. They argue that science often encounters either an under-critical or an over-critical environment. In the under-critical situation there is already a consensus on the best way forward, and this ensures ready, and uncritical acceptance of research that supports this pre-judgement. In the over-critical mode, the political adversaries are sharply divided and any scientific claim is subjected to intense scrutiny from scientists from the rival camps. The result is endless technical debate (Jasanoff 1990).

Science is often invoked in environmental conflicts for its symbolic value rather than for any of the sorts of substantive outcomes discussed above. Research programmes can be established, laboratories commissioned, eminent scientists recruited or at least invited to visit, and conferences sponsored. Such activities show that Governments or Companies care and such apparent inputs to the scientific process seem to be reassuring to the press and the public.

The boundary between science and resource management

I have described this boundary elsewhere as turbulent (Cullen 1990). Managers and scientists come from different intellectual traditions and work in markedly different cultures. They have a fairly poor understanding or tolerance of each others cultures.

Given the biophysical and the social uncertainties of resource management, it is easy to see why some scientists have disdain for resource managers and may regard them as unskilled, unprincipled or uncaring. They commonly have the view that if we use the best scientific advice, then we can minimise these uncertainties and come up with better management approaches. This technocratic view is perhaps best encapsulated in the title of a book by Wildavsky (1979) 'Speaking Truth to Power '.

Resource managers, on the other hand, often have unfortunate experiences with scientists. There has been little scientific study into the usefulness of science in natural resource management. Some work has been done looking at the scientific inputs to coastal planning in California where the scientific input was seen as useful, but not crucial. The reasons for this are as follows:

Scientific experts are often wrong,

Scientific experts are often contradictory,

Scientists often take on the philosophy of the agency that employs them,

Most scientists err on side of caution,

Many issues are not related to science but to values,

Most coastal ecosystems are so dynamic that prediction is very questionable,

Non-scientific information is often more persuasively argued.

Resource managers know that simple technocratic solutions, borne out of a 'rational' model are nor workable. They operate in a bargaining environment where they seek solutions that maximise the benefits to a range of powerful interests. These interests have become more wide ranging in the last 30 years with the emergence of a more democratic model of decision-making following the moves to public participation and now public ownership of natural resource issues.

Contributions of science to environmental conflicts

Science can contribute to environmental management and the resolution of environmental conflicts in several specific ways.

Description

Inventory of what exists in the system and identification of the key processes and functions. This may include identification of values of both a short term, and a long term nature.

Diagnosis

Analysis of past environmental damage and the present condition of the resource. Identification of problems, including causes and consequences of ecological disturbance.

Prediction

Assessment of the capability of the resource to support various functions. Identification of possible hazards, special values and probable ecological effects of specific resource uses.

Prescription

> Recommendations on the requirements to maintain the resource within acceptable limits of change. Normally based on predictive models that can be run over an appropriate time period. The selection of the appropriate time period is critical, and often done poorly.

Implementation

> Advice in formulating management actions. Routine measurements or monitoring can provide a feedback loop for management on the efficacy of management actions and information on the number and extent of violations.

Limitations on the contributions of science and scientists

Well trained scientists are skilled at identifying the assumptions of their own argument and that of opponents. They also have a keen appreciation of the limitation of particular measurements and predictive tools or models. Science advances to subjecting new propositions to vigorous challenge using these various tools.

Non scientists often believe that there exists an agreed scientific truth that can be transmitted to policy makers. I do nor believe science ever finds an immutable truth. It finds a series of what are hopefully better and better approximations of the truth, that serve as good working models until they are replaced by a better 'truth'. We all know that scientists are an argumentative lot, and that it is the challenging of assumptions, of methods of measurement and interpretations of data through which better hypothesis are developed and may eventually replace the earlier 'accepted truth'. Scientists tend to be most interested in and to focus and argue about areas of ignorance; managers are concerned to find knowledge that is not under challenge.

This disputation can be unsettling to resource managers and the general public who have an expectation that there is some truth and the scientists will find it. When they hear disagreement they often fail to appreciate that this is the fundamental process of science; rather they are likely to believe one or both scientists are flawed or have been bought of by one of the competing interests.

A second widely held fallacy is that science can be value free. Perhaps the most sobering example is forestry, where the failure of forestry to take on board the widening range of community values, both in their management perspectives and in the science that advised such management. The results have been catastrophic for forestry and the forestry profession who persisted with a simple production model long after the community had identified a much wider range of benefits that come from forests. Similar problems have been evident with other natural resources including irrigation and fisheries agencies that have taken a blinkered view of the resource they manage, which is reflected in the science they listen to.

Effective resource management requires an ability to detect emerging community values and to ensure a knowledge base is developed before significant conflicts arise. Many resource agencies have scientific advisory committees, and others have a knowledge strategy which sets priorities and ensures appropriate research is undertaken.

It is apparent that many of the questions managers raise of science cannot be answered by science as it is practiced, at least in the short term. Scientific fashions of the last 50 years have been for reductionist science that looks at particular processes, and studies of whole systems such as the Great Barrier Reef, the Murray Darling Basin or the Lake Eyre Basin seem largely beyond us both because of their spatial and temporal scale and because of the disciplinary boundaries we erect to compartmentalise knowledge. Large scale scientific studies are rare, and it is even more rare to find such studies being seen a excellent science. A notable exception appears to be the Port Phillip Bay Environmental Study, undertaken by CSIRO and collaborators, where a simple conceptual model of the system evolved with growing understanding of the system, and was used to establish hypotheses of critical linkages that required testing.

The boundary rider problem in science

Scientists jealously guard the boundaries of their science, and will savage non-scientists who have the temerity to meddle with what they consider is a scientific question. The drawing of sharp boundaries between science and policy seems crucial to the political acceptability of the advice (Jasanoff 1990). This boundary is often negotiated between the scientists and the managers. When the boundaries hold, the advice from the scientific community can be invested with an unshakeable authority, almost regardless of the quality of the actual science or advice being given. When the boundary is breached, the decision moves to more public arenas such as television, and the experts role is diminished.

We have another interesting boundary example before the Australian courts at present. There is an investigation underway about the health impacts of passive smoking. The scientists concerned apparently decided to only consider 'peer reviewed'science. The tobacco lobby has objected that this is a device to exclude the data and the conclusions they seek to put before the inquiry. In my own area, I am aware that work done by industry lobby groups, or even done by reputable scientists funded by such lobbies, is discounted. This is a serious challenge for science. We promote science as rational, being based on observations and conclusions from those observations; yet in some ways we ignore these guidelines for deciding truth and sometimes use a criteria such as the source of funding.

Science and environmental conflicts

There are several characteristics of environmental conflicts:

They have several different parties involved.

They have several different issues of interest to different players.

There is uncertainty about how the ecosystem will respond to various operations and possible accidents.

Environmental information, especially predictive models, is often poor and not available to all players.

There is uncertainty about how the various political players will act.

There are high emotions since all participants believe strongly in the virtue of their own position and the self interest of all opposing positions.

The conflicts are very public, being played out for the evening TV news so it is easy for participants to get locked into extreme positions and find it hard to back down.

There are five elements that are common in environmental conflicts. All elements may be observed in a particular dispute, or some may be more dominant than others. The different elements require different strategies to resolve them.

a. Interest or Distributional Elements

Interest elements refer to the self interests of the people involved. Players may be competing to exploit a resource for mineral extraction or for tourism against those who are the present beneficiaries. They have a personal financial involvement in the outcome, and believe that it is necessary to sacrifice the interests of others so their needs can be met. They may not even recognise the needs of others.

b. Value Elements

Value elements involve more fundamental belief systems about the importance of things like our cultural responsibility for land, wilderness, conservation, development and use of resources and so on (e.g. Martin 1991). Players need not have any personal involvement, nor even to know the area at all, to have a strong position on these values. People can co-

exist with different values but conflict arises when players feel that another set of values is foisted onto them.

c. Data Elements

Data elements arise when people lack the information to make wise decisions. They may be misinformed about likely outcomes or may disagree about what data are relevant. The relevant data may not exist, or they may be held by some of the players who decline to share them. Players may not trust the data provided by other players, or may not accept the relevance of data that does not support their position. They may disagree on the appropriate techniques to analyse or interpret the data.

d. Labelling Elements

Labelling elements enter a conflict when players label other players with negative labels that may introduce misconceptions and stereotypes. Greenies, dole bludgers, miners and blacks can all be used as pejorative terms to avoid listening to what the people are saying and responding to the substance of their concern.

e. Structural Elements

Structural elements are introduced by the organisational structure we erect to manage the resource. Conflicts between parks agencies and minerals and energy agencies and between resource use and environmental protection agencies are common. Significant conflicts may occur between state and federal interests. These conflicts tend to be driven by forces outside the people in the actual dispute. The actual players may have limited authority to do other than represent their agency/state viewpoint.

When scientists disagree

Advocacy Science

It is common for scientists to appear on several sides of an environmental issue, sometimes as ardent advocates of one particular outcome. As someone once quipped 'For every PhD one can find an equal and opposite PhD. ' For those of us who appreciate the process of conjecture and refutations of science this is no more than the healthy tension between conflicting interpretations that shows the essential process of challenge which is integral to science. Lay persons tend to see such assertions not as inputs to a scientific dialogue but as the outputs of science that are obviously flawed since they cannot agree. As Susskind and Cruikshank (1987) point out, such 'advocacy science ' tends to cancel itself out causing non-scientists to ignore the scientific element entirely since 'if they can't agree, how are we supposed to? ' Advocacy science, where scientists see themselves as technical spokespersons for a particular viewpoint can lead to a 'battle of the print outs. ' The size and presentation of the printout becomes a substitute for arguing for the appropriateness of conceptual and computer models and their underlying assumptions. Bellett et al (1990) identify the inequality of power and resources in such adversarial proceedings relating to the health impacts of 'Agent Orange ' in the Royal Commission environment.

I argue that such advocacy science is a prostitution of science that does not contribute to wise solutions of problems, nor to the professional standing of science.

Is there Real Disagreement?

It is first necessary to determine if there is a genuine conflict between scientific parties in a dispute. Scientists are often skilled in using rhetorical devices to sway opinion even when there is little conflict over the substance. A statement like 'There is no evidence to show ... ' might mean there are no data, there are inconclusive data, or the analyses undertaken are not relevant or are incomplete. It does not mean there is evidence to support the counter view. This is a debating device to disparage the opposing position, yet non-scientists might think such statements show a strong conflict over the substance of the debate (Ozawa and Susskind 1985).

Scientists may also cause confusion by presenting facts in selective ways. The same fact can be presented in different ways to support differing perspectives. In the debate in the ACT on the addition of fluoride to drinking water it might be claimed that ten people in the ACT will suffer fluorosis if the water is treated. Alternatively, the same assertion could be presented in terms of only 0.003% of the Canberra population being at risk from fluoride poisoning. Such rhetorical devices imply scientific disagreement when there may be no disagreement on the facts.

Disputes over Methods

Scientists tend to embrace favoured approaches to particular problems, often founded in their training or available equipment. This can lead to disagreement with those who favour other methods. An example would be in trying to assess the likely damage of a release of contaminated water into a stream. Some would choose to use laboratory toxicity studies where the impact of the contaminants on test species are assessed under standard conditions. Others would argue that such data has very limited application to the field where a mix of species experience varying environmental conditions over daily and seasonal time scales. These scientists might argue that biological monitoring of the stream is the only way to determine such impacts. Yet others would put fish or other test organisms in the stream in cages and observe their longevity. Such strategies are only appropriate to document impacts, not predict them before discharge.

All methods have various strengths and limitations. Honesty about both is a prerequisite to advancing our knowledge.

Errors and Repeatability

There can be errors in measurement and in logic. Results that are unexpected are usually treated with caution until other scientists have been able to repeat the measurements. Other errors can be introduced by different methods of interpretation. For example how reasonable is extrapolation beyond the range of actual measurements? How valid is any surrogate measure that may have been adopted? How valid are the statistical tools that have been applied?

Resolving science intensive conflicts

Data Availability

If our society seeks wisdom in the resolution of environmental conflicts, such settlements must be built upon all the relevant information that can be made available at the time, and a clear identification of the remaining uncertainties (Dorcey 1983). I argue that scientists have a professional responsibility to the community to help clarify the data elements in any environmental conflict. This is a fundamental responsibility of any group calling itself a profession, and it is a responsibility at both the individual and at the professional association level. Organisations like the Institution of Engineers enshrine such aspects in their code of ethics. Since many environmental scientists are employed by Government agencies the role of the professional associations such as ASL and the Environment Institute of Australia are particularly important.

Advocacy science is undesirable since it rarely leads to all relevant information being available and to the uncertainties being admitted and analysed in terms of risk analysis. Advocacy science, where uncomfortable data is ignored or suppressed is a parody of what good science should be. A better outcome would result if scientists co-operate to minimise the risks of being wrong. A working approach that ensures all the best technical evidence is incorporated regardless of which 'side' it seems to support is essential to wise outcomes and to the professional integrity of scientists

It is normal in science to share data and observations as support for particular theories or interpretations. Scientists may restrict access to data while they are interpreting it, but seek to publish their findings as soon as possible. This is unlike the normal adversarial legal proceedings where information may be restricted in an attempt to surprise opponents.

In environmental conflicts there are real dangers if one player (a Government agency or a developer) is seen as trying to suppress information. This may escalate the value element of a conflict where one group is seen to be trying to foist its views on the wider community. The Hydro Electricity Commission in Tasmania in the great dam debates operated as though the data elements were the key to the conflict, and they were restrictive about what data they released. The conflict was eventually resolved on value elements, not data elements.

There is a community expectation, now enshrined in various Freedom of Information Acts, that if public money is used to collect data on the environment, then those data should normally be public property available to all. Certainly as a principle of conflict resolution the wide availability of data seems a prerequisite to identifying satisfactory outcomes that meet the needs of all players (Dorcey 1983). Creative solutions to problems are unlikely to emerge when critical data are kept secret.

Scientific Forums

Professional associations have a role in providing a forum where the various scientific viewpoints can be argued. It may be that such meetings can come up with conclusions that can be communicated to the parties involved and the press. The very likelihood of an independent scientific scrutiny might well temper some of the wilder claims of protagonists.
Joint Fact Finding

In many conflicts there will be inadequate data, or lack of agreement on what data needs to be collected to address the issue. Science normally works by trying to break down an issue into a series of questions.

There are considerable advantages if the various players can agree on these various questions and agree on what data are needed to test a key assumption about which there is disagreement. If there is limited trust between the parties it is useful to collect jointly or commission the collection of the required data. It is then difficult for one party to attempt to disown or discredit the results at a later stage. This joint work might extend to the collaborative building of forecasting models such as used in the Adaptive Environmental management approach of Hollings (1978).

A specific area where joint fact finding might be productive in Australia is in setting appropriate standards. It seems inappropriate to import standards from other environments, or to allow advocacy science to dominate the process. This is obviously an area where scientists might do a better job in a substantive sense than administrators or lawyers who seem more concerned with process than substance when involved in administrative reviews and appeals hearings. The activities of political lobbyists in these standard setting exercises is also a concern that a joint fact finding approach could overcome.

Facilitation

There is a growing literature on approaches to resolving environmental and other disputes (e.g. Susskind and Cruikshank 1987; Fisher and Ury 1981) and there is an emerging role for a third party to act as facilitator or mediator to help the parties reach agreement. Such help from a third, independent party holds promise in science-intensive conflicts.

The facilitation role involves mainly managing the processes by chairing the discussion and ensuring an orderly resolution, or at least orderly addressing of the various issues. Mediation goes beyond just helping with process and helps with substance as well. The mediator becomes an active explorer of the issues, challenging evidence and framing critical questions to all parties.

Both facilitation and mediation roles can demand the use of plain English by the various protagonists in a bid to widen understanding. Periodic progress reports identifying what there appears to be agreement about as well as what remains as disagreement can help to structure the debate and show all parties that progress is possible. The third party might help all players by admitting he does not understand some aspect and seeking a further explanation of it.

The mediator may regularly paraphrase the arguments on both sides and identify the common ground and common assumptions. This may lead to rephrasing of the key questions into an answerable formulation, and it might lead to the parties altering their positions.

Scientists have the opportunity to make significant contributions to help resolve environmental conflicts. They can only help, because there are many non-scientific elements in most conflicts, which have to be resolved through the normal political mechanisms. There are often data elements in environmental conflicts, and the scientist can help by ensuring all participants understand what we know about a particular system, and the uncertainties and risks of various courses of action.

There are conflicts which do not take place in the formal arena of an Advisory Committee or Public Inquiry. The debate about the desirability of removing phosphorus from detergents in such an example in which I was a protagonist. There are a number of interesting features of this debate.

- Views are very strongly held by players
- Published papers and evidence does not seem a significant element in forming these views. Many protagonists do not know the scientific literature in the field.
- Participants commonly attribute improper motives to participants with differing views. Insults are common.
- Science is often seen a tool to bludgeon ones opponent (the thickness of the print-out) rather than a means of finding a way forward.
- There is often not an effective bargaining arena where opposing views can be presented and argued. Proponents argue in the press or through private lobbying and rarely directly exchange information with those of opposing views.

Summary and conclusions

There is an increasing diversity of pressures on our natural resources, and an intensification of the pressures due to population growth. Our organisational arrangements for managing resources rarely allow integrated whole system management, and commonly introduce quite artificial boundaries between interests and scientific disciplines that take considerable energy to manage

The ecological sciences often get confused in the public mind with environmental dogma in the political context. The ability of ecology to make useful predictions is limited, but is increasing. Managing natural resources and managing science have in common that they are both operating in a conflict management environment where outcomes are decided by bargaining between different viewpoints. Science is no more rational than resource management in this regard, despite the wish of scientists to occupy the moral high ground of rationalism.

The scientific community needs to understand the game it is playing in. Playing tennis when everyone else on the same ground is playing golf is not the way to harmony. Scientists are going to have to develop better skills in conflict management, and how knowledge can contribute to better decisions if they seek to maximise their influence.

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Science and tourism infrastructure on the Great Barrier Reef: learning from experience or just 'muddling through'?

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ABSTRACT

Learning from the experience of past developments is essential if we are to develop a capacity for better predictions in environmental impact assessment (EIA). To be efficient, this learning process must be planned with close collaboration between managers and scientists. Over the past 13 years, a wide range of infrastructure has been developed to support the tourism industry within the Great Barrier Reef Marine Park. Many of these proposals had few precedents in coral reef environments and have included more than 23 different tourist pontoons, 5 floating hotels, artificial islands and reefs, underwater restaurants, boardwalks, and numerous resorts and marinas. In this article, I review what is known about the impacts of these structures in the Great Barrier Reef Marine Park and the activities that they support. Examples are used to illustrate the role that science has played in the assessment process and how the collaboration between scientists and managers could be improved. I show that the process of learning from these developments has not followed the idealised pattern of incremental acquisition of knowledge, but, rather, has been punctuated by significant events. Moreover, the nature of decisions about tourism infrastructure and the information needs for assessment have changed as the demand for new sites and experiences has increased.

INTRODUCTION

In the 13 years since the last *Science and the Great Barrier Reef Conference*, tourism has grown to become the major commercial use of the Great Barrier Reef Marine Park. Between 1985 and 1995, the number of permitted commercial tourism vessels within the Marine Park increased from around 275 (Driml 1987) to more than 1300 vessels (Williams, in press) and the total permitted capacity increased from around 1.1 million visitors per annum to over 10 million. This enormous growth has been accompanied by development of a wide range of infrastructure within and adjacent to the Great Barrier Reef Marine Park to support the tourism industry (figure 1). Proposals have been received for, among other things, artificial islands and reefs, day-trip pontoons, underwater restaurants, floating hotels, and a large number of resorts and marinas. The environmental assessment and management of these projects has required considerable resources from the Great Barrier Reef Marine Park Authority (GBRMPA). Many of the offshore developments had few precedents in coral reef environments and the Authority has had to develop new policy to guide their assessment. Listing of the Great Barrier Reef on the World Heritage register in 1981 presented managers with the additional challenge of determining if and where such major infrastructure projects were appropriate in a World Heritage Area. These issues continue to be controversial and to consume large proportions of the Authority's time and resources.

In this article, I review what has been learned from the past 13 years of tourism development on the Great Barrier Reef. Learning from past development decisions is an important part of environmental impact assessment (EIA), because it allows better prediction and planning for future projects (Hilborn and Walters 1981, Fairweather and Lincoln Smith 1992). Here, I examine how lessons learned from the assessment of three classes of tourism development on the Great Barrier Reef – floating hotels, day-trip pontoons and coastal marinas – have

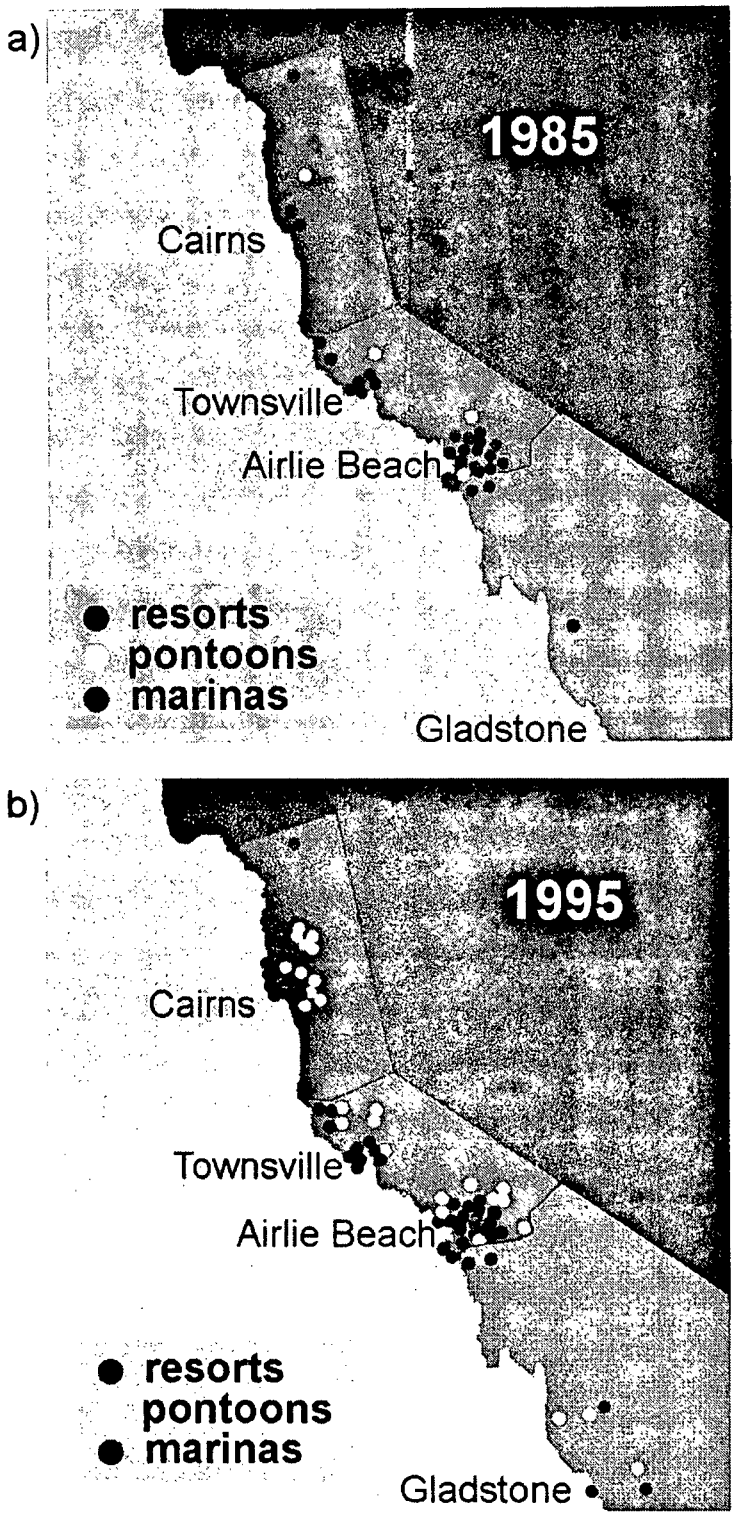


Figure 1. Changes in the number and distribution of island resorts, pontoons and marinas within the Great Barrier Reef region between a) 1985 and b) 1995

been transferred into policy. Public policy is the most tangible measure of the collective knowledge of an institution because it is developed from the decisions and prior experience of a range of individual administrators (Lindblom 1959). It is also the only means by which that knowledge is captured and communicated to others within and outside the institution and, subsequently, to new decisions. Policy is, therefore, a critical output of the process of learning. I begin by contrasting the current 'idealised' view of adaptive learning and the traditional framework of public policy development to identify factors that accelerate and

constrain the learning process. Case studies are used to show how these factors have influenced policy for the management of tourism infrastructure in the Great Barrier Reef Marine Park.

Learning from environmental decisions

Scientific theorists typically advocate an 'adaptive' approach to learning about the environmental impacts of major developments (Hilborn and Walters 1981, Walters 1986). Adaptive management views development decisions as akin to scientific experiments, in which predictions about the likely environmental consequences of the proposal under a given policy setting are tested by planned scientific monitoring once the project is implemented. Information obtained on the accuracy of the predictions and, therefore, the effectiveness of the policy is then used to modify the approach to subsequent, similar developments (figure 2). To be effective, adapative learning depends on five critical components: 1) close collaboration between managers, scientists and stakeholders to identify the major issues of concern and develop appropriate mitigative actions; 2) quantitative predictions about the type and magnitude of impacts that are expected; 3) pre- and post-development monitoring to test the accuracy of the predictions; 4) post-project review of the assessment process; and 5) the transfer of knowledge acquired in the assessment to subsequent decisions.

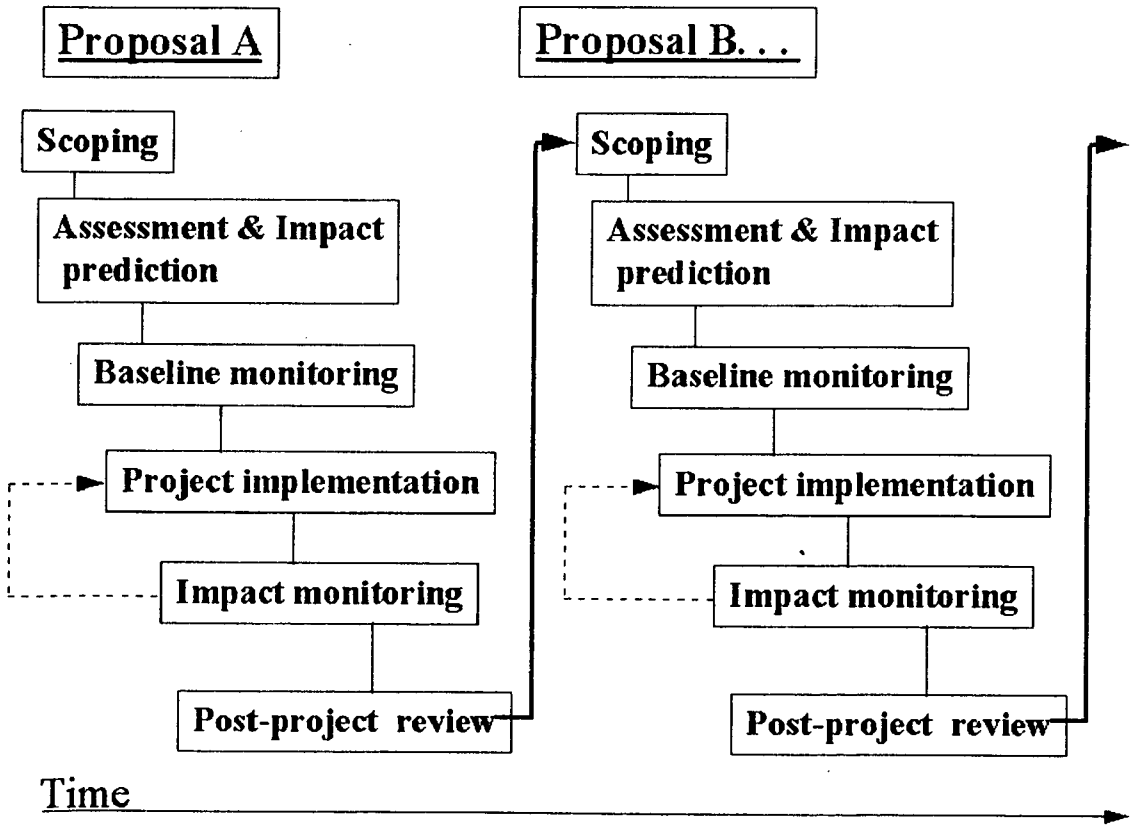


Figure 2. Relationship between the major components of environmental impact assessment and the flow of information from one development to the next in an adaptive learning approach *Adapted from Glasson et al. (1994)*

Unfortunately, many of these components are missing from the way EIA is currently practiced in Australia (Buckley 1991, Coopers and Lybrand 1994). Predictions of the environmental effects of major developments are usually qualitative and, therefore, not amenable to measurement and there has been a lack of commitment to monitoring and

post-project review (Buckley 1991, Fairweather and Lincoln Smith 1992). The adaptive approach has also been criticised because it is at odds with the way real policy is developed (Lindblom 1959, McLain and Lee 1996). For example, adaptive decision making assumes efficient transfer of information from one development decision to the next and that the framework for decision making is flexible enough to respond to new information. The desire for consistency in public policy means that there is rarely the opportunity for such flexibility. According to Lindblom (1959), most policy evolves through a series of small, successive changes to existing settings (a process he referred to as 'muddling through'), rather than through the rapid advances that are implicit in the adaptive approach. Existing policy frameworks, therefore, are likely to exhibit considerable inertia and contain a large historical component (Wilder 1993). 'Learning' in this form of policy development is mostly concerned with how well existing policy addresses the major issues and is less concerned with the mechanism by which it does so. 'Good' policy is achieved when there is general consensus that it is the best possible approach to an issue (Lindblom 1959). In the following sections, I describe important historical milestones in the development of policy for tourism facilities in the Great Barrier Reef Marine Park and examine how effectively the components of adaptive learning have been applied to refine the management response to these structures.

Offshore structures in the Great Barrier Reef Marine Park

For most of its length, the Great Barrier Reef is more than 20 km from the coast of mainland Australia. In the early 1980's, a number of proposals were received to develop stable, permanently moored tourism facilities on the Great Barrier Reef to enhance the experience of visitors to the outer reef. Although there was some initial opposition to these structures from environmental groups, the tourism industry and the Ministerial Council for the Great Barrier Reef Marine Park saw them as having potential to relieve the pressures on reef islands which were already under considerable stress from high levels of visitation (GBRMPA 1985). There is some evidence that they have been successful in doing this. Recent studies show that approximately 34% of first time visitors and 12% of return visitors to the Great Barrier Reef see the reef from permanently moored platforms (Moscardo pers. comm.).

Two types of offshore structures – floating hotels and day-trip pontoons – have been the subject of the most detailed environmental assessments within the Great Barrier Reef Marine Park and will be discussed here.

Case Study 1: Floating Hotels

Perhaps the best known and most well-documented assessment of an offshore structure in the Great Barrier Reef Marine Park was the Four Seasons Floating Hotel (FSFH) that was installed in the lagoon of John Brewer Reef, off Townsville, in 1988. This was a five storey resort-style hotel (89.2 m long x 27.6 m wide x 24.2 m high) that had accommodation for up to 366 guests and 100 staff and which served as a base for a range of reef activities including fishing, wind surfing, scuba diving, snorkelling, coral viewing and fish feeding (Harriott and Saenger 1995). The hotel was built in Singapore and shipped to the Great Barrier Reef, where it began operating in March 1988. As the first floating resort of its kind in the world, the venture received much international attention. It was not, however, a commercial success. Average occupancy during its time at John Brewer Reef was around 20% and the resort ceased operating within 12 months of opening. It was subsequently sold and relocated to Vietnam (Muldoon 1990, Harriott and Saenger 1995).

Impact Assessment and Monitoring

In many ways, the FSFH development was a major milestone in policy development for tourism facilities in the Great Barrier Reef Marine Park. When it was first proposed in 1984, there were few relevant planning and regulatory instruments to guide its assessment. The Central Section of the Marine Park had not been zoned and specific amendments to the Regulations of the *Great Barrier Reef Marine Park Act 1975* were necessary to allow structures in unzoned sections of the Marine Park to be controlled by Marine Park permits (GBRMPA 1986). Moreover, at that time, there was uncertainty about the legal status of

offshore structures. Australia had not yet ratified the Third United Nations Convention on Law of the Sea (UNCLOS III) and its declared territorial sea extended only 3 nm from baseline[1] (Rothwell and Haward 1996). Development of the FSFH prompted the federal government to introduce new legislation to extend Commonwealth civil and criminal law to structures outside territorial waters. This new legislation, the *Sea Installations Act 1987*, also contained provisions for minimum safety and environmental standards for the design, installation and operation of offshore facilities. Complementary State legislation (Queensland *Offshore Facilities Act 1986*) had earlier been passed for structures in waters adjacent to Queensland.

Because of its uniqueness and location within a World Heritage Area, the FSFH proposal was subject to EIA under the provisions of the Commonwealth *Environment Protection (Impact of Proposals) Act 1974*. Like most documents of its type (Buckley 1991, Fairweather and Lincoln Smith 1992), the draft Environmental Impact Statement (EIS) contained mostly qualitative predictions of the expected impacts of the facility, with the principal exceptions being predictions about the engineering performance of the structure and matters that were controlled by licences (e.g. effluent quality). Direct impacts were expected to be from cropping of patch reefs to allow passage of the hotel into the lagoon, disturbance to marine life around the structures by shading and moorings, pollution of water and air associated with waste disposal and desalination, reduced visual quality of the surrounding environment and the possibility of accidental grounding of the hotel. Anticipated secondary impacts included the effects of increased boat traffic, scuba diving, and anchor damage on marine life (Bastin and McGinnity 1988). With the exception of cropping of the patch reefs, these effects were all expected to be relatively minor.

The Great Barrier Reef Marine Park Authority adopted a conservative approach to impact management. Permits for the resort were issued in stages to allow feedback on the implementation of each phase of construction. General approval to operate was conditional upon the development of a resort management plan, a comprehensive environmental monitoring programme, insurance of the facility, provision of a bond for environmental rehabilitation in the event of damage caused by the structure or its removal, compliance with standards for public health and safety and with guidelines for site management (Dutton 1986). Details of these conditions were specified in a legal contract between the Authority and the proponent.

The monitoring programme contained a combination of studies intended to detect the direct effects of the facility on the surrounding environment and determine its compliance with permit conditions. Major components included an examination of changes in the quality of lagoonal waters and sediments, compliance monitoring of wastewater effluent, surveys of the marine benthos and fishes, and surveys of the attitudes and patterns of use of John Brewer Reef by other stakeholders. An additional study examined the survival of corals transplanted from the cropped patch reefs.

Overall, the monitoring studies showed few detectable effects on the surrounding environment associated with the installation, presence or removal of the resort (Harriot and Saenger 1995). Apart from the cropped patch reefs, no major changes were detected in coral assemblages surrounding the resort (Harriott and Saenger 1995). Colonies transplanted from the cropped reefs survived well (98 % survival), but the physical disturbance and debris caused by the excavations killed most of the remaining organisms on the tops of the affected reefs and produced some signs of stress in those remaining on the sides of the bommies (Harriott and Saenger 1995).

There were also few detectable changes in the quality of lagoonal waters and sediments during the time that the hotel was present (Harriott and Saenger 1995). Treated effluent from the resort was released in open water about 5 km from the resort and was not expected

[1]Australia extended its territorial seas to 12 nm in November 1990 and, in 1994, declared a 200 nm Exclusive Economic Zone and ratified UNCLOS III.

to affect lagoonal waters. Technical problems encountered during the commissioning of the waste water treatment plant, however, meant that the biological oxygen demand (BOD), and concentrations of suspended solids and *E. coli* of the effluent frequently exceeded permit conditions.

The most striking effect of the development was the attraction of large predatory fishes (e.g. lethrinids and lutjanids) and smaller aggregations of grazing (e.g. scarids and siganids) and scavenging fishes (e.g. mullids) to the hotel and its associated pontoons. These aggregations dispersed within months of the structures being removed (Harriott and Saenger 1995).

Major users of John Brewer Reef, including day visitors, charter boat passengers, private boat owners and fishermen, were generally positive about the presence of the resort, with approximately 30 % of those surveyed reporting an increase in visits to the reef (Harriott and Saenger 1995). There are, however, indications that public attitudes to floating hotels on the outer Great Barrier Reef have since changed. Only six public submissions were received on the draft EIS for the FSFH (Det Norske Veritas and Coastal Ecosystems 1985), four of which came from environmental groups concerned at the loss of 'wilderness values' in the Marine Park. While the resort was being built, permit applications were received for very similar projects at Fitzroy Reef and Lady Musgrave Island in the Capricornia Section of the Great Barrier Reef Marine Park. Many more submissions (38) were received on the draft EIS for the Fitzroy Reef proposal (Marine Biologic 1988). Again, the top ranking issues were the perceived loss of wilderness values (17 submissions) and long-term degradation of the environment (17 submissions). Eleven submissions each identified the need for an overall management plan for reef developments to prevent *ad hoc* proliferation of floating hotels and other structures. Although a permit was issued for the Fitzroy Reef hotel, it did not proceed for financial reasons (GBRMPA 1992).

The greater number of submissions on the Fitzroy Reef hotel reflected public dissatisfaction with the number of structures that were being proposed in the Great Barrier Reef Marine Park. Between 1983 and 1987, the Authority received permit applications for at least 3 floating hotels and 21 pontoons. Repeat surveys of the attitudes of Cairns residents in 1985 and 1991, showed a significant decline in support for floating hotels, with < 12 % of respondents favouring their development in 1991 (Alder 1996). This level of public concern prompted the Ministerial Council for the Great Barrier Reef to initiate a review of the status of offshore developments in the Marine Park, the outcome of which was a 2 year moratorium on floating hotels, that came into effect in 1988. The moratorium was intended to allow time for the results of monitoring studies associated with the FSFH to become available. Unfortunately, these studies did not directly address the principle concern expressed about offshore structures; loss of wilderness values (Carey 1993).

The Learning Process

The FSFH development provided a positive early example of environmental management in the Great Barrier Reef Marine Park. The resort was installed, operated and removed with only minor direct effects on its surrounding environment. This can be attributed this to close collaboration between the proponent, the GBRMPA and other responsible agencies early in the design stages of the project and to the flexibility allowed with a non-permanent, floating structure (Harriott and Saenger 1995). The strict environmental management procedures developed for the FSFH, including the staging of approvals and the formal contractual arrangement between the Authority and the proponent were seen as a successful model for the management of subsequent developments and became policy in 1989 (Appendix 1).

Administration of the monitoring programmes, however, was less than ideal, with late and uncoordinated reporting of results by consultants, delayed release of information and a lack of coordination between monitoring and site development for some studies (Harriott and Saenger 1995). These difficulties compromised the ability of the Authority to react quickly to information as it became available. In 1989, steps were taken to address this problem when the Authority introduced policy that made monitoring programmes mandatory for all

major structures developed in the Great Barrier Reef Marine Park (GBRMP 1989). Consultants employed by the proponent were to be managed directly by Authority staff, who provided direction on the scope and experimental design of the monitoring studies. This arrangement was supplemented by external expert review of the proposed study design and of the consultant's final report. Minimum requirements for monitoring studies have also been supplied to consultants since 1992. These incorporate a commitment to sampling before and after the development proceeds and the use of multiple control sites (i.e. the modified BACI designs described by Underwood 1993). Collectively, these procedures are intended to control the rigour, quality and independence of monitoring studies and are practiced by few other environmental agencies in Australia (Coopers and Lybrand 1994). They can be considered an example of 'best practice' in adaptive learning (Carey 1993, Whitehouse 1993, Underwood 1995).

Case Study 2: Day-trip Pontoons

Moored platforms, or pontoons, began to be used as a basis for day-trips to the outer Great Barrier Reef in the early 1980s. The first pontoons installed in the Great Barrier Reef Marine Park were relatively simple, rectangular steel or aluminium barge-like structures (approx. 10 m x 30 m) that were held in place by a system of anchor blocks and heavy chains on the sea floor. They were used as a stable platform on the outer reef for activities like snorkelling, scuba diving, fish feeding and glass-bottomed boat trips and were serviced by catamarans capable of transporting 150–200 passengers per day (Muldoon 1990). The past 10 years have seen considerable changes in the number, design, capacity and technology of pontoons and their anchoring systems. There are currently 23 permitted pontoons and associated structures within the Marine Park. Fourteen of these are day-trip destinations and the other nine are ancilliary pontoons for helicopters and seaplanes. Most (18) are located within the Cairns and Whitsunday regions of the Marine Park (figure 1). The latest structures are multi-level platforms that contain underwater observatories, docking facilities for a variety of vessels, barbeque and dining areas, freshwater showers, overnight accommodation for caretaking staff, separate platforms for scuba diving and snorkelling and additional pontoons for helicopters and seaplanes. The largest pontoons are currently surveyed for up to 700 people per day, although most operate at just under half this capacity. Individual sites may cater for > 50 000 snorkellers per year (Inglis and Shafer unpubl. data).

Impact Assessment and Monitoring

Permit applications for pontoons are assessed by GBRMPA staff against a set of criteria contained within Regulations of the *Great Barrier Reef Marine Park Act 1975* (Regulation 13 AC(4)). These require consideration of the likely effects of the development on the biophysical environment, public health and safety and other uses of the area. Pontoon applications have not usually required preparation of a formal EIS, but must contain information on the engineering design, proposed location and day-to-day operation of the facility and a brief description of the environment in which it is to be located (GBRMPA 1989).

There has been a strong commitment to monitoring the direct impacts of pontoons. The first study was initiated voluntarily in 1986 by a tour guide company (Reef Biosearch) and subsequent programmes have been done at the behest of the GBRMPA. A comprehensive review of eleven pontoon monitoring studies was recently completed by Nelson and Mapstone (in press). In general, the programmes have examined three types of impacts of pontoons: effects on benthic assemblages (mostly corals), effects on fishes, and effects on water quality.

Studies of the benthos have usually examined changes in coral assemblages immediately beneath the pontoons (the pontoon 'footprint') and the impacts of secondary activities such as snorkelling and scuba diving on the surrounding reef. Overall, there is weak trend toward reduced abundance of most corals within the 'footprint' of the pontoons, presumably as a result of shading. Some taxa, such as the Pocilloporids, appear unaffected by the pontoons

and, in some instances, have even increased marginally in coverage within the pontoon footprint (Nelson and Mapstone, in press).

Despite the high levels of use, no consistent patterns of change have been associated with snorkelling from pontoons. Coral cover in the snorkelling areas has variously increased, declined or remained similar to that at comparable control sites. The only significant effect detected in the seven studies that examined changes in corals associated with snorkelling was a 7-fold increase in the percentage of damaged colonies at a single pontoon site. Recent research within the CRC Reef Research Centre has shown considerable variation among sites in the rate at which damage is caused by snorkellers and scuba divers (Inglis and Shafer, unpublished data, Rouphael and Inglis 1995) that is associated with differences in the biological characteristics of the reef and how the activities are managed on a day-to-day basis.

As with the FSFH, the most striking effects of pontoons, are the aggregations of fishes beneath them. The species composition of these aggregations varies widely among pontoon sites, but most contain large numbers of predatory fishes (e.g. Carangids, Lethrinids, Lutjanids and Serranids, Nelson and Mapstone in press), which can be up to 20 times more abundant at the pontoons than at control sites on the reef. Sweatman (1996) has shown that these aggregations have a strong diurnal pattern that broadly corresponds with the arrival and departure of the tourist vessel. The size of the aggregations is influenced by the size of the pontoon and whether or not fish-feeding occurs as a regular activity. There is no evidence that the feeding aggregations deplete fishes from other areas of the reefs or that they affect local populations of fishes and invertebrates.

Data on water quality have been collected at only four pontoon locations and, in general, are too few and variable to make any substantive conclusions on the effects of pontoons on nutrients. There is no evidence for any major decline in water quality associated with activities on these structures.

The learning process

The review of pontoon monitoring by Nelson and Mapstone (in press) was critical of the administration of many of the programmes. Despite management of the studies by the Authority, there was considerable variation in experimental design, sampling methodology and the variables measured. This prevented a comprehensive analysis of environmental impacts. More seriously, the ability of most studies to detect meaningful changes was severely limited. Many began after the pontoon was installed or included only a single survey before it was in place. The experimental design often changed during the study and most were completed within 18 months of installation, thereby preventing any examination of changes in coral assemblages over time scales relevant to the life-histories of most species. Moreover, the studies were almost all done in the absence of any prior predictions of the magnitude of impact that might be expected or deemed acceptable by the Authority. Thus, it was unclear if the studies were measuring appropriate variables or had sufficient power to detect even moderate in the environment. A number of these problems were also raised by expert reviewers of the programmes, but their comments appear to have had little influence on the way subsequent studies were implemented (Nelson and Mapstone, in press). In some instances, it seems that clear choices were made to sacrifice the scientific rigour of the monitoring programmes for more immediate concerns of financial and political expedience.

Nevertheless, the monitoring studies have provided useful feedback on the design and site management of pontoons. Major problems such as shading of corals in the pontoon footprint and damage caused by movement of the anchor chains were identified by early studies and were mitigated in later developments by locating the pontoons over sand and modifying the anchoring systems so that they would not drag. There is now general agreement that with appropriate site selection, mooring design and site management, the direct impacts of pontoons on the biological environment are relatively minor and reversible on removal of the structure.

Policy development for the assessment of pontoon proposals has, however, been driven mostly by concerns for risk and liability (Cook 1992). Guidelines for the assessment and installation of pontoons were developed in response to several notable failures of pontoon structures during severe storm events. In 1988, a doughnut-shaped concrete pontoon installed at John Brewer Reef sank at its moorings just two weeks after it was installed. 'Fantasy Island', as it was called, was eventually salvaged after more than 18 months of negotiation between the Authority and the developer (Muldoon 1990).

Several other structures have been damaged by cyclones or have caused localised impacts to corals during severe storms. Not long before the FSFH began operating, a category 2 cyclone ('Charlie', central pressure 995 hPa) passed within 75 km of John Brewer Reef. Although, the hotel itself was not damaged, several ancilliary pontoons broke free of their moorings and were damaged. In December 1990, a category 4 cyclone ('Joy', central pressure 940 hPa) came within 90 km of pontoons at the Agincourt reefs, north of Port Douglas. Movement of the pontoon's anchor chains severely damaged surrounding coral colonies. Monitoring studies in place at the time suggested that damage at the pontoon site was no greater than that caused by cyclonic waves on nearby reefs (Nelson and Mapstone in press). Nevertheless, the GBRMPA viewed movement of the anchoring system as undesirable and took steps to tighten engineering requirements for pontoon developments (Cook 1992). In 1992, cyclone Fran (category 3, central pressure 970 hPa) damaged pontoons at Lady Musgrave Island and Wistari Reef in the Capricorn Section of the Marine Park. At Lady Musgrave Island, the pontoon itself broke free of its moorings and was grounded on a nearby reef. At Wistari Reef, the mooring chains of the pontoon shifted and damaged a number of large coral colonies under the pontoon.

Draft guidelines for the assessment of pontoon proposals were introduced in 1989, after the sinking of Fantasea Island, and were subsequently modified in 1991 and again in 1992 in response to the failure of anchoring systems on pontoons at Agincourt, Lady Musgrave and Wistari reefs. The guidelines incorporated requirements for bonds to cover salvage or removal of the facility, insurances against third party liability and rehabilitation, and general criteria for the design of pontoons and anchoring systems. Because of the lack of available information on cyclone characteristics in the Great Barrier Reef and uncertainty in predicting the properties of cyclonic waves and pontoon performance within the reef matrix, the draft guidelines were conservative. They contained design criteria that were based on the probability that a category 4 cyclone would be encountered during the design life of the pontoon (taken to be 10 years, Cook 1992). In fact, a category 4 cyclone has an estimated average recurrence interval of > 500 years for most areas on the Queensland coast (Massel et al. 1996) and the criteria have recently been criticised by tourism operators and some engineers as being overly conservative and expensive to comply with. The policy remains in draft form and is currently under review by researchers at the CRC Reef Research Centre. Importantly, despite the prominence of this issue in guiding the design of pontoons and their anchoring systems, monitoring studies to assess the engineering performance of the structures under field conditions have only been implemented in the last few years.

As with floating hotels, there has been an increase in public dissatisfaction with the number of pontoons proposed in the Great Barrier Reef Marine Park. Twenty eight percent of public submissions received during the rezoning of the Cairns Section of the Marine Park in 1989 cited offshore developments as a major concern, making it the fourth highest ranking issue. In 1991 alone, 18 applications were received for installation or replacement of pontoons in the Cairns Section (GBRMPA 1992). During the previous zoning in 1982, offshore developments did not rate within the top ten issues (Alder 1993). As a result of this concern, a 'No Structures Sub-Zone' was introduced into the Cairns zoning scheme in 1992 to allow some areas close to Cairns to be free of human structures.

Case Study 3: Marinas

Coastal marinas have been among the most controversial tourism facilities developed in the Great Barrier Reef region. Unlike many of the offshore developments, marinas are not unique to coral reef environments within the Great Barrier Reef Marine Park and their direct biophysical impacts are relatively well known (MacMahon 1989). These include loss of marine habitat from land clearance, reclamation and dredging, changes in water flow within marina basins and reduced water quality associated with waste disposal, refuelling, antifoulants and effluent discharge.

There are several reasons why marina proposals have been controversial. First, unlike offshore developments, they are usually built close to existing communities, often as part of a larger resort complex. They, therefore, have the potential to affect a broad range of established uses of the surrounding environment. Second, assessment of these developments within the Great Barrier Reef region is complicated by complex jurisdictional responsibilities. Most resort and marina complexes straddle the boundaries between the Great Barrier Reef Marine Park and adjacent mainland or island areas that are under the jurisdiction of the Queensland State government or local authorities. Thus, although activities based at these facilities may occur wholly within the Great Barrier Reef Marine Park, responsibility for environmental planning and assessment of the terrestrial component of the developments is usually the responsibility of State and Local government agencies.

Magnetic Keys

One of the most controversial of recent proposals was the Magnetic Keys development on Magnetic Island, off Townsville. This development, first proposed in 1983, went through several proponents and at least five separate environmental assessments under both State and Commonwealth legislation (Whitehouse 1992). The original concept was for a 240 room resort hotel, tavern, retail and commercial center, backpacker accommodation and a marina in Nelly Bay on Magnetic Island. It involved freehold land, Queensland Crown land, Queensland Marine Park and the Great Barrier Reef Marine Park and required approvals from at least six different agencies from three levels of government. The Authority's role was limited to considering the environmental effects of the marina on the fringing reef at Nelly Bay, as this was the only part of the development that was within the Great Barrier Reef Marine Park (Whitehouse 1992). After an assessment process that extended over four years, a permit was issued for construction of the marina in 1988. Site works began the following year, but after a series of appeals and stoppages, finally ceased in December 1990, when the proponent went into receivership. At that stage, the breakwalls of the marina were mostly complete, the marina basin had been partly excavated and work had started on the main entrance channel. The site has remained in this unfinished state for nearly six years. In 1993, expressions of interest were sought from private developers to complete works at the site and a further draft EIS was prepared for a smaller residential and marina development (Sinclair Knight Merz Pty Ltd 1995). A decision on the future of the site is still pending.

Impact Assessment and Monitoring

The GBRMPA came under strong criticism from some sectors of the local community for its decision to issue a permit for the original marina proposal. The decision was challenged in the Administrative Appeals Tribunal and was subject to independent review by the Commonwealth government (Whitehouse 1992). At issue was whether the Authority had acted properly in considering the environmental effects of the marina and whether suitable procedures were established to manage its impact. Criticisms centred on the adequacy of scientific and technical information used to make the assessment and provisions for environmental rehabilitation following abandonment of the site.

Information used in the permit assessment came initially from a Public Environment Report (PER) prepared by the proponent (McIntyre and Associates 1988) that was mostly concerned with the direct effects of the marina on the environment of Nelly Bay. The report contained few details on the methods proposed for construction of the marina or their predicted effects on the surrounding environment. Basic information was included on the fringing reef of Nelly Bay, which was considered to have a moderate coverage (30–40 % cover) and diversity of living corals that was typical of other reefs in the region. No data

were presented from other sites on Magnetic Island to support this assertion. Descriptions of other biological communities were similarly based on secondary information and were not supported by the use of any primary data. The socio-economic impacts of the development related principally to its onshore components and included concerns for a change in the character of the island and perceived loss of public space and visual amenity. Again, assessment of the significance of these concerns was largely qualitative, with few supporting data being provided.

The GBRMPA and a number of expert reviewers were critical of the lack of information in the PER. As a result, the proponent was requested to prepare a second report to provide additional details on the regional significance of the Nelly Bay reef and modelling studies of patterns of water flow, sediment transport and water pollution in the surrounding area. Further information was also requested on the proposed construction methods and environmental monitoring programme. The report was submitted within one month of the request, but was again criticised by reviewers for containing insufficient information on the ecological value of the Nelly Bay reef and on environmental safeguards during construction (Whitehouse 1992). GBRMPA initially refused a permit for the development, but in a later meeting with the proponent, sought and agreed upon modification of the environmental safeguards for construction of the marina and thereafter agreed to issue a permit. A Deed of Agreement was signed between the Authority and the proponent that included requirements for environmental monitoring, external review of the construction methods and an agreement by the permittee to remove the structures and rehabilitate the site in the event of wreckage or abandonment. This latter component entailed a surety of $500 000 and rehabilitation insurance to a value of $20 million (Whitehouse 1992). Before the construction works began, comprehensive baseline monitoring studies were done of the benthic biota and water quality in Nelly Bay and a number of other control reefs on Magnetic Island.

The learning process

The Authority issued guidelines for the assessment of marina developments in 1988, in response to the Magnetic Keys proposal and request for permits for a number of other marinas within the region. In 1988–89, applications were received for at least nine other marinas within or adjacent to the Great Barrier Reef Marine Park. The guidelines included recommendations for the choice of location and construction methods for marinas that were intended to reduce their direct environmental impacts (GBRMPA 1989). They were later modified and published as a set of generic guidelines to assist marina developers plan their projects (GBRMPA 1994).

The failure of Magnetic Keys highlighted a number of issues for the management of coastal developments that entail major site works. First, despite the intent of the Deed of Agreement between the Authority and the proponent, there was a clear recognition that the direct impacts of marina construction were irreversible and that rehabilitation was not possible. In fact, the proponent had not secured insurances to cover rehabilitation of the site after it was abandoned. Premiums for this form of insurance were estimated to be in the order of $170 000 p.a. and were considered too expensive to be viable (Whitehouse 1992). The actuarial risk reflects both the expense of site rehabilitation and the disturbing history of financial failure of large resort and marina developments within Queensland and elsewhere. Researchers at Griffith University have recently estimated that up to 25% of proposed resorts go into receivership before they are completed (R. Buckley, unpubl. data). In his review of the Magnetic Keys development, Whitehouse (1992) argued that it was not appropriate for the GBRMPA to assess the economic viability of major developments because it lacked the requisite information to make such assessments and because decisions about risk in business ventures lay most appropriately with the entrepreneur. As this case has shown, however, the risks are not insubstantial and, where public resources are involved, are also borne by the broader community.

Although debate over issuance of the Marine Park permit for the marina in Nelly Bay focussed on the inadequacy of biological information contained in the PERs, much of the

public concern appears to have been over changes in the 'character' of the surrounding area (Whitehouse 1992). The fragmented nature of approvals for the development, meant that these concerns were never adequately addressed in any of the environmental assessments. Instead, public objections appear to have been channelled into issues of scientific merit that were not central to the debate and which did little to reduce the uncertainty in decision making. The socio-economic impact, visual quality and appropriateness of developments of this type within the Great Barrier Reef Marine Park are issues that need to be considered for the development *in toto* and against a background of regional planning. There are currently no such plans in place for tourism within the Great Barrier Reef Marine Park and, therefore, no framework against which concerns for lost amenity can be weighted. Developments such as Magnetic Keys and the more recent Port Hinchinbrook resort and marina near Cardwell will continue to be controversial as long as this is the case.

DISCUSSION

The three case studies described in this paper show that the development of policy for tourism infrastructure in the Great Barrier Reef Marine Park has largely been reactive. Major advances have most often been driven by large and controversial projects, with policy intended to avert the difficulties encountered with past developments. The principal tools used in the assessment process – EIA and Marine Park permits – are reactionary instruments that are used to predict and manage the direct impacts of individual projects. In general, they do not allow assessment of the secondary and cumulative effects of tourism developments (Court et al. 1994). There are clear signs, however, that for all three classes of infrastructure, the major sources of controversy have changed over the past 13 years, from being principally concerned with direct impacts to a greater focus on cumulative effects and questions of site allocation. Monitoring studies have shown that the biophysical impacts of offshore structures, in particular, can be substantially mitigated by good site choice and project management, but the cumulative effects of increasing numbers of structures and the associated social issues of displacement have not yet been addressed effectively. Dealing with these issues will require a change in emphasis from project-specific environmental assessment to broader, strategic planning for tourism development in the Great Barrier Reef region and will entail more sophisticated use of social and economic planning instruments than has been applied to date.

The need for regional tourism planning has been identified a number of times over the past 20 years (e.g. Bastin and McGinnity 1988, Whitehouse 1992). A tourism workshop convened by the GBRMPA as early as 1980–81 recommended that '*a variety of reef experiences* (should) *be made available*' and that '*differences in scale and cost of facilities will correspond to differences in function and location*' (GBRMPA 1981). Implementing a strategy to ensure that the existing range of opportunities within the Great Barrier Reef Marine Park is maintained will be a major challenge for the Authority in the coming years and will require close collaboration between the GBRMPA, the Queensland State and Local Governments, the tourism industry and other major stakeholders in the Great Barrier Reef Marine Park.

Unlike most resource management agencies in Australia, the GBRMPA has had a long-standing commitment to the use of monitoring as a learning tool. Monitoring studies have proved to be useful in refining and assessing the effectiveness of policy, but have not been central to its development. Procedures in place to guide the administration of monitoring programmes, including management of consultants by the Authority and the use of expert reviewers, are generally of a high standard, but their implementation has not always reached the same heights. The contribution of monitoring to environmental management could be improved through better coordination with site works and clearer objectives. Environmental monitoring and assessment invariably involve both a mensurative component (i.e. measuring changes in the environment) and a judgemental component (i.e. evaluating the significance of any changes). Whilst considerable effort has gone into developing guidelines for the first of these features, all three case studies point to a need for more guidance on the latter. For example, the draft EIS for the FSFH was criticised for a lack of detailed

information on the coral communities at John Brewer Reef. At the time, the GBRMPA did not consider that a detailed inventory of biological characteristics of the reef was necessary (Bastin and McGinnity 1988). Clearly, this was not the case in the Magnetic Keys development. In his review of the GBRMPA, Whitehouse (1993) recommended that specific guidelines be developed for undertaking surveys of corals for environmental assessments, that included criteria for determining the significance and sensitivity of the marine environment within the study area. Nelson and Mapstone (in press) made similar recommendations for pontoon monitoring studies. Simple descriptions of the percentage cover of corals at a reef site do not give meaningful representations of its biological or aesthetic value. Done (1996) has recently proposed a strategy for assessing the biological value and sensitivity of coral reefs that is based on the projected age structure of the assemblage and its ability to recover from disturbance. The approach has yet to be tested, but holds considerable promise for future environmental assessments. Other useful models could include the minimum standards developed by the U.S. National Research Council for environmental assessments of offshore oil and gas structures. Under these guidelines, proponents are required to supply authorities with a characterisation of major habitat types, a catalogue of representative species, information on seasonal patterns of distribution and abundance, basic information on ecological processes, basic information on factors determining the vulnerability of various species and the potential effects of various agents of impact (Peterson 1993).

There is also a need to broaden the scope of monitoring studies from the current focus on the biophysical environment to other areas that are critical to decision making, including the engineering performance of structures and changes in the socio-economic environment of the Great Barrier Reef Marine Park. The lack of targeted monitoring in these areas has left considerable uncertainty surrounding appropriate design standards for offshore structures and the cumulative effects of tourism facilities on other users of the Great Barrier Reef Marine Park. Social impact monitoring is unlikely to be project specific and, therefore, will most appropriately be funded as part of a regional planning programme, rather than by individual developers.

The case studies I have presented here have all been relatively well documented. They represent a small, but significant, proportion of the environmental assessments of tourism developments that the GBRMPA has been involved in over the past 13 years. This wealth of experience has often been slow to make its way into formal policy, to the extent that there is now a risk that knowledge could be lost if experienced staff move on to new positions. There is still considerable scope for more detailed analysis of past permit decisions to aid policy formation and to capture existing knowledge. For example, research into the cognitive and administrative processes of decision making within the Authority would shed light on how scientific information is weighted against other political and social inputs (Underwood 1995). Understanding how policy is developed and applied to resolve competing interests within the GBRMPA will make environmental assessments more transparent and efficient.

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Appendix 1. Chronology of important milestones in and policy development for the assessment of tourism infrastructure in the Great Barrier Reef Marine Park

Major Events	Policy Development
Pontoon installed at John Brewer Reef Permit application for the Four Seasons Floating Hotel (FSFH) at John Brewer Reef	
Draft EIS completed for Four Seasons Floating Hotel (FSFH)	
Impact Assessment Study (IAS) on the proposed Magnetic Quays development	Permits required for structures in unzoned sections of the GBRMP Study commissioned on environmental assessment of offshore structures
First pontoon monitoring study	Review of offshore structures by GBR Ministerial Council *Offshore Facilities Act* (QLD) passed
FSFH issued permit to operate Public Environment Report (PER) on Magnetic Quays development Cyclone Charlie damages pontoons at FSFH FSFH begins operation at John Brewer Reef 'Fantasy Island' installed at John Brewer Reef (sinks two weeks later)	*Sea Installations Act 1987* (Commonwealth) passed Proposals for offshore structures, dredging or reclamation to be subject to public review
Floating resorts proposed for Fitzroy Reef and Lady Musgrave Island Second PER on Magnetic Quays development Permit issued for Magnetic Quays marina (9 other marina proposals under consideration)	Contracts introduced for complex permits Two year moratorium on floating hotels Reactive monitoring introduced for construction projects Guidelines introduced for assessment of marinas, pontoons and mariculture projects Authority to manage developer-funded monitoring and site supervision Guidelines for wastewater treatment at island resorts
FSFH removed from John Brewer Reef after financial difficulties Bund wall collapses on Daydream Island marina	Permit assessment fees introduced Duration of permits increased from 1 to 3 years
Work ceased on Magnetic Quays Cyclones Joy pontoons at Agincourt Reef	Policy guidelines for establishment of pontoons revised after failure of several anchoring systems
18 applications for installation or relocation of pontoons in the Cairns Section Cyclone Fran damages pontoons at Lady Musgrave Island and Wistari Reef	'No Structures Sub-Zone' introduced in rezoning of the Cairns Section Whitehouse review of Magnetic Quays
Major foreshore and harbour works at Heron Island	Fish feeding guidelines issued Policy on establishment and maintenance of pontoons Minimum monitoring requirements supplied to consultants
	Review of the Marine Park tourist permit system
draft EIS on Magnetic Quays redevelopment	
	Study of the impacts of fish feeding Review of pontoon monitoring studies and engineering guidelines Moratoria on new permits in the Cairns and Whitsunday regions

Understanding Great Barrier Reef economics[1]

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ABSTRACT

There is a history of economic research on the Great Barrier Reef, dating back to the Royal Commissions into oil drilling in the 1970s. A summary of the approaches to economic research and the results of the research, showing changes over time is presented. Comments are made on how the results of the research have been used for management. The paper then focuses on directions in ecological economics; on how economic information might be used in planning and in monitoring ecologically sustainable development e.g. the Strategic Plan; how economic instruments might be used in management; and how economic information might be related to other social and ecological information in the future.

INTRODUCTION

Economists would tend to view the task of managing the Great Barrier Reef as comprised of two broad and often related areas; allocation of resources between competing demands for use, and ongoing management of the resources. Approaches and techniques from economics can assist in both these undertakings. Some of these approaches have been around for over two hundred years in the form of neoclassical economics, but new approaches have recently been developed to address resource allocation and management which are aimed towards achieving ecologically sustainable development. This new movement in economics is termed 'ecological economics'. This paper covers what economic research has been undertaken for the Great Barrier Reef in the past, some results of research of some of this research and how this information was used in allocation and management. Looking to the future, a brief discussion of ecological economics provides a context for suggestions for future economic research to assist management of the Great Barrier Reef.

Brief history of economic research

The creation of the Great Barrier Reef Marine Park (GBRMP), zoning of the sections of the Marine Park and site allocation within management plans are examples of the allocation of resources between competing demands for use. Economics directly addresses allocation of resources by providing measures of economic values and methodologies for trading-off such values, such as Cost Benefit Analysis (CBA). Some of the direct uses of the Great Barrier Reef, for example commercial fishing, can be valued by market information. Many resource uses, including for example, recreational fishing, waste assimilation functions and conservation of biodiversity, do not have markets or market values. There are a number of ways of approaching resource allocation where there are non-market values, one is to undertake non-market valuation studies to place dollar values on such resources. Another approach is to recognise non-market values by placing constraints on the resources available for direct use, and then employing standard economic analysis within those constraints. Both approaches have been adopted in economic studies undertaken to assist resource allocation in the Great Barrier Reef.

The first Great Barrier Reef allocation decision was the creation of the GBRMP, and the exclusion of mining, oil drilling and some other potential resource uses. The 1975 decision to declare the GBRMP came after considerable public protest at the prospect of oil drilling

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(due to fears of serious threats to the reef from oil spills). A Royal Commission into the pros and cons of oil drilling had made fairly vague findings the previous year. At the time of the Royal Commission, no comprehensive oil exploration had been undertaken and reserves were assessed as likely to be 'fair' to 'poor'. The Commissioners were unable to assess the potential net benefits of oil production from the area (Wallace et al. 1974). An economic study by Fitzgibbons and Cochrane (1972) attempted to assess the likely benefits of oil production and set these against potential losses to the tourism industry (calculated using a crude travel cost analysis), on the assumption that oil drilling and tourism were mutually exclusive over the entire reef. Hundloe (1995) claims that this elementary Cost Benefit Analysis was important to the findings of the Royal Commission.

Over the two decades since 1975, several economic studies, covering a range of uses, have been undertaken. Some of these have been conducted by academic researchers independently of the management agency, the Great Barrier Reef Marine Park Authority (GBRMPA), but most have been commissioned by GBRMPA. Research into commercial fishing in the early 1980s was jointly commissioned by GBRMPA and Queensland fisheries management agencies and some later research was funded by the fishing industry. Economic research has been sporadic rather than regular and comprehensive. The better known research includes: economic importance (direct and flow-on) of commercial fishing (Hundloe 1985; Bishop 1988, 1992) and recreational fishing (Hundloe 1985; Blamey and Hundloe 1993), the charter boat industry (IASR 1985) and of tourism in general (Driml 1987a, 1994a); regional economic impacts of reef-based activities (Driml 1987b); willingness to pay for protection from crown-of-thorns starfish (Hundloe et al. 1987); willingness to pay for recreational fishing (Blamey 1991); and consumer surplus arising from tourism to various sites (Sloan 1983, Hundloe et al. 1987, Stoeckl 1994). The following is a brief assessment of why the research was undertaken and how results were used in allocation and management.

Economic information played a part in resource allocation via the progressive zoning of sections of the GBRMP. Studies of the commercial fishing, charter boat, recreational fishing and tourism sectors provided descriptions of the extent of these activities and some idea of absolute and relative economic importance. A principle adopted in initial zoning plan development was to minimise the adverse effects of zoning outcomes on existing direct uses. Studies of the regional economic impacts of direct uses (Driml 1987b) identified not only the direct employment supported by these sectors but also the flow-on economic activity and employment supported in coastal regions. In all cases, economic information was used along with information from other sources in making resource allocation decisions via zoning. There are no examples of use of a full CBA approach or the use of dollar estimates of non-market values in zoning.

There remains a need to make resource allocation decisions for the GBRMP. This includes reviewing zoning plans and developing management plans at a finer scale than zoning plans. Management plans are being developed for areas where competition exists between different uses and between individual operators for reef sites in high demand, such as the area off Cairns. Where constraints on use have already been set by zoning plans, and by management principles (such as respecting sites important to traditional owners), the resource allocation decisions that are left to be made within these constraints could be construed as economic decisions. Economic research could assist managers in determining efficient and equitable allocations and in designing economic instruments to assist in allocation. To date, there has been little or no management planning research that has involved the collection of economic data.

The other broad area identified where economics can contribute is in informing ongoing management of the GBRMP. There are a number of cases where economic research has been commissioned to address particular management problems.

A major study of the economics of commercial fishing was conducted in the early 1980s. there were two objectives of this research. The first was to obtain an estimate of costs and earnings of the industry and from these data to estimate the need to restructure (that is , reduce effort in) the fishery. The second was to estimate the regional and state-wide importance of the industry, in terms of the value of output, income and jobs (Hundloe 1985). A study of the recreational fishery was also undertaken, but had little influence on policy development at the time. A repeat of the economic study of the commercial fishery

was undertaken for 1986 (Bishop 1988) and this was updated for 1992 based on catch and price data (Bishop 1992), but no further data collection on costs and earnings has been undertaken.

Concerns about outbreaks of crown-of-thorns starfish led to a major research effort, which included two economic studies. One study addressed the costs and benefits of various control methods (Hundloe et al. 1987). As it was necessary to place a value on the benefits of control, it was necessary to estimate the economic value of the reef to visitors and non users. Economic values were derived via the travel cost method (TCM) and the contingent valuation method (CVM). The former has a slightly misleading name which may lead non-economists to think it involves nothing more than adding up the costs of travel to get to a destination (fares, fuel, etc). This is quite wrong. The data on the cost of travel is nothing more than base data for a modelling exercise which aims to derive a demand schedule for a site which is able to be compared to a demand schedule for, say, butter. More specifically, a demand curve for the resource in question is estimated by regressing actual visitation rates for different geographic zones on explanatory variables, one of which is travel costs. By examining how demand is expected to respond to the imposition of various hypothetical entry fees, the net economic benefits to consumers can be estimated (Stoeckl 1994). By contrast, the CVM is based on survey data where respondents indicate their economic values in hypothetical markets (Hundloe and Blamey 1992). As with other stated preference techniques such as conjoint choice modelling, CVM can elucidate answers to questions such as: 'What would you be willing to pay to ensure that the environmental quality of the Reef was maintained into perpetuity (because you want future generations to enjoy it or because you believe nature has a right to be protected)?'. That is, this, and related techniques attempt to obtain non-use values and future preservation values. Social values will be reflected in CVM estimates to the extent that they exist in the community and are judged by respondents to be relevant to the valuation issue at hand.

The TCM and CVM approaches were used by Hundloe et al. (1987) to measure the willingness of visitors to pay for access to reef sites. The other study undertaken was a risk assessment by Parslow and Hundloe (see Hundloe 1990, for a brief overview of results). These pieces of research indicated that adult visitors (in 1986–87) were willing to pay $8 over and above their commercial boat fares and other travel costs to visit coral sites in good condition.

A controversial issue for GBRMPA and fishery management agencies is competition for resources between commercial and recreational fishing. A study of recreational fishing was commissioned by GBRMPA in the early 1990s (Blamey and Hundloe 1993). This consisted of a repeat of the earlier study (Hundloe 1985) of catch effort and economics of recreational fishing, plus a non-market valuation (CVM) directed at estimating the willingness of recreational fishers to pay for access to reef sites and willingness to accept compensation for losing access (Blamey 1991). The research by Blamey and Hundloe pointed to a decline in recreational fish catches in certain popular locations and, while not all fisheries managers were willing to accept the results, provided a catalyst for more attention being placed on over-fishing.
The aggregate willingness to pay for access by recreational fishers lay between $52 and $124 million in 1991–92. Compensation required if they were forced to stop fishing was considerably higher than this. In economic jargon, this is associated with a shift in the 'property rights': in the former society owns the fishing grounds, in the latter the fishers do. The results of asking these radically different questions were similar as to those found in other studies where the property rights were changed; that is, the amount fishers would need to be paid to stop fishing was many times what they would be willing to pay to continue fishing. In the real world (and even in an hypothetical world) what one is willing-to-pay is constrained by one's income and wealth (one's ability to pay). The original allocation of a property right can have a very significant impact on economic values. While the right to fish is probably not a good case, the rights to clean air and water, a beautiful view and a number of other non-market goods and services are not logically able to be taken from the community and assigned to one owner or a sub-set of the community. This suggests that the valid measure is willingness-to-accept compensation, and, furthermore, reinforces the polluter-pays principle.

For some years now, the GBRMPA has been concerned that funding for management of the GBRMP has not kept pace with increasing demands for management with increasing use

levels. A study of the gross economic value of direct uses of the Great Barrier Reef World Heritage Area was undertaken for GBRMPA and published in 1994 (Driml 1994a). This study revealed that gross value was close to $1 billion in 1991–92, made up of $682 million expenditure by tourists, $128 million in returns to commercial fishing, $94 million spent on recreational fishing and $20 million spent on research (GBRMPA and AIMS only). A doubling of visitor numbers and tourism vessels from 1984 to 1992 was demanded. The report also benchmarked economic values and revenue raising against other World Heritage Areas and protected areas. Information from this study was used by GBRMPA to emphasis the need for sufficient funding to maintain these values.

Advice has been sought on means of funding management (for example, ABARE 1992) – but options identified including comprehensive user pays, or auctioning tradeable permits have only partially been taken up.

Although individual economic studies have been comprehensive at the time of execution, and potentially valuable at the time, many have not been repeated or updated and do not necessarily reflect the situation today. The GBRMPA has commissioned advice on programs for socio-economic research and the use of economics in planning and management on a number of occasions (James Cook University 1978, Unisearch 1984, ABARE 1992, and Driml 1994b). The Great Barrier Reef Consultative Committee has taken an interest in issues of funding and use of economic instruments for management and has provided advice to the Commonwealth Minister for the Environment and GBRMPA on these issues.

Recently, GBRMPA convened a Socio-Cultural and Economic Research Advisory Committee to provide advice on research priorities in these fields. The GBRMPA has an indicative socio-cultural and economic research program, and annually approves expenditure for projects in this program. However, limitations to resources has meant that few projects are undertaken each year. The result is that the GBRMPA does not yet have a comprehensive or permanent program for gathering, recording and using economic data.

Directions in Ecological Economics

It was mentioned in the introduction that the discipline of economics is undergoing changes with the development of ecological economics. The aims for ecological economics have been stated as:

> Ecological economics addresses the relationships between ecosystems and economic systems in the broadest sense. These relationships are the locus of many of our most pressing current problems ... but they are not well covered by any existing discipline ... (ecological economics) will include neoclassical environmental economics and ecological impact studies as subsets, but it will also encourage new ways of thinking about linkages between ecological and economic systems (Costanza 1989).

Ecological economics has developed alongside an increasing global interest in ecologically sustainable development and provides a framework for applying sustainable development principles. Issues of intra and intergenerational equity can be addressed by identifying who benefits and who bears the costs of decisions on resource use, now and in the future. Alternatives to the standard practice in economic analysis of discounting the future can be used.

The use of the 'precautionary principle' in development of policy is a response to the uncertainty inherent in our knowledge of natural systems. The adoption of 'safe minimum standards' (SMS) as limits on resource use imposed externally to the economic system is one means of implementing the precautionary principle in economic analysis. Non-market valuation has a place in ecological economics as does the use of economic instruments for management, and the construction of ecological-economic models. Approaches to trade-offs between competing uses of resources, including multi criteria analysis (MCA) and CBA (modified to incorporate SMS), can be consistent with ecological economics.

A number of directions for the use of ecological economics in management of protected areas were identified in a recent paper (Driml 1995) and are summarised here.

- Improving the methodology of and confidence in non-market valuation – further research is needed into consistent application of non-market valuation methodology to Australian protected areas.

- Contributing to trade-offs between conservation and alternative uses, incorporating complex trade-offs in multiple use situations – there is potential for greater use of trade-off approaches including MCA and CBA.

- Adopting a sustainability approach to management of protected areas – identifying the levels of expenditure on management required to maintain the resources of protected areas, and providing this funding, is essential to sustainability (Driml and Common 1996).

- Investigating ecological-economic modelling of uses of protected areas – options exist for modelling, but information limits to modelling complex ecological systems are the major constraints on ecological-economic modelling.

- Contributing to securing adequate funding for management of protected areas – economics can assist in identification of the appropriate split between public finding and user pays, and design of efficient and equitable user pays instruments.

- Contributing to the economic well being of traditional owners of protected areas – economics can assist in identifying the economic importance of resource use by traditional owners and in developing commercial ventures where desired (Altman and Finlayson 1993).

- Use of economic instruments in management – economic instruments can complement regulatory approaches to management and improve the efficiency of resource use (ABARE 1993).

- Integrating economic information into the operations of management agencies – ecological economics provides a platform for a stronger link between economic activities and ecological and social values.

The economic research and analysis applied to the Great Barrier Reef to date has been integrated with information on ecology and social values in an informal sense by the planners and managers. As the whole effort in managing the Great Barrier Reef has been directed towards sustainable development type outcomes, it could be said that ecological economics has been practiced for some time in respect to the Great Barrier Reef, albeit in a limited way.

Potential future applications of ecological economics to Great Barrier Reef management.

It is important that managers of multiple use protected areas such as the Great Barrier Reef put a priority on having good economic information and making better use of it in the future, because they will come under increasing pressure to make resource allocation decisions between competing uses. The demands for different uses of the Great Barrier Reef are increasing with growth in; the mainland population, tourism, demand for seafood and demand for access for recreation. Adding to these demands is greater awareness of the rights of traditional owners and continuing concerns for conservation, from a well informed population in Australia and the rest of the world.

The other key area in which managers would benefit from economic information is in determining appropriate levels of expenditure on management and funding of management. The current trend in respect of protected areas is for appropriations from consolidated revenue to be cut and for managers to be required to raise revenue from users, as happened in the 1996 Budget. Managers would benefit from research that could set the broad context for funding for management. Such research could identify the level of expenditure required to meet requirements for ESD. It could also identify who benefits from such expenditure and who should pay, and suggest efficient and equitable means of implementing user pays for each sector. A relevant issue is that the management agencies are responsible for managing for the provision of both public goods and private goods. It is not possible to set up efficient markets for public goods and the provision of public goods

should be continued to be funded by governments on behalf of society; however, private goods could be provided with the use of economic instruments to cover costs and private economic efficient allocation of services. Management agencies need to be armed with information such as that outlined above, so they can try to resist cuts in funding beyond what is efficient.

Some comments on the potential for specific applications of ecological economics in management of the Great Barrier Reef follow. These comments mainly apply to GBRMPA but some are relevant to other management agencies with responsibilities in the Great Barrier Reef World Heritage Area, including the Queensland Fisheries Management Authority and the Queensland Department of the Environment.

The GBRMPA will continue to need to make allocation decisions between competing users of resources, at the broad scale of determining which areas of the Great Barrier Reef are available to user groups, and at the finer scale of allocating access amongst individual tourism operators, commercial fishers etc. Information on potential economic values of different uses can assist in broad scale allocation. The decision models of CBA and MCA which have been mentioned above can be used to assist the organisation of the information needed for trade-offs. CBA requires measurement in dollar values while MCA provides a means to compare values initially measured in different units. Social values can be incorporated to some extent in these methodologies. CBA can be used to identify who benefits and who bears the costs of resource allocation options, while MCA employs socially derived weights for different outcomes. In cases where a large number of possible management options are under consideration, analysis using CBA may be limited to a small number of key scenarios. MCA may offer a more flexible way of handling a multiplicity of management options.

Economic instruments such as tradeable quotas and permits can assist in efficient fine scale allocation by creating a market for the rights of access. This minimises the need for agencies to be involved on a day to day basis at this level of allocation. Such systems can be designed to ensure that specified environmental limits are met; however ongoing monitoring is likely to be required given the difficulty of establishing precise ecological carrying capacities.

Economic research can be used in the design of appropriate fee structures for applying the 'user pays' principle. Economic research can be used to: identify what costs are appropriately recovered from users, and from which user groups;. estimate the willingness of visitors or other users to pay for the services they enjoy; and identify who bears the cost of fees that may be set, for example, whether they are likely to be absorbed by tour operators or are able to be passed on to visitors.

The inclusion of economic information alongside indicators of reef use and environmental quality could be of use when assessing the ecological sustainability of the Marine Park and the various industries and activities taking place within it. Regular collection of economic indicators, including measures of non-market values, could assist evaluation of plans and policies. Monitoring of economic indicators should be an integral part of the monitoring program for the 25 year Strategic Plan. The GBRMPA has recently embarked on a project to develop State of the Environment reporting for the Great Barrier Reef and this is intended to include economic indicators.

There is potential to apply ecological-economic modelling to extractive uses such as fishing and non-extractive activities such as tourism. One notable example of ecological-economic modelling of tourism in coral reef areas is the work reported by Dixon et al. (1992) for Bonaire Marine Park in the Carribean. Here, a threshold limit for scuba dives per year on coral reef sites, above which impact becomes significant, was defined from scientific surveys of dived and undived sites. It was postulated that the threshold may be able to be raised with greater management inputs in the form of diver education, more even distribution of divers between dive sites, control of land based pollution and greater monitoring effort. The economic benefits of diving in Bonaire Marine Park were calculated in the study. The study points to the potential for modelling the trade-off between higher management costs and the benefits that may be gained by accommodating greater numbers of divers, to optimise net benefits within a sustainability threshold, and over a long planning horizon. This may be a useful area for the future application of ecological economics to managing the Great Barrier

Reef. A collaboration between ecologist Vicki Harriott and economist Derrin Davis at Southern Cross University seems to be heading in this direction (Harriott et al. 1995, Davis and Tisdell 1995). However modelling of complex ecological impacts of tourism could be very data intensive. It may be that the complexity of such modelling means it is only justified for very ecologically important sites in high demand

Conclusions

This range of information presented at this conference is proof of the diverse types of information which together are important to management of the Great Barrier Reef. The issue of integrating ecological economics information with information from other disciplines is therefore important for management of the Great Barrier Reef. There are two aspects to this issue, the extent to which existing methodologies integrate material from other disciplines, and the ability of people involved in management to integrate information from disciplines which do not adopt a multidisciplinary approach. It has been claimed in this paper that ecological economics does attempt to integrate at least ecological information and some aspects of social values. Full realisation of the potential contribution of ecological economics in management of the Great Barrier Reef depends upon managers being trained in interpreting and integrating economic information.

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Understanding the tourist market

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ABSTRACT

The early management of reef tourism struggled with an uncertain and piecemeal visitor data base. During the 1980s some progress was made with the occasional site specific study of visitors but only in the last three years has a systematic, scientifically sound assessment of visitors been collated. At the broad level, global tourism trends and secondary analysis of broad Australian and Queensland tourism data sets provide valuable contextual information for reef visitor analysis. At a more focused level, the sheer size of the market to the reef can be assessed from the environment management charge data while subtle information on travel motivations, activities and travel patterns is now emerging from CRC Reef Research survey conducted by the James Cook University Department of Tourism. This paper will focus on building confidence in a comprehensive data base of tourist survey research. It is argued that using and benefiting from an information base on visitors is a vital step in linking managerial action to sound social science research activity. Within the scope of this paper, a focus on international tourism data trends will initially be presented followed by some key results from the CRC Reef Research regional survey studies identifying travel patterns and repeat use visitors. Cooperative possibilities between researchers and managers for understanding the tourist market diversity are suggested.

INTRODUCTION

One of the more colourful volumes to be written about planning in recent years is Wyatt's 1989 monograph entitled Intelligent Planning. The style of the book is whimsical and anecdotal. Wyatt leads readers gently through seven steps in planning and appraises three common styles of management. The three management styles he discusses are management by legislation, management by consensus and management by information. All three, Wyatt argues, have valuable perspectives but management by information is the most appealing because it both embraces and supplements the other two approaches. The steps in planning identified by Wyatt are accompanied by management activities and are summarised in table 1.

Table 1. Steps in intelligent planning and management

Dominant steps	Defined as:	Desirable management activities
Think	absorb information about the problem	**Develop an information base**
Analyse	consider key features of the problem	**Use and benefit from the information base**
Aspire	assess the communities goals and priorities for the area	Itemise and rank community issue
Suggest	outline new options	Provide a first summary of information for solving problems
Test	learn about consequences of options	Feedback on options– **use data base or new research if possible**
Evaluate	appraise the options	Use decision rules to evaluate options
Select	make the decision	Identify indicators, identify follow-up **research and information needs**

For the present paper Wyatt's analysis is valuable in highlighting that the information needs of decision makers are usually early on in the planning process and that developing an information base and then using and benefiting from that information base are vital early steps.

An international perspective

The early management of reef tourism struggled with an uncertain and piecemeal visitor data base. Recent developments in tourism research are capable of providing the required kind of information base and it is desirable to build a confidence in the use of such a resource for contemporary managers.

Research relevant to understanding tourism and the Great Barrier Reef World Heritage Area has been conducted at several levels of analysis. The first level is data on international tourism trends which includes information on changing technology, changing patterns of international travel and changing expectations of tourists. The second level of data is that collected at a national level on both international visitors to Australia and domestic travel within Australia. A third level is data collected at the state and regional level by the Queensland Tourist and Travel Corporation (QTTC). The fourth level is data collected at a regional level by various organisations notably the CRC Reef Research tourism survey group. This section will review only the international tourism trends and the most recent CRC Reef Research tourism data. Accounts of the national and state level data relevant to the reef broadly support the global and local views and are available in the paper by Moscardo et al. 1996 in the State of Great Barrier Reef World Heritage Area report.

International tourism trends

The World Tourist Organisation (WTO) is the international body charged with the responsibility of compiling statistics on international tourism and predicting future tourism trends. In order to fulfil these responsibilities the WTO works to identify factors which are related to and influence patterns of tourism. This section will review both current and predicted international tourism trends drawing out the implications for the management of tourism to the Great Barrier Reef World Heritage Area.

The WTO predicts that international tourism arrivals worldwide will reach in excess of 930 million by the year 2010. This will mean that international tourism will have doubled in the 20 years between 1990 and 2010. Figure 1 shows both world and major regional tourism figures and forecasts for international tourism arrivals for the period 1975 to 2010. This figure indicates not only major growth in tourism in these two decades but also some major changes in the patterns of tourism. Clearly there is a change away from Europe and the Americas as prime destinations. The Great Barrier Reef World Heritage Area is thus located in one of the fastest growing tourism destination regions in the world. Another major change in international tourism is predicted for the sources of international travellers with the fastest outbound growth occurring in the all parts of Asia, Africa and the Middle East. In particular there is clearly a trend towards more intraregional growth. In other words, international travellers from East Asia and the Pacific are increasingly visiting other countries in East Asia and the Pacific. Specifically the WTO notes that in 1990 73% of international arrivals were generated from countries within the same region and they predict that this will grow to 80% in the year 2010.

The WTO does not directly monitor domestic tourism, that is travel within one's own country, but their assessment is that this will also continue to grow at rates similar to that experienced and forecast for international tourism. Again growth in domestic tourism is likely to be greatest in East Asia and the Pacific and South Asia.

Data in the preceding section is based on tables reported by the WTO (1996) and McIntosh, Goeldner and Ritchie (1995).

In addition to these changes in the spatial distribution of tourism a number of other trends in tourism have been identified at the global level. These can be seen as falling into two

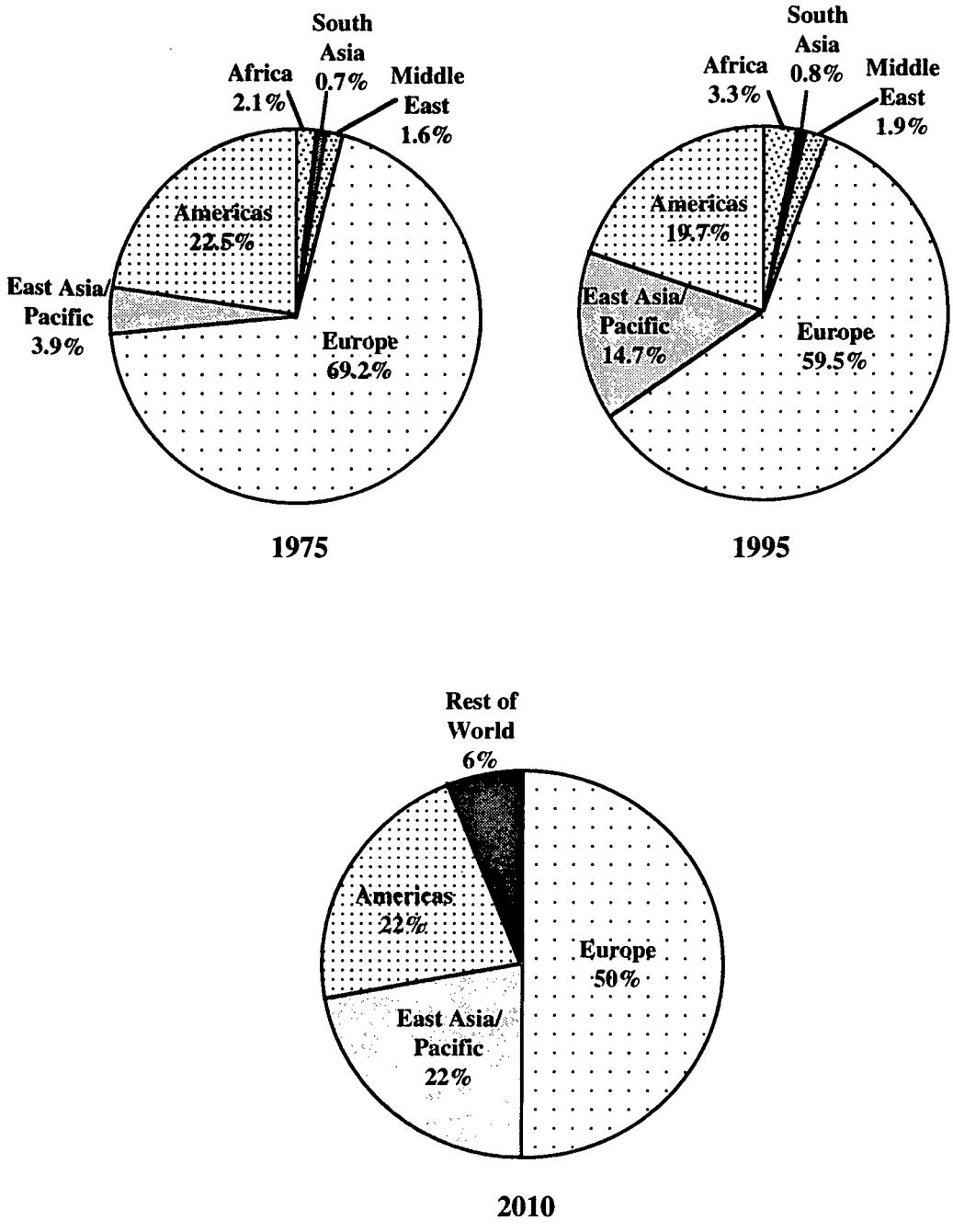


Figure 1. Percent share of world arrivals 1975 and 1995 *Source: World Tourism Organisation (WTO) 1996:16*

major categories, changes in the nature the travel experience sought, and changes in the technology associated with tourism. In the first category are such changes as:

1. decreasing use of package tours and increasing demand for individualised itineraries and independent travel.

2. increasing demand for multiple activity opportunities

3. moves towards shorter breaks

4. increasing travel experience and demand for quality services

The second category includes changes to transport capacity, the increasing use of computer systems for reservation and promotion, and the use of technology to create tourist

experiences. Changes to transport technology are likely to have the most visible impacts on tourism. Currently growth in tourism is limited by capacity at major international airports and a number of changes in aircraft technology are likely to substantially alter this situation in the early years of the 21st century. These changes include:

1. the use of satellite navigation which will allow for much greater use of airports and shorter more direct flight paths

2. increases in the capacity of aircraft. All major aircraft manufacturers are developing planes with the ability to carry between 850 and 1000 passengers. These are expected to be operational by the year 2003.

3. decreases in flight times. Boeing, for example, is developing new aircraft with the capacity to cut flight times between Australia and the Americas by half. In summary, it is likely that within the next decade that Australia will no longer be a long haul expensive destination for international travellers.

There are several other technological developments of relevance to the Great Barrier Reef World Heritage Area. In 1989 the use of small submarines taking 10–20 tourists into marine environments was predicted. Such tour opportunities are now available and are a feature of many reef day trip tours in the Caribbean. The use of virtual reality has also become widespread and is being used increasingly in tourism to provide virtual experiences of a range of environments and activities including such things as snow skiing and horse riding. These developments have the potential to both increase pressure on the Great Barrier Reef World Heritage Area through the provision of more ways to access the reef environment, and to decrease pressure by developing alternative tourist experiences.

Information in the preceding section was derived from WTO (1990, 1993), Ballantyne (1995) and Shafer and Moeller (1989).

Another major change in global tourism is the growth of cruising. In 1990 11 million people were listed as cruise passengers making this the 11th largest travel concentration in the world. Growth in cruising in the last 15 years has been in excess of 10% per annum and this growth is supported by major increases in capacity. In 1990 14 vessels with a capacity of in excess of 1000 passengers were being built. Three of these vessels will carry more than 4000 passengers and crew and use large catamarans as transport vessels to carry passengers to islands and reefs. Cruising is currently dominated by North American passengers cruising in the Caribbean (accounting for nearly half of all cruising). As with all other aspects of tourism this emphasis is shifting towards increased cruising opportunities in the Asia Pacific region. If, as predicted, there are increased opportunities for shorter, cheaper air travel to the Asia Pacific then cruising will be able to grow dramatically in this area.

Information in the preceding section was taken from WTO (1990, 1991), the Cruise Shipping Report (1990) and CLIA (1994).

Explanatory factors

In attempting to understand the patterns of international tourism outlined in the previous section the WTO has identified a number of social, demographic and economic factors which are related to tourist behaviour. This first two sets of factors are those related to capacity to travel. In general, rising living standards and the spread of democracy have resulted in greater opportunities for travel especially from developing countries in Asia. Changes in the structure of the family with increasing participation of women in the workplace and decreasing birthrates have allowed for more flexibility in organising travel times and thus the increase in shorter breaks. These factors combine to make a travel a more commonplace activity resulting in greater experience and the pressure for more intensive, specialist and independent travel.

Implications for the Management of Tourism in the Great Barrier Reef World Heritage Area

This overview of global tourist trends can be seen as having five major implications for the management of tourism in the Great Barrier Reef World Heritage Area.

1. Managers can expect increasing numbers of both international and domestic tourists to come to the region. This growth in tourism is likely to continue at least at the same rate as in previous years. If the predicted changes to transport technology eventuate it is likely that numbers of international tourists to the region could expand very quickly. The pressure to provide access and facilities so that tourists can visit the Great Barrier Reef will increase.

2. Managers can expect that international tourists coming to the Great Barrier Reef World Heritage Area are increasingly likely to be from Asia. Tourists from these countries are rapidly increasing in travel experience and thus are increasingly likely to be independent travellers and to visit more often for shorter periods. Managers will have to think carefully about their current images of international travellers since the reality is changing rapidly.

3. For all tourists increasing travel experience and education will result in demands for more active experiences and greater quality in services. Expectations for quality interpretation will rise.

4. Managers can expect pressure to introduce submarines to provide greater reef access.

5. Large scale cruising could become a major activity in the Great Barrier Reef World Heritage Area. Again, predicted changes to transport technology could make Cairns a cheaper and more accessible destination and provide the necessary tourist markets to support the use of large cruise vessels moving through the Great Barrier Reef World Heritage Area.

The regional international base

In order to provide specific tourist market information the CRC- Reef Research project has developed a program of detailed visitor studies. This substantial research effort involving teams of researchers interviewing on-land and on-vessel visitors from Cooktown to Bowen (with further work planned in the Whitsundays and further south in 1997–8) is linked to questions in state-wide and national surveys of visitors. While these existing Australian and Queensland findings cannot be reported due to time, there is a very encouraging commonality in the market segments being identified from data source to date source.

In general the spatial distribution and types of tourist visiting the Great Barrier Reef have been identified as of particular value to managers (Benzaken 1993; Kenchington 1993). The present paper will report on these two aspects of tourism to this region using the information gathered in a major survey of visitors to a region adjacent to the Central Section of GBRMP. In particular the survey results will be used to investigate overall patterns of use and the relationships between patterns of use and visitor characteristics.

Method

In the first stage of the research a sample of 1664 surveys were collected from visitors to the North Queensland region. The aim of the research project was to gather information about reef tourism from as broad a range of visitors as possible. To achieve this aim surveys were handed out at local and regional tourist information centres, at transport nodes such as ferry terminals, major tourist attractions and on a variety of commercial reef tourism operations. These operations included day trip operators using large catamarans with pontoons moored at the destination reef, large catamarans visiting sand cays, smaller boats travelling both to reefs and to islands, cruise boats and dive trips. The overall response rate was 80 per cent.

International visitors accounted for 36 per cent of the sample, with a further 23 per cent interstate visitors, 33 per cent residents from coastal regions adjacent to the Great Barrier Reef and 9 per cent visitors from other parts of the region. The average age of the sample was 37 years (Std Dev = 15) with a median age of 33 years. The mean length of stay for visitors not on a recreational day trip was 25 days (Std Dev = 47), although more than half of the sample were staying in the region for less than 12 days.

RESULTS

Understanding Frequency of Visit

Respondents were asked to use a map of the region to indicate their actual and intended travel itinerary. They were also asked about actual and intended visits to the Great Barrier Reef focusing on the types of operation used to access the Great Barrier Reef and points of departure.

As the major focus of this paper was on investigating the relationships between travel patterns and visitor characteristics the data were examined to identify travel patterns. Three travel pattern groups were identified.

1. Visitors who had not been and were not going to the reef on the trip to the region (24% of the sample). Labelled THE DO NOT VISIT GROUP.
2. Visitors who had been on one reef trip during their stay and did not intend to visit the reef again (34%). Labelled THE ONE TRIP ONLY GROUP.
3. Visitors who had been once and intended to go again during their stay (9%) and visitors who had been to the Great Barrier Reef more than once during their stay in the region (22%) labelled THE REPEAT VISIT GROUP.

The two groups who had visited the reef were used to further examine patterns of reef access. Table 2 summarises the date on types of reef operation used. Clearly day trips using large catamarans travelling to pontoons moored at a reef are popular operations especially for visitors who travel only once to the reef. Visitors who go more than once are more evenly spread across the different types of operation. Of particular interest is the difference between first and second trips for those who go to the reef more than once. More detailed analyses of this information suggested that these visitors sought variety in their reef experiences with 74% choosing a different kind of operation for their second trip to that used on their first trip. This was particularly the case for large day trip operations with 83% of the visitors choosing a different type of operation for their second experience. Visitors going on dive trips were the most likely to repeat that experience (47% repeated a dive trip). The respondents also chose variety in their departure points with nearly 70% choosing a different location for their second trip.

Table 2. Types of Tourist Operation and Visitor Trip Frequency

	Visit Once	(Visit more than once) First Trip	Second Trip
Type of Operation			
Day Trip (Pontoon)	50%	34%	12%
Day Trip (no Pontoon)	9%	12%	10%
Cruise (more than one night)	7%	7%	5%
Dive Trip (more than one night)	4%	8%	8%
Dive Trip (day trip)	4%	13%	17%
Charter Fishing	-	2%	5%
Day Trip (Island/s)	19%	20%	38%

The major question driving the analyses reported in this section was why do some people not visit the reef, why do some only visit once, and why do some repeatedly visit the reef? To answer this question a number of visitor characteristics likely to distinguish among these

three groups were explored. The characteristics investigated included sociodemographic features (such as length of stay or transport used), activity participation and motivations for, or benefits sought from travel experiences.

Table 3. Summary of Analyses of Socio Demographic and Trip Features

Feature	Do Not Visit Group	The One Trip Only Group	The Repeat Visit Group
Mean Age (SD)	**39 years** (15)	36 years (15)	35 years (15)
% travelling with children	**24%**	19%	16%
% travelling with friends	16%	21%	24%
% International	8%	38%	**54%**
% Interstate	21%	26%	25%
% Intrastate	16%	8%	5%
% Local residents	**55%**	27%	16%
% using private vehicle	**55%**	37%	31%
% using bus	7%	13%	24%
% using plane	11%	17%	16%
Mean Length of Stay in region (SD)	16 days (28)	17 days (25)	**35 days** (62)

Table 3 contains a summary of the analyses conducted for sociodemographic and trip features. Only analyses which found differences between the groups significant at the .01 level are reported. The results reported in table 3 tell us that visitors who do not go to the reef are older, more likely to be travelling with children, more likely to be using their own vehicle, to be staying for a shorter time and to be domestic visitors. It is also worth noting that the biggest differences were usually found between this group and the two groups of actual reef visitors. It is noteworthy however that repeat reef visitors did have much longer trips and were more likely to be international than were visitors going to the reef on only one occasion.

Significant differences were also found among the three groups for activity participation and these are summarised in table 4. Two major points can be made about the results in table 4. Firstly, the DO NOT VISIT group generally have low rates of participation across the full range of activities. Secondly, in this table the largest differences usually lie between those who visit more than once and the other two groups. This is particularly the case for more physically strenuous activities such as walking and rafting and for the more nature based activities such as seeing wildlife and bird watching.

The final set of characteristics which were investigated were the benefits sought from travel. Table 5 provides information on the travel benefits sought by the three groups. Again, a clear pattern emerges with the REPEAT VISIT group valuing learning and excitement more highly than the other groups. The ONE TRIP ONLY group place the highest value on the social benefits of travel. Investigations were also conducted into the levels of satisfaction expressed for reef experiences by the two groups who had visited the reef. There were no difference between the two groups for overall satisfaction but the repeat visit group were more likely to say they would visit the Great Barrier Reef again if they returned to the region (87% versus 74%).

Table 4. Summary of Analyses of Activity Participation

Activity Participation	The Do Not Visit Group	The One Trip Only Group	The Repeat Visit Group
Swimming	41%	74%	78%
Snorkelling	22%	66%	72%
Scuba Diving*	8%	20%	34%
Sailing*	16%	20%	29%
Visiting islands	29%	55%	66%
Viewing Marine animals	17%	40%	49%
Visit Beaches	48%	69%	75%
Rainforest Walks*	45%	64%	91%
Bushwalks*	19%	26%	37%
Camping*	19%	22%	35%
Birdwatching*	11%	17%	26%
Mangrove Visits*	10%	15%	23%
Canoeing*	10%	9%	14%
White water rafting*	4%	9%	64%
Seeing wildlife	22%	39%	52%
Visiting national parks	28%	43%	58%

* Difference is Greatest Between The Repeat Visit Group and the Other two groups.

Table 5. Summary of Analyses of Travel Benefits Sought

Travel Benefit	Do Not Visit	The One Trip Only Group	The Repeat Visit Group
Travel in General			
Learn/develop new skills	moderate	high	high
Be with family & friends	high	low	very low
Seek Excitement	low	high	high
Travel to the Great Barrier Reef			
Be with family & friends	-	moderate	low
Learn about the Great Barrier Reef	-	high	very high

Source: Moscardo (1996).

SUMMARY

The research identified three main types of visitor to the coastal regions adjacent to the Great Barrier Reef. The first group who did not visit the Great Barrier Reef can be described as older, more likely to be local residents, travelling with children for shorter stays with low levels of activity participation. The second group who visit the Great Barrier Reef only once during their stay in the region were younger with shorter stays in the region and moderate levels of activity participation particularly for more strenuous and nature based activities and with mainly social travel motives. The third group of repeat reef visitors were the youngest, most active, most international, with the longest stays and motives relating to self development and nature experience.

DISCUSSION

The visitor profiles described in the previous section are consistent with other major surveys of visitors to this coastal region. None of the previous studies, however, investigated actual reef travel behaviour and so were not able to connect these visitor or market segments to types of operation used or frequency of reef travel. The present study provides this connection. Several important management implications can be drawn from the results which have been described. The first and most important is that of growth and change in demand for operations. Clearly there will be continued growth in demand for reef operations with growing visitor numbers to these coastal regions and this will provide continued support for large day trip operations which are the preferred option for one time and first time reef visitors. As the region matures as a destination, however, and attracts higher proportions of repeat visitors, the present study results suggest greater demand for smaller more specialised operations at a greater variety of locations. Demand is likely to both support existing high use nodes and spread use to other areas. Currently the Great Barrier Reef Marine Park Authority allocates two types of permits to commercial tourist operators – site specific and roving permits which allow the operator to move around several reef locations. Roving permit operations are harder to monitor and control. So the increased demand in currently low use areas will be for smaller boats with roving permits. Given that visitors using these operations are more active and more interested in reef contact, then this increased demand will result in more pressure on a broader range of sites.

Finally, the visitors who do not go to the reef need to be considered. Why does this group not go to the Great Barrier Reef? It could be that the appropriate opportunities are not available. In that case further research could indicate new opportunities for tourism operators. It could be argued that encouraging more reef visits is inconsistent with sustainable use. It should be remembered, however, that this group are less likely to be exposed to interpretation about the reef and less likely to support its conservation. In particular the study found that this group were consistently, although not significantly, less likely to describe the Great Barrier Reef as valuable, living, complex, unique, fragile or beautiful. More than half of this group live on the coast adjacent to the Great Barrier Reef and so their reluctance to visit the reef is a lost opportunity to promote more sustainable behaviours where they live.

The need to understand repeat visitors and smaller newer operations better is a critical management imperative deriving from this CRC Reef Research regional study. This target group will be a focus of on going research by the tourism survey team but their efforts could usefully be focused by managerial reactions and concerns which would be warmly welcomed.

From the present data it appears that managers are faced with the dilemma of allocating use or access to two growing but not necessarily compatible uses, that is large site specific day trip operations and smaller, roving, more reef intensive operations. If, as this study indicates, there is a tendency to move to smaller, more specialised operations, then managers need to understand that current allocations of access to any one particular type of operation may restrict future growth and opportunities for other types of operations.

CONCLUSION

As the CRC Reef Research tourist survey program move into top gear and generates considerable visitor data there will be increasing opportunities to provide many different perspectives and views of the tourist market. It is possible to move beyond the classification of visitors by age and nationality to segments based on activities, motivation, satisfaction,

type of trip and patterns of travel. None of these possibilities will be intelligently pursued by managers however if they do not believe that there is a flexible scientifically sound tourism data bank. The theme of this paper is that intelligent planning requires a knowledge that the information exists and a confidence to use it. Further by highlighting the broad and powerful international tourism trends in growth and styles of future tourism it is hoped that managers will be motivated to anticipate and plan for new futures in reef tourism. This paper presents a small appetiser to a much larger menu of contemporary reef tourism data. As researchers we encourage you to work with us to sample and become familiar with a valuable resource for maintaining our reef resources.

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Understanding visitors and use through social sciences research

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ABSTRACT

It is argued that while social science research methods have been used in understanding visitors and use of the Great Barrier Reef Marine Park, much of this research lacks a coherent theoretical and methodological framework, is represented as `piece-work' and has not always focused on core issues in reef planning and management, but has been more likely to meet localised market research or public relations requirements of private and public sector organisations. The fragmented, ephemeral and perceived limited usefulness of social research to date has seen this type of research being relegated to the back stage of reef research generally and of limited value in reef planning and management. In addition, the consequent gap in funding and application between social science and bio-physical research is a continued focus of concern amongst social researchers, where ultimately planning and management must address questions of human use and valuation of the reef environment, issues which can only be addressed through appropriate social research methods and conceptual frameworks. It is argued that in planning for human use of the reef, social research can provide a broad array of critical information to reef planners and managers, but that it must be focused on the requirements of those involved in the planning and management process. An approach is discussed whereby a range of methodologies both qualitative and quantitative are used to identify and spatially analyse reef use and values of users. This information is integrated with biophysical data through a geographic information system providing the basis for informed decision making and a framework for adaptive management.

SESSION 6

Reef connectedness

Chair: John Tanzer

Rapporteur: David Williams

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Keynote Paper:
Connectivity and the replenishment of fish populations on coral reefs
P Doherty
(abstract only)

•

On the assumption of larval dispersal among reefs: caution advised
G Jones
(abstract only)

•

Genetic evidence for connectivity, past and present:
implications for management
J Benzie
(abstract only)

•

Patterns of coral diversity within the Great Barrier Reef
C Veron
(abstract only)

•

Larval transport modelling in the Great Barrier Reef
M James,* L Mason and L Bode

•

Connectivity and the replenishment of fish populations on coral reefs

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ABSTRACT

Coral reef fishes depend upon patchy benthic habitats. On the Great Barrier Reef, the spatial scales with greatest relevance to fish population dynamics are those of reefs and regions. Although adults may not freely migrate among reefs, their pelagic larvae may; especially in regions of strong longshore flow. Scenarios can be proposed where all replenishment of a particular reef comes from upstream and local stocks will not be sustained if the source(s) are allowed to deteriorate. Similarly, the value of local management action will depend upon the contribution of spawnings from a given reef to future generations. Many groups of reefs will be self-sustaining networks in which each reef features as both 'source' and 'sink', although not all elements will have equal value because of variable connectivity. Given the spatial and temporal complexity of these relationships, reliance upon computer simulations seems inevitable but acceptance of this approach will depend upon rigorous falsification of testable hypotheses. Since 1983, progress towards this goal has involved increasing sophistication of the physical models and new data on the swimming behaviour of larval fishes. Although some caveats still attach to the utility of simulation models, they offer substantial potential to influence allocation decisions within a multi-use marine park. Successful models developed for the Great Barrier Reef Marine Park offer even more promise in the developing world where marine protected areas may be the only strategy allowing sustainable fishing.

On the assumption of larval dispersal among reefs: caution advised

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ABSTRACT

This paper reviews the evidence for a the restricted dispersal of the larvae of coral reef fishes and the potential for self-replenishment of semi-isolated populations. Evidence includes: (1) The persistence of endemics with dispersive larvae on isolated islands. (2) Accidental and planned introductions of marine organisms, which frequently establish populations that persist locally and expand slowly. (3) The theoretical implausibility of a static system of 'source' and 'sink' populations, unless both ends of the system have self-replenishment mechanisms. (4) Point source observations, that show a dilution of larvae with increasing distance from isolated reefs. (5) Genetic studies that showing high levels of population sub-division among reefs in close proximity for some species. (6) Observations showing static concentrations of larvae at certain positions on reefs. (7) Observations on larval swimming abilities, which suggest that larval destinations are not likely to be determined (solely) by hydrodynamic processes. (8) Larval marking - ultimately the only non-equivocal means of tracking larvae from their natal reef to destination. On this last topic, I describe the results of a recent experiment in which the otoliths of 10 000 000 embryos of the reef fish Pomacentrus amboinensis were labelled in situ at Lizard Island, and 15 marked juveniles were recaptured in the process of settling 20 days later at the same location. The fact that any larvae were recaptured at the same site suggests that a high level of self-replenishment occurs in this population. In conclusion, although there is ample evidence for larval dispersal and connectivity on evolutionary time scales, on time scales relevant to local population dynamics, a degree of self-replenishment may be very important. Implications for models of population dynamics and the management of reef fishes are briefly discussed.

Genetic evidence for connectivity, past and present: implications for management

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ABSTRACT

Genetic data obtained over the last decade has provided evidence that the genetic structure of populations of many marine species are not at equilibrium. They indicate patterns of gene flow reflect dispersal events thousands, if not millions, of years ago. These findings raise questions about the mechanisms leading to the origin and maintenance of marine biodiversity. They seriously question the extent of dispersal that occurs today, and the nature of connectedness of marine populations. These data also indicate time lags between dispersal events and their effects on population structure. The use of genetic markers that evolve at different rates can help elucidate these issues. However, even if there are time lags acting on large (ocean) scale population structure, molecular approaches can provide useful information on the information on present day dispersal at small scales. Such approaches demand the identification of specific hypotheses and the circumstances in which they can be tested. When these criteria are met, genetic approaches can yield vital information to assist management by determining the connectedness of marine populations, the nature and time scale of recruitment, and potential genetic impact of anthropogenic and natural change.

Patterns of coral diversity within the Great Barrier Reef

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ABSTRACT

Patterns of coral species diversity within the Great Barrier Reef are little known, but it *is* known that they are complex, being determined by both cross-shelf and latitudinal physical-environmental gradients.

There is a comparatively weak latitudinal gradient within the Great Barrier Reef with species numbers decreasing (and intra-specific changes occurring) only towards its southern end (Capricorn and Bunker Reefs). The reason is mostly environmental: the Capricorn and Bunker Reefs have no high islands, or terrigenous substrates and the reefs themselves are morphologically simple and surrounded by deep water. In general, there is much more variation across (east-west) the Great Barrier Reef than down its length. The relatively shallow, turbid, terrigenous coastal waters, protected from strong wave action and subject to seasonal river flooding, with attendant pulses of low salinity, silt and organic nutrients, support a reef and inter-reef fauna and flora of a very different character to that found offshore. Also, high (continental) islands mostly occur inshore, and it is these islands that provide much of the Great Barrier Reef's habitat diversity and probably house the greatest number of species.

A pseudo-latitudinal distribution effect is often seen in inshore communities, where coral species compositions tend to resemble those of higher-latitude locations rather than adjacent offshore locations. The resemblance between inshore and high-latitude communities of eastern Australia is seen in the relative abundance of some major groups of species (e.g. most *Turbinaria* and *Acanthastrea* and many *Acropora*), and in the similarities of ecomorphs, especially explanate and encrusting morphologies. There are certainly multiple reasons for this: the primary one is physical-environmental (shared terrigenous substrates and turbid water as opposed to carbonate substrates and clear water), but relative lack of *Acropora* dominance may also be relevant.

Larval transport modelling in the Great Barrier Reef

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ABSTRACT

This paper concentrates on a review of developments at James Cook University in the modelling of large-scale larval dispersal and reef connectivity in the Great Barrier Reef region, based on numerical hydrodynamic models. The principal modelling objectives have been the evaluation of potential source-sink relationships and the identification of effective source reefs. The second-generation models provide improved spatial resolution, incorporate fully non-linear dynamics, and use a revised model of the East Australian Current. Issues to be discussed include: statistical uncertainty arising from Monte Carlo sampling involved in numerical simulations; model realism and computational cost; model calibration and validation; and the role of uncertainty (both statistical and model-based) in the application of model results.

INTRODUCTION

Management of the Great Barrier Reef Marine Park must consider the Great Barrier Reef as a complex system, in which the overall dynamics of corals, fish and other organisms are strongly influenced by the linkages between reefs, due to the transport of organisms by water currents. For example, spawning fish on one reef will produce larvae which may be carried considerable distances before eventually recruiting to the stock on another reef. Thus, depending on the vagaries of the hydrodynamics, any given reef in any given season may act as a source of recruits for other reefs, some of which could be tens if not hundreds of kilometres away. These source-sink relationships are believed to play an important role in the progression of outbreaks of the crown-of-thorns starfish, *A. planci* (Kenchington 1977; Williams et al. 1984). While the ultimate causes of the initial outbreaks remain uncertain, secondary outbreaks appear to result from the downstream transport of larvae from reef to reef.

The principal management approach presently employed in the Marine Park involves the definition of multiple-use patterns in zoning plans. These specify the activities permitted on each reef, and include zones in which extractive industries may take place, as well as protected zones where activities are severely limited. If fishing activity is permitted to reduce significantly the breeding stock on a reef, then any role played by that reef as a source of larvae for other reefs may also be significantly diminished. Thus management decisions which specify where fishing may take place have the potential to alter the reef-to-reef connectedness, and hence to alter the system's dynamics. In general, decisions implemented at the scale of a single reef may have regional, rather than merely local, effects.

Uncertainty about the system's responses to management actions (or lack of action) is a widespread problem for environmental managers and has led to the promotion of the so-called 'precautionary principle' (e.g. O'Riordan and Cameron 1994; Wildavsky 1995). The uncertainties that are present in practically all aspects of Park management can be discussed in two senses: system uncertainty and parameter uncertainty (Blockley 1980). Parameter uncertainty refers to measurement and sampling errors in estimates of system variables such as population densities, and to errors in estimates of fecundity, growth rate, mortality, etc. System uncertainty arises from a lack of understanding of how the system is structured and how it functions – i.e. the lack of a thoroughly tested system model.

This situation is, in principle, no different from that faced in engineering planning and design. Coastal engineers, for example, may be forced to make design decisions in the presence of considerable uncertainty about extreme water levels or extreme wave heights (parameter uncertainty). The models used in the design of an offshore platform (e.g. to

predict the platform response to wave loading) are subject to uncertainty, especially in relation to the behaviour of the foundation materials. Traditionally, engineers have dealt with uncertainty by using safety factors: the structure is designed so that the ratio of estimated strength to expected maximum load is significantly greater than unity. In some cases, appropriate safety factors have been determined after a long history of trial and error. In more recent developments, attempts to control failure probabilities involve explicit probabilistic methods based on extreme value statistics, partial safety factors (one for each design variable) and models of system uncertainty.

However there are at least two important differences between marine park management and engineering design. In most areas, engineers have the advantage of a long history of experience. As a result their models are well tested and relatively reliable. Secondly, in those areas where models are not so well tested, there exists a relatively well understood scientific background (mathematics, physics, chemistry, materials science, etc.) which is not merely descriptive, but provides a sound mathematical basis for modelling system dynamics.

Models which are based on well-established science have the potential to significantly reduce parameter uncertainty. Returning to the view of the Great Barrier Reef as a system of interconnected reefs, one factor which plays a major role in determining the pattern of reef connectivity and its spatial and temporal variability is the hydrodynamic field – the water currents. The characterisation of particle transport and large-scale reef connectivity requires synoptic data on water currents over large areas and over long time periods. Estimating the seasonal and interannual variability requires these synoptic data over many years. It is impossible to estimate these data by field measurements alone. At best one can hope for several years of current measurements at a small number of locations. The sampling uncertainty in using these data to estimate the hydrodynamic field is enormous. However this uncertainty can be reduced by using a numerical hydrodynamic model, calibrated and validated using field data, to interpolate over the entire field, and to extrapolate in time. The large sampling uncertainty is replaced by the smaller uncertainty in the data used to drive and calibrate the model, and a relatively small model or system uncertainty.

The current field itself is of little interest to management. In the context of this paper, it is the role played by the currents in determining the ultimate fate of larvae which is of interest. Other factors, essentially biological, may also be important: for example, the behaviour of larvae and their ability to control their positions in the water column; the ability of larvae, when carried close to reefs, to detect and actively move towards suitable habitat; larval mortality, especially due to predation when close to reefs. However the hydrodynamic regime can certainly be regarded as determining the *potential* for transport of larvae from one reef to another, while the biological factors control the extent to which that potential is realised.

The remainder of this paper summarises developments in the numerical modelling of large-scale larval dispersal and reef connectivity in the Great Barrier Reef. The summary is essentially restricted to work done at James Cook University (JCU), where the only comprehensive connectivity model has been developed. In the second section of the paper, the body of published work is briefly discussed. The third section deals with the second-generation models now under development at JCU, and several issues arising in this work including statistical uncertainty, spatial resolution, physical aspects, and model calibration. The fourth section concludes the paper with some comments on model reliability and its relevance to management.

Dispersal modelling

In most of the work so far published on larval dispersal modelling in the Great Barrier Reef, attention has been given to the transport of larvae of the crown-of-thorns starfish (COTS), with some additional applications to the dispersal of fish and coral larvae. At JCU the principal modelling objectives have been the characterisation of large-scale larval dispersal patterns and the evaluation of potential source-sink relationships. Models have been limited to the Cairns and Central Sections of the Marine Park, for which large-scale patterns of larval dispersal were obtained. The main results appear in Dight et al. (1988; 1990 a,b), James et al. (1990), Dight (1991), James and Scandol (1992), Scandol (1994) and Dight and James (1994). Some research (e.g. Black 1988, 1994; Black and Gay 1990; Black et al. 1990, 1991; Black and Moran 1991; Gay et al. 1990; Sammarco and Andrews 1988;

Sammarco 1994; Wolanski et al. 1989) has concentrated primarily on modelling larval retention by reefs, self-seeding, and the initial aggregation and transport of coral larvae off reefs and within small clusters of reefs. Black, Burrage and co-workers have also examined the question of shelf-scale advection of COTS larvae by prevailing currents (Black et al. 1995). This work has concentrated on hindcasting currents, based on economical linear systems models of low frequency motions (Burrage et al. 1994), and ultimately on the fate of larvae.

Crown-of-thorns starfish larvae

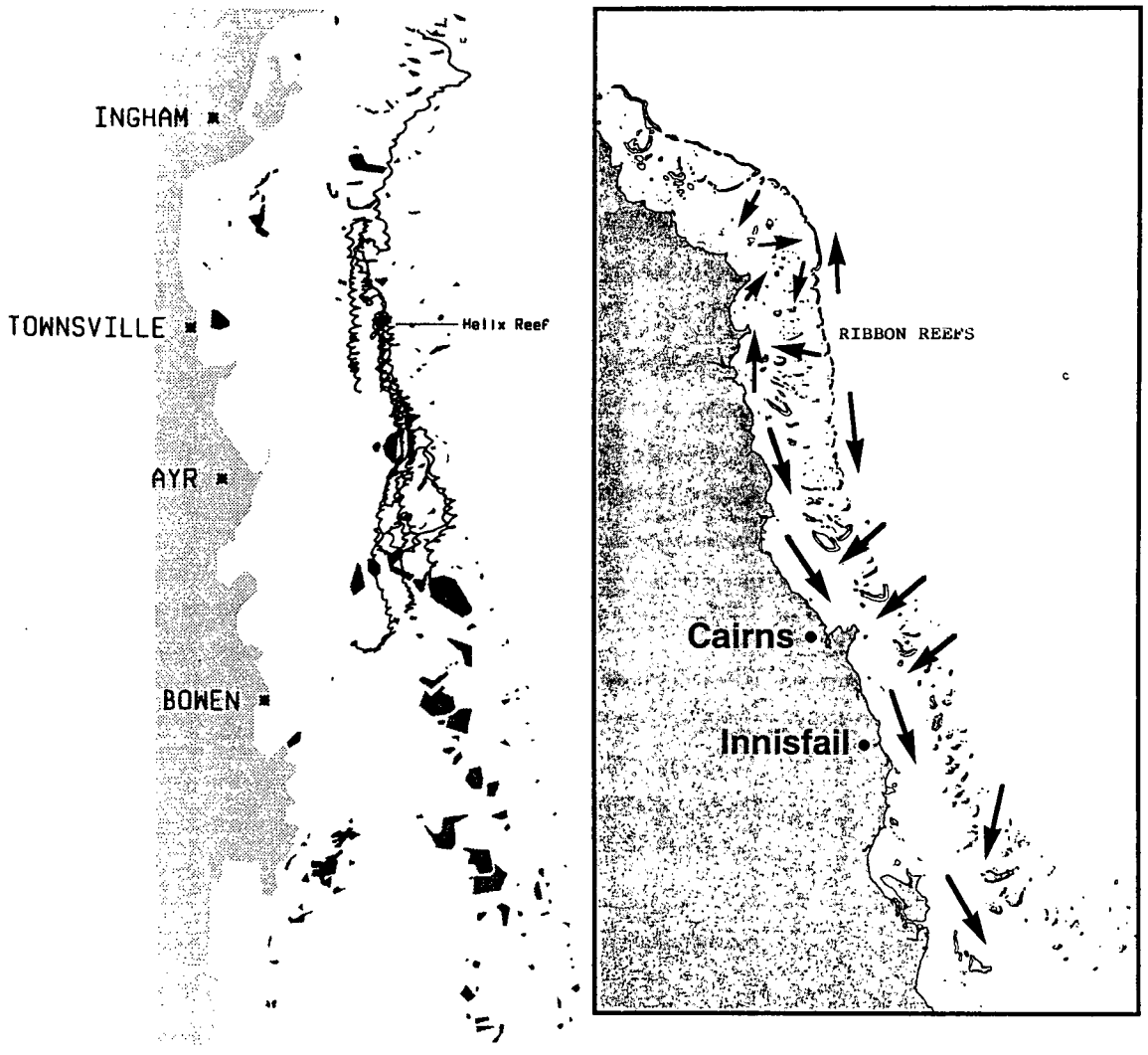
The dispersal simulations performed at JCU in the 1980s and early 1990s used hydrodynamic data generated by a numerical model that solves the depth-averaged long wave equations on a computational grid with a resolution of 5 nautical miles (nm). The equations were solved separately for different forcing mechanisms corresponding to: the East Australian Current (EAC); each of the seven major tidal constituents; and each of a set of spatially uniform wind vectors ranging in speed from 5 to 40 knots and covering 360 degrees in direction. Details and results of the hydrodynamic model were presented, compared with field observations in the Cairns Section of the Great Barrier Reef, and discussed in Dight et al. (1990a), where it was concluded that the model results correspond well with our general understanding of the large-scale features and dynamics of water circulation in that region. The same conclusion was reached in relation to model performance in the Central Section (Dight et al. 1988).

The dispersal simulations employed a particle tracking model in which larvae are passively advected by the net current, estimated at any time from a linear combination of the three hydrodynamic components. This approach made it possible to perform the large number of replicate simulations necessary to characterise the shelf-scale dispersal patterns with the limited computing resources available at that time. Larvae were assumed to be passive, neutrally buoyant particles, well-mixed in the water column, so that vertical structure in the current could be neglected.

In each simulation, the state of the tide and the point in the historical wind record at which to begin particle tracking were randomly selected to represent the occurrence of a spawning event. Since transport of COTS larvae was of particular interest, only segments of the wind record corresponding to the spawning season of the starfish were used to initiate the simulations. Each larval cloud was represented by seven particles arranged initially in a regular hexagon (with one particle at the centroid) with an axis of 0.5 nm, and located at either the eastern or western extremity of the source reef.

If a simulated particle trajectory intersects a reef during the larval competent period, the tracking model records a 'connection event' and the reef is designated as a sink reef. The model assigns a connection weight to each sink reef, the value of which depends on the size and shape of the reef and the incident bearing of the particle relative to the reef (Dight and Black 1991). This weight is a measure of the proportion of larvae from the source reef that have the potential to recruit to that sink. Rules for assigning the weights are based on the results of extensive simulations of advection in the vicinities of individual reefs, using a model with a resolution of 500 m (Dight and Black 1991). This approach overcomes, to a limited extent, the inability of the shelf-scale model, with a relatively coarse resolution of 5 nm, to resolve details of flows at the reef scale. The program also has the ability to model predation mortality which may be suffered by larvae intersecting with reefs during the precompetent phase. In all simulations, COTS larvae were assumed to become competent to settle after 14 days in the plankton, and to die after 28 days if suitable habitat had not been encountered.

Simulations from sample sets of source reefs were carried out for the Central Section (Dight 1991; Dight et al. 1988) and for the Cairns Section (Dight 1991; Dight et al. 1990 a,b; Dight and James 1994; James et al. 1990). From each source reef, forty spawning events were simulated using randomly selected tidal and wind histories. Figure 1(a) shows the simulated trajectories of the centroids of six such events from Helix Reef. Each trajectory corresponds to a different current regime, and the variability in dispersal is evident. Connection weights resulting from the simulations were analysed in an attempt to detect dispersal patterns in two directions: across the shelf and along the shelf. In spite of the variability in the data, some distinct patterns emerged.



(a)

Figure 1. (a) Particle trajectories representing six simulated dispersal events from Helix Reef, each under a different randomly selected combination of wind and tide. Each trajectory corresponds to the particle initially at the centroid of the larval cloud. (b) Dominant larval transport patterns during the summer months, obtained by integrating the results of dispersal simulations from a sample set of source reefs.

In the Central Section and in the southern part of the Cairns Section (south of the ribbon reefs) there is a tendency for larvae to be transported: (1) onshore across the shelf towards the lagoon; and (2) along the shelf towards the south (figure 1(b)). Flows in the main lagoon tend to be directed along the isobaths. This, combined with the cross-shelf onshore larval transport, tends to concentrate larvae in the vicinity of inner matrix reefs adjacent to the main lagoon. These results are in agreement with the observed southward trend in the spread of *Acanthaster* outbreaks. Also, the longshore transport of the concentrated pool of larvae within the Great Barrier Reef lagoon means that reefs bordering the lagoon are in prime locations to receive recruitment. Therefore reefs such as Green Is., Feather, Ellison, Otter, Bramble, John Brewer, Lodestone, Holbourne Is., Bait and Credlin, appear *a priori* to be most exposed to *Acanthaster* recruitment. All these reefs have a history of COTS infestation and high coral mortality.

The situation is different in the northern part of the Cairns Section (figure 1(b)). Here the ribbon reefs present a significant barrier to penetration by the EAC, and the blocking effect of the relatively dense reef matrix on the shelf greatly reduces the wind-driven currents.

These factors inhibit the development of long-shore currents in this region. As a result the patterns of larval dispersal resulting from the simulations are more isotropic. Cross-shelf transport is significantly less pronounced than in the southern Cairns Section and in the Central Section. The southward transport of larvae is also much less dominant.

These results led to two important conclusions (James et al. 1990; Dight and James 1994): (1) that the northern region is partially closed and self-recruiting, while regions to the south are open systems in which populations of some species are maintained by larval recruitment from the north; and (2) that the source of outbreaking populations of COTS in the region of Cairns and further south in the Central Section of the Great Barrier Reef, lies within this northern region. While the patterns of connectivity generated by the early models do not preclude the possibility of outbreaks arising independently across several degrees of latitude (Engelhardt pers. comm.), they do suggest that substantial populations of COTS may be maintained in the northern region, from where populations occasionally propagate southwards, resulting in the pattern of outbreaks that has been well documented.

The sample simulations described above generated broad-scale patterns of larval transport that are in excellent qualitative agreement with observations of the two recorded episodes of COTS activity. Systematic surveys of reefs in the Great Barrier Reef, conducted since 1985 by the Australian Institute of Marine Science (AIMS), recorded information on the presence of starfish (Baker et al. 1991). The availability of these survey data, combined with earlier recorded observations, made it possible to investigate in a more quantitative manner the consistency between simulated larval dispersal patterns and the apparent propagation of COTS populations. If the central hypothesis underlying this work is correct – that passive hydrodynamic dispersal of larvae plays an important role in recruitment – then dispersal simulations from a given set of source reefs should identify those sink reefs with the greatest potential to receive larvae during any spawning season. For any set of surveyed reefs, there ought to be a positive correlation between some integrated measure of exposure to settlement, as estimated by the dispersal simulations, and the later presence of outbreak populations.

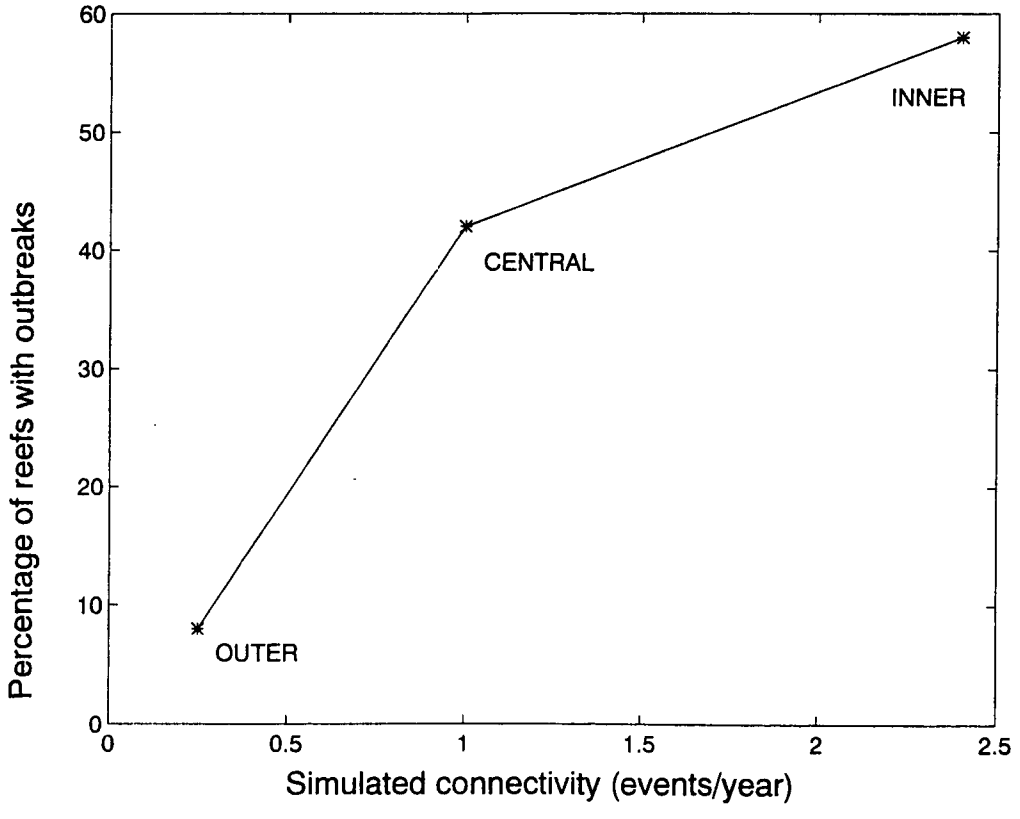


Figure 2. Relationship between the simulated measure of connectivity to surveyed reefs in each cross-shelf zone and the percentage of surveyed reefs in each zone that were affected by COTS outbreaks

Reefs in the Cairns and Central Sections that were recorded as carrying active outbreaks during the period 1979–1989 were used as sources in a programme of intensive simulations of COTS larval dispersal (James and Scandol 1992). Only events with connection weights greater than 10% were recorded. Analysis of the results revealed a positive correlation between potential recruitment and the observed presence of outbreak populations. The correlation was particularly strong when different cross-shelf zones were considered separately (figure 2).

The simulation programme was extended to include as sources all reefs in the Cairns and Central Sections. The ultimate purpose of these simulations was to generate a database of reef connectivity to drive a model of the population dynamics of COTS (Scandol and James 1992; Scandol 1994). Such a model integrates the connectivity data with data on growth rates of starfish and coral, as well as feeding rates and fecundity relationships with starfish size. It also allows expression of the complex network dynamics of the Great Barrier Reef system, as contained in the connectivity matrix. A population model therefore has the potential to provide a much more informative representation of the *Acanthaster* phenomenon than do the connectivity data alone.

The population model was developed and calibrated against the AIMS survey database. Replicate simulations using the fitted model (figure 3) agree well with the observed outbreak dynamics (Scandol 1994).

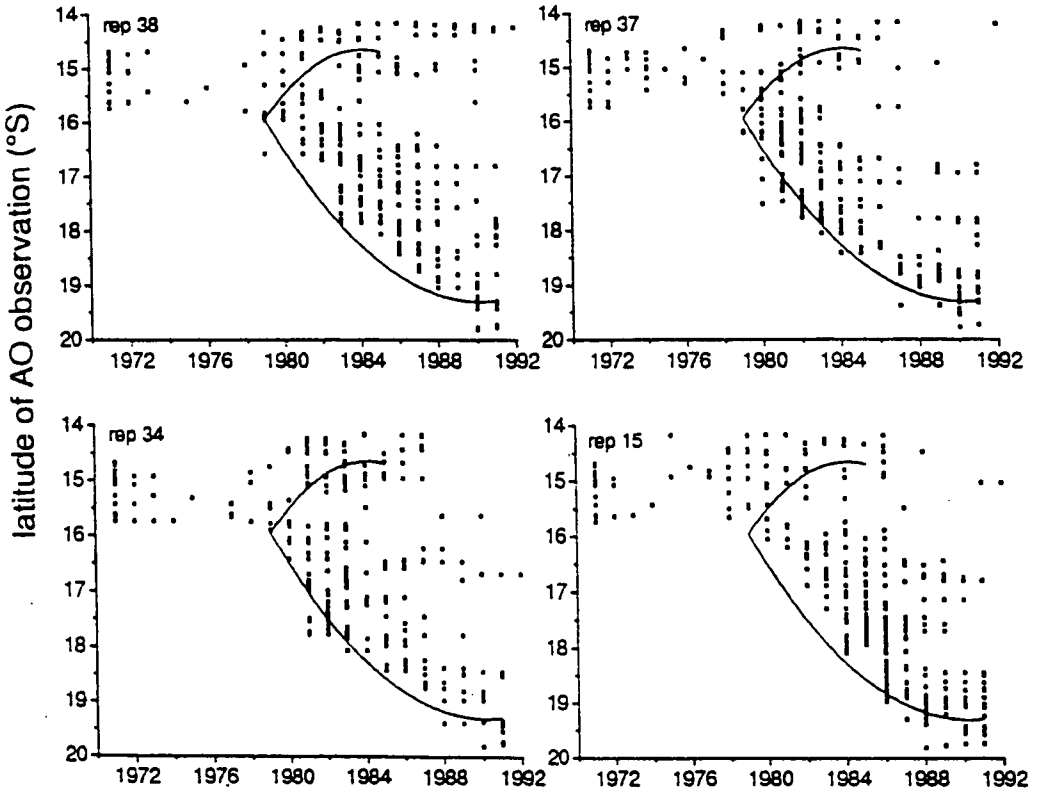


Figure 3. Four example replicate simulations using the fitted COTS population model. The latitudes of active outbreaks (AO) are plotted against time. Also shown on the plot are the curves fitted to the survey data by Moran et al. (1992).

Other species

The simulations described above were performed with COTS larvae in mind. However many other reef invertebrates and fish also spawn during summer, so it is reasonable to compare the modelled larval distributions with observed features of the distribution and abundance of species other than COTS. For example, high abundance and diversity on mid-shelf reefs of

many species with pelagic larvae may, at least in part, be a consequence of the asymmetric cross-shelf flows which tend to transport larvae across the reef matrix towards the lagoon and concentrate them in the vicinity of those reefs (Dight et al. 1988).

Bikaunieks (1995) used the models to simulate the spawning and dispersal of the larvae of a common damselfish, *Pomacentrus wardi*. Spawning was modelled in regular episodes, with timing related to lunar phases. Hydrodynamic variability transformed the regular

reproductive sequence into a highly stochastic record of potential recruitment at various sink reefs. The results closely resembled reported patterns of recruitment of these fishes (e.g. Doherty and Williams 1988).

Dispersal modelling – current research

While the earlier simulated larval distributions suggest that hydrodynamic variability can explain much of the spatial and temporal variation in recruitment, a number of modelling issues remain to be addressed. These are the subjects of current research at JCU. They include: the question of statistical uncertainty in the results; the influence on the results of using a computational grid which is too coarse to resolve clearly the details of currents at the sub-reef scale; and the neglect of physical aspects such as the non-linear interactions among the various dynamical forcing factors.

A major objective of this research is to understand the relationships among three important issues: model realism, computational cost, and uncertainty in model results. For example, improving the refinement of the model grid will make the modelled currents and particle trajectories more realistic, but may vastly increase the cost of running the model. This would in turn reduce the number of replicate simulations which could be performed in a given time with given computing resources, thereby increasing the sampling error in the connectivity results, and possibly leading to little or no overall improvement in the reliability of those results.

Second-generation models which have recently been developed will enable investigation of these factors. Reef bathymetry data are now digitised, and a computer-based system is available to facilitate the setting up of shelf-scale models of any desired grid resolution. The hydrodynamic model is fully non-linear, and the particle tracking model employs a second-order integration algorithm, providing better accuracy in regions of high curvature of the particle trajectories. It is now also feasible to perform simulations in which the larval cloud is represented by thousands of particles.

Statistical uncertainty

Larval dispersal is a stochastic process, subject to natural variability in the hydrodynamics and in the spawning behaviour of organisms. While tidal currents are essentially deterministic and the spawning of some species (e.g. corals) is known to correlate well with the state of the tide, the tidal phase at the time of spawning cannot be predicted in advance for *all* species: it must be regarded as a random variable. Wind-driven currents vary in an unpredictable manner over the duration of larval transport. The EAC (previously modelled as steady-state) also varies over time in a way which is not well understood (Burrage et al. 1995). Therefore the patterns of larval dispersal are not predictable and can be characterised only in a statistical sense. Long-term data on dispersal are required to describe the seasonal, inter-annual and spatial variability in larval availability, in a manner which can be of value to management. These data could be analysed in a number of ways, including, for the species of interest:

(1) Estimating the probability that in any year, *significant* transport of larvae occurs from any given reef to any other reef. This would result in a matrix of connection probabilities.

(2) Estimating, for any given reef, the probability that in any year the total number of larvae available exceeds a given level. These annual probabilities could provide a basis for assessing the risks associated with exploitation of the species on that reef.

(3) Estimating the long-term strength and reliability of any given reef as a source of larvae for other reefs.

(4) Estimating the long-term monthly or annual distribution of larvae over any region of the Great Barrier Reef.

Larval dispersal models can be used to estimate *potential* reef connectivity as determined by the hydrodynamic field. Long-term statistics can be generated by performing replicate simulations of dispersal, with each replicate using an independent set of input parameters obtained from historical data by Monte Carlo sampling. For example, the tidal phase at the start of a replicate simulation can be obtained by randomly sampling the tidal cycle; the sequence of wind vectors driving the simulation can be randomly selected from the historical wind record.

There are several issues of sampling error involved: a finite sample is taken from the infinite population of combinations of tidal phase and wind record segment; historical wind measurements are generally available only at point locations, but must be used to characterise the entire wind field; and the total wind record available is of relatively short duration (e.g. 20 years), but must be used to generate long-term (i.e. hundreds of years) statistics. *The uncertainty in the final estimates will be determined, at least in part, by the sample size employed and the natural variability of the modelled processes.* Figure 1(a) illustrates the degree of variability that may be expected among dispersal events encountering different combinations of wind and tide. Differences due to changing the initial tidal phase by six hours, with all other parameters unchanged, are shown in figure 4. Particle distributions are depicted after 700 hours of simulated dispersal of a cloud of larvae that was initially distributed in five separate patches over Michaelmas Reef. There is significant variation between the two simulations, in the extent of dispersal and in the ultimate fate of particles.

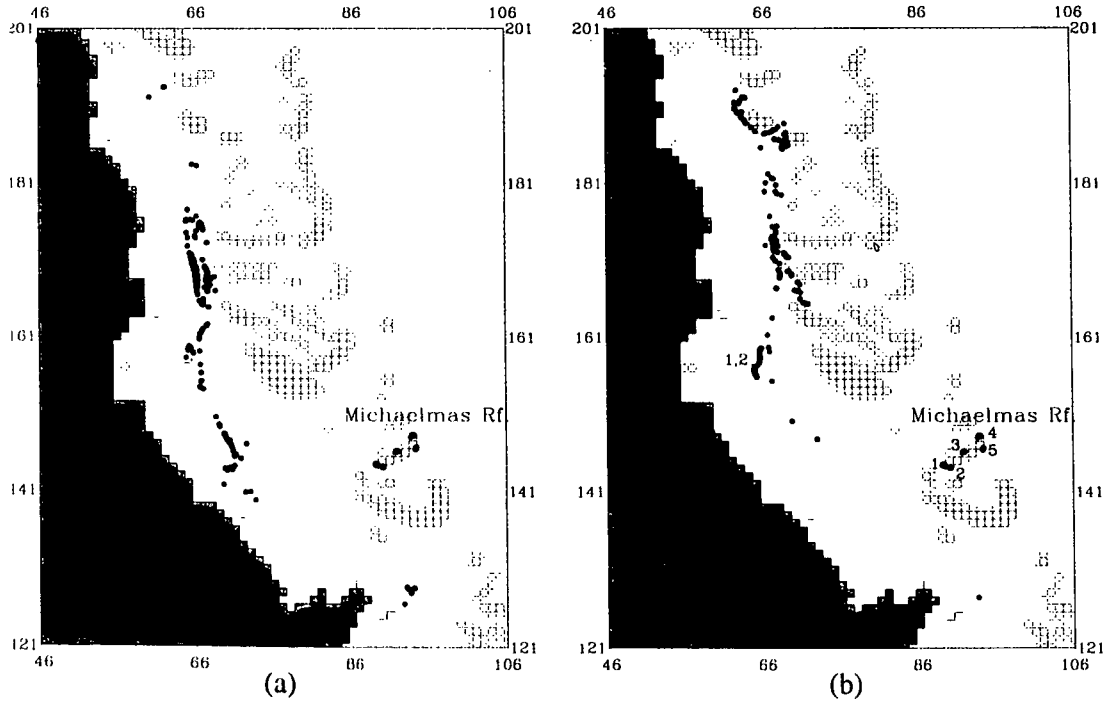


Figure 4. Particle distributions after 700 hours of simulated dispersal of a cloud of larvae initially distributed in five distinct patches on Michaelmas Reef. The initial tidal phases of the two simulations differed by six hours, resulting in significant differences in the particle distributions. Figure 4(b) also suggests the potential importance of the location of spawning events. Patches 1 and 2 remained coherent, while patches 3, 4 and 5 were widely dispersed.

For some input parameters there are no historical data. For example, very little is known about the locations of *A. planci* spawning events, or the effect on dispersal patterns of varying those locations. The earlier simulations were initiated with a particle cloud in the shape of a hexagon, centred on the eastern or western extremity of the source reef. The present model is capable of readily simulating a variety of initial distributions of larvae. Figure 4(b) suggests the potential importance of the location of spawning events. Of the five distinct larval patches, two amalgamated and remained coherent, while the others were dispersed over a wide area. The initial distribution of larvae should therefore be randomly sampled from a set of distributions thought to cover all reasonable possibilities, including: larvae uniformly distributed over the reef; larvae in a line distribution following a segment of the reef crest; larvae in a discrete patch randomly located on the reef crest. Scientific understanding of spawning events could be incorporated in a Bayesian approach to assign likelihoods to these different possibilities.

Another source of sampling error is the number of simulated particles used to represent the larval cloud. The set of points used can be regarded as a sample from the extremely large (hundreds of millions) population of possible points. The sample size was severely limited (seven particles) by computing resources in the earlier work. Limited sensitivity analysis was performed in an attempt to assess the effect of using such a small sample size (Dight 1991). No significant differences were found when the number of particles was increased to 25. With the present modelling system much larger numbers of particles can be employed, providing a more detailed picture of the dispersing cloud (figure 5). However it remains to be determined if the additional information has a significant influence on the large-scale dispersal statistics.

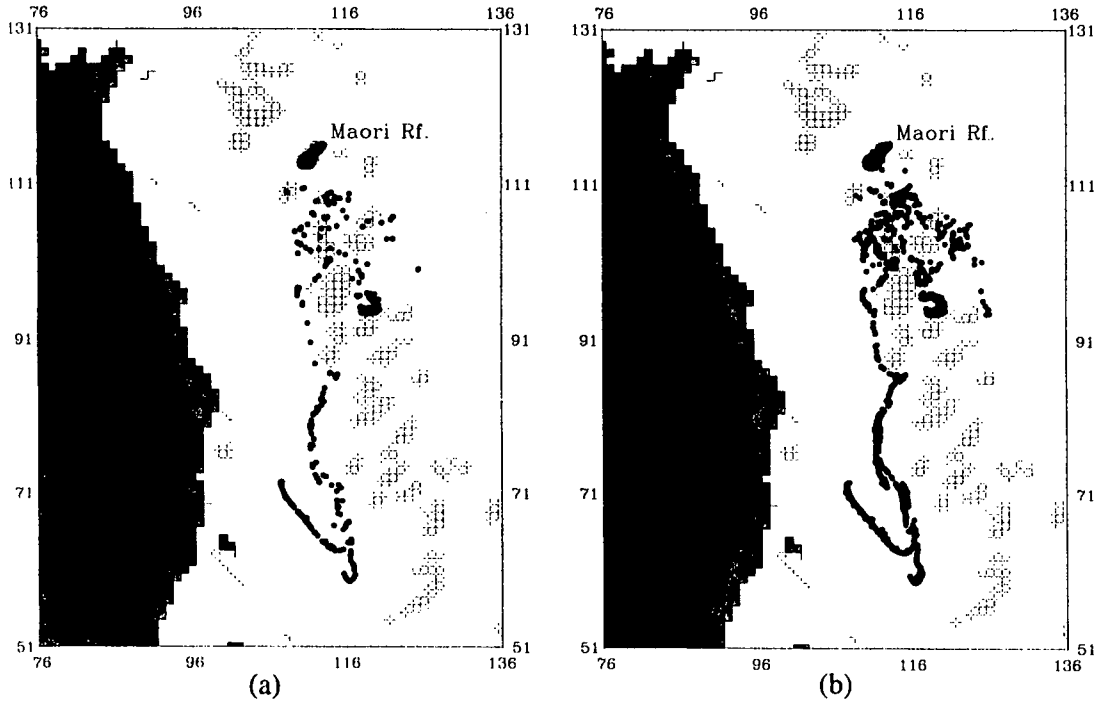


Figure 5. Particle distributions after 600 hours of simulated dispersal of a cloud of larvae initially uniformly distributed over Maori Reef: (a) using approximately 350 particles to represent the cloud; (b) using approximately 2000 particles

Spatial resolution

One of the more severe criticisms of the earlier models (e.g. Oliver et al. 1992; Wolanski 1993) concerned the use of a computational grid which only poorly resolved the details of water currents at the reef and sub-reef scale. The criticism is based on the notion that fine-scale features of the hydrodynamics (1) control the entrainment of particles on to reefs, and hence the likelihood that modelled larvae carried to the vicinity of a reef could actually settle; and (2) could significantly delay the passage of precompetent larvae past a reef by

trapping them in eddies or by carrying them into 'shadowed' areas where the current is, at least temporarily, very small. The first of these criticisms was partially countered by using the results of intensive fine-scale simulations around stylised reefs (crescentic, lagoonal, planar) to develop a parameterisation of the entrainment process. However it is difficult to assess the reliability of this approach in application to the diversity of reef shapes and sizes in the Great Barrier Reef.

There is a high computational cost involved in reducing the grid scale. For example, a two-fold improvement in resolution leads to about a ten-fold increase in computing time and costs. The benefits of improved model resolution must therefore be assessed against the increased cost. The modelling objectives must also be taken into account, as nothing is gained by employing a fine-scale model, at considerable expense, if the modelling objectives can be adequately met by a coarse-scale model.

Clarke (1994) modified the original particle tracking model to incorporate the effects of particle delays in a manner similar to that used by Parslow and Gabric (1989). Delays of, for example, half a tidal cycle, produced no significant changes in the domain of particle trajectories generated by a set of forty replicate simulations. However there were significant changes in the distribution of potential connectivity over reefs in that domain, with a larger number of sink reefs sharing the available larval pool because of greater dispersion of the particles. These results are not unexpected, but suggest that the question of particle trapping and delays should be investigated more closely.

Worthington (1996) has carried out simple fine-scale simulations using a selection of single reefs from the Great Barrier Reef to determine the extent to which trapping and delay of particles occur. That is, given a cloud of particles carried to the vicinity of a reef, what proportion of particles is delayed for a significant time? Results suggest that only a small proportion of particles is significantly affected, and that a grid resolution of 0.4 nm may be sufficient to capture those effects.

Figure 6 presents snapshots of the computed current vectors from a 1.0 nm model and a 0.5 nm model. It shows significant differences in current magnitude and direction in some regions where the finer grid is better able to resolve the reefs and channels. In other more

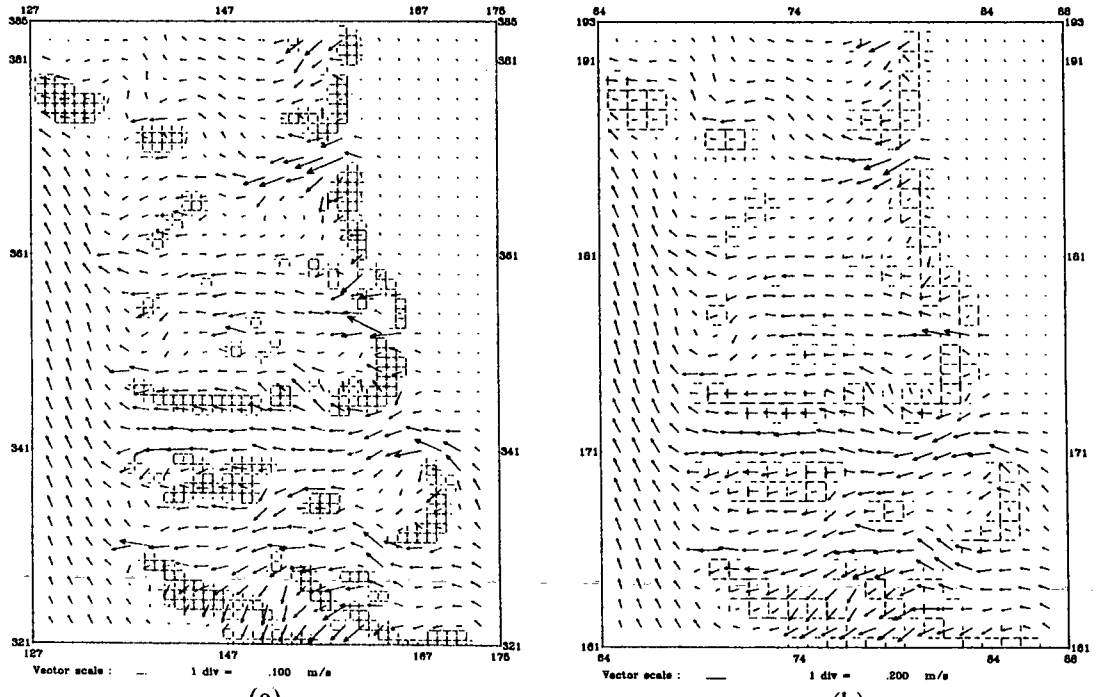


Figure 6. Computed current vectors from two models with grid spacings of (a) 0.5 nm and (b) 1.0 nm

open waters, the differences are much less significant. Because the differences, as shown in figure 6, are generally localised and change with time, their influence on particle trajectories and on the overall statistics of larval dispersal remains to be determined.

Physical aspects

The modelling approach used in the 1980s and early 1990s neglected certain aspects of the physics of water motion. This enabled the large number of replicate simulations to be performed with available computing facilities. The present models are more complete in these respects, but the computational cost is high and must be assessed against the improvement in performance.

Temporal variation in the wind vector was originally modelled by stepping through the discretely sampled wind record, and switching between steady-state current fields as the wind vector changed. This neglected the inertial lag as water currents change with the wind. Sensitivity analysis was conducted (Dight 1991) by incorporating a hydrodynamic response time into the existing particle tracking model. This approach, which was computationally expensive, produced some significant changes in the large-scale larval distributions, including an intensification of the cross-shelf asymmetry in transport observed with the simpler model. With the present approach, however, the full equations of motion are solved during the simulation, and all inertial effects are naturally included.

Another major criticism of the earlier models concerned the linear superposition of the separate solutions under wind, tidal and EAC forcing. This approximation, which neglects non-linear interactions among the three components, was a major factor in reducing the computational cost of performing replicate simulations of dispersal. It was argued that the non-linear terms are small except in shallow waters which account for only a small proportion of the model domain (e.g. very close to reefs). The strongest effect should therefore be found at the reef and sub-reef scale. It is conceptually simple to deal simultaneously with the three forcings, and more powerful computing facilities now make it feasible to do so in the new model.

In a further important approximation, the earlier models assumed a steady state EAC. In those models, the point of bifurcation at which the poleward and equatorward arms originate is held constant in a location which results in poleward flow over most of the model domains employed. The on-shelf southward current field plays an important part in determining the dominant southward transport of larvae generated by the models.

Field work and oceanic models (Burrage et al. 1995) suggest however that the EAC is not in a steady state but experiences significant short-term variation, especially in the latitudinal zone in which the bifurcation occurs. Longer-term variation related to the El Niño effect may also be present. Therefore, the on-shelf influence of the EAC could vary significantly, and have an important effect on the long-term statistics of larval dispersal. New models are under development which will ultimately enable the variability in the EAC to be incorporated in the larval dispersal simulations (Bode et al. 1996).

Model calibration

The physics of large-scale water motion is generally well understood. In principle, for any given bathymetry, forcing and boundary conditions, the hydrodynamic field can be modelled to a high degree of accuracy. In practice, however, input parameters are not well known and must be estimated by a model-fitting procedure (calibration) in which parameters such as boundary conditions are varied until the model results conform with the general understanding of the hydrodynamic field, and agree as closely as possible with measured currents and water levels.

The physical locations of current meters may be important for successful model calibration. There may be regions of the model domain where model results are quite insensitive to variations in the boundary conditions. Field observations in such locations will be less effective for calibration than measurements in locations where model results are more sensitive to boundary conditions. There will also be many locations (e.g. 'near' reefs) where current measurements are significantly affected by reef geometry, turbulence and fine-scale features which do not reflect the background current regime and cannot be resolved by the

computational grid used. Data from such locations would be of dubious value for model calibration.

The calibration process has received a considerable amount of attention from researchers in recent years (Lynch and Davies 1995). Formal optimisation methods are being developed, in which some measure of lack of fit between model results and observations is minimised. Approaches of this kind have not yet been employed in Great Barrier Reef models, but are receiving increasing attention from oceanographic modellers.

Model reliability

The modelling work at JCU has two broad objectives: to improve our understanding of the role of physical processes in the ecology of the Great Barrier Reef; and to provide information on that role which can be of use to managers of the Marine Park. For example, zoning decisions could be assisted by the identification of reefs which are effective and efficient suppliers of larvae to other reefs, or of reefs which are vulnerable to the effects of exploitation because they suffer from an unreliable supply of larvae.

The first objective is bound up with the pursuit of scientific 'truth', and is therefore much concerned with the scientific realism and validity of models. In the present context, model validation involves testing the ability of a calibrated model to forecast or hindcast field observations which were not used in the calibration procedure. Such a test cannot, in practice, be deterministic. Ultimately, a statistical approach is required to analyse the sampling and measurement errors in the data used to drive the model and in the data against which the model is tested, to determine if lack of fit should be attributed to these deficiencies or to model errors. At the same time, account must be taken of the above issues concerning the locations at which data are measured: a model with a spatial resolution of 5 nm should not be tested against data measured in the near vicinity of reefs.

The second objective, relating to management, requires a different approach. Scientific validity, *per se*, is not necessarily the central issue here. A view similar to that adopted in engineering may be more appropriate, in which model reliability and the robustness of decisions made on the basis of model results are the issues (Blockley 1980). This can be illustrated by a simple hypothetical example.

Suppose one of two reefs, A and B, is to be selected for zoning with protected status, and the choice is to be based on the role of each reef as a source of larvae for other reefs. That is, the more effective and efficient source reef will be selected. A numerical model of larval dispersal has been used to perform a large number of replicate simulations of larval dispersal from each reef, under randomly sampled conditions of tide and wind. Connectivity values from the simulations have been integrated to produce two numbers, C_A and C_B, which are estimates of some defined measure of the effectiveness of each reef as a source. Figure 7 shows the combinations of C_A and C_B for which either reef A or reef B would be selected. The model's connectivity results are represented by the point P, suggesting that reef B should be selected.

The estimated measures of source effectiveness are subject to sampling error because of the limited number of replicate simulations performed, and the finite length of the historical wind record. The estimates are also subject to model error, as the model contains a variety of assumptions and approximations. Should the model results be employed, or should the decision be delayed while further (expensive) modelling and field work is carried out to improve their accuracy? This depends, at least in part, on the sensitivity of the decision to uncertainty in the estimates. For example, if by analysing the sampling and modelling uncertainties it could be established, with 95% confidence, that the true values of C_A and C_B lie in the ellipse surrounding point P (figure 7(a)), then the decision to select reef B could be regarded as robust, and it would not be necessary to determine the two measures any more precisely.

This is analogous to testing (in a statistical sense) whether C_B is *significantly* greater than C_A, given the sampling and modelling uncertainties, and rejecting the null hypothesis that $C_B = C_A$. If the analysis resulted in a 95% confidence ellipse which intersected both regions of the diagram (figure 7(b)), the null hypothesis might not be rejected, leading to the

conclusion that the model is unable to reliably distinguish between A and B. A decision analysis would then be required, taking account of the risk and cost associated with making a choice which later proved to be unfavourable.

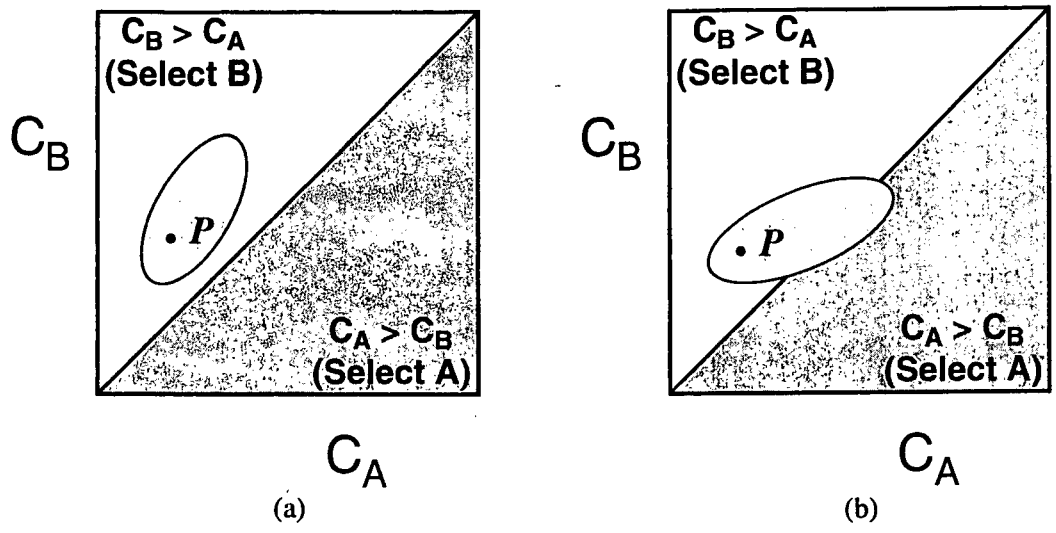


Figure 7. Application of simulated connectivity results in the selection of an effective source reef. C_A and C_B are model-based estimates of the effectiveness of each reef and the point P represents the model results. The uncertainty in the results is indicated by the 95% confidence ellipses.

The key requirement is for an assessment of the uncertainty in model results, *in relation to the management objectives*. It is the model's reliability as a management tool, rather than its scientific validity, which is the central issue. In this approach, the question of scientific validity is not ignored. Instead, it is treated as one of the factors determining the model's ability to achieve its objectives.

CONCLUSION

Simulated larval dispersal patterns obtained from the first-generation dispersal models at JCU strongly suggest that reef hydrodynamics play a major role in determining the spatial and temporal variations in larval availability. Recently developed second-generation models with improved spatial resolution and fully non-linear dynamics can provide more realistic currents and particle trajectories. However the improved realism involves a significant computational cost which could increase the difficulty of performing the large number of replicate simulations that are vital for the characterisation of the long-term dispersal patterns required by management. An important aim of present research at JCU is to achieve an appropriate balance between computational cost and the need for model realism, since both factors influence the model's ability to meet the objective of providing useful information for management.

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SESSION 7

Managing the Great Barrier Reef World Heritage Area

Chair: Ian McPhail

Rapporteur: Helene Marsh

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Keynote Paper:
Can the Great Barrier Reef World Heritage Area be managed sustainably?
I Low
(abstract only)

•

The changing roles of aboriginal people in the management of the Great Barrier Reef.
Noel Pearson and A Leibler-
(presented by A Tanner, abstract only)

•

State of the Great Barrier Reef World Heritage Area report
J Oliver
(abstract only)

•

The Great Barrier Reef: multiple-use marine park and world heritage site
P Valentine*, T Webb, H Marsh and P Lucas

•

Community involvement in the management of the Great Barrier Reef
D Tarte and E Hegerl
(abstract only)

•

Can the Great Barrier Reef World Heritage Area be managed sustainably?

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ABSTRACT

The Council of Australian Governments agreed four years ago on a National Strategy for Ecologically Sustainable Development. In principle, the Commonwealth and Queensland Governments are therefore committed to managing our natural assets sustainably. In the case of the Great Barrier Reef, its listing as a World Heritage Area also imposes a responsibility to the international community for management of an asset deemed to be of global significance.

Any credible definition of sustainable development must include the notion that the pattern of development is able to be sustained: if not indefinitely, certainly at least for several decades. The Brundtland Commission defined sustainable development as meeting the needs of this generation without reducing opportunities for future generations.

The 1996 State of the Environment Report identified our poor knowledge base as a serious impediment to sustainable development. In the case of the Great Barrier Reef, the management approach of the Marine Park Authority was singled out for praise as an example of practice which is admired internationally. However, we are not in a position to say whether the Reef Region is being managed sustainably. Recent monitoring programs have not been in place sufficiently long to give a clear picture. There are worrying signs of degradation, mostly associated with activities on the adjoining land.

This raises a problem identified in the report as one of the most serious impediments to sustainability: our inability to take an integrated approach to environmental problems. The fragmentation of responsibility between different spheres of government and between different departments of the same government prevents the sort of systematic approach that is needed if complex natural systems are to be managed sustainability. In those terms, our inability to manage the Great Barrier Reef World Heritage Area sustainably is a failure of political will.

It is our responsibility to all future generations of Australians to manage the natural assets of this country sustainably. In the case of the Great Barrier Reef, it is also our responsibility to the international community. It will require a fundamentally different approach from that used in the past. Governments at all levels behave as if the first priority should be a well-managed economy which will allow all other problems to be solved. The State of the Environment Report observed that we will have little chance of achieving a sustainable pattern of development while we maintain such a naive approach.

Awareness of ecological issues must be built into all levels of social and economic planning if we are to achieve the goal of sustainability.

The changing role of Aboriginal people in the management of the Great Barrier Reef

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ABSTRACT

The Great Barrier Reef Marine Park was created at a time in Australia when the fallacious theory of *terra nullius*, that the continent was not owned by its indigenous peoples, was assumed to be the law of the land. In relation to land and sea it was assumed that Australia's indigenous peoples had no legally recognisable interests. Since the creation of the Marine Park, the Great Barrier Reef Marine Park Authority has sought to recognise in some respects the traditional interests of indigenous people in access and use of the Reef and its resources, as well as making some small progress towards involving indigenous peoples in its management.

With the recognition of native title in the *Mabo Case*, there has been increased awareness of the indigenous view of the Reef as a cultural seascape, comprising sites of significance and resources vital to the sustenance of indigenous cultures. Indigenous aspirations for recognition of their rights and interests in the Reef, and their concerns about non-indigenous impacts on the cultural and ecological values of the Reef, and their concern to be involved in its management, have not yet been realised. Clearly management is related to tenure issues, but rather than native title providing the impetus for negotiating a settlement of indigenous aspirations in the Marine Park, it appears that a protracted process of opposition to the notion that indigenous people have an interest in the Reef will ensue over the coming years. This oppositional attitude is not necessarily the preferred course for users of the Park, nor of the Marine Park Authority. Rather it is emanating from Government. This course may prove to be contrary to the best interests of future management of the Reef.

The Reef adjacent to Cape York Peninsula presents particular policy questions: it represents the only area of the Reef that is not subject to intense tourist activity and onshore residential and agricultural impacts.; There is now a movement towards the creation of a regional conservation area on the east coast of Cape York Peninsula, representing the last area on the eastern coast of Australia which has not been submerged by development. The question is whether the character of the adjacent Marine Park will reflect a commitment to maintaining this last bit of eastern Australian coastline, in a state of maximum ecological integrity. Should the character of tourism and other commercial exploitation in the Far Northern Section of the Great Barrier Reef Marine Park be different to the exploitation south of Cooktown? I believe that the Reef north of Cooktown should not be approached in the same way as has occurred in management of the more densely settled coastline of Queensland. These are real questions for discussion and decision by Australians concerned with the Reef's future. These are questions of utmost importance to the indigenous peoples for whom the Reef represents an integral part of their cultures and their identities.

Status of the Great Barrier Reef World Heritage Area report

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ABSTRACT

State of the Environment Reporting is increasingly being seen as an important part of environmental management. The Great Barrier Reef Marine Park Authority with assistance from other state and federal agencies, has decided to produce a report on the State of the Great Barrier Reef World Heritage Area in early 1997. The report will include physical, chemical, biological and socio-economic data as well as a section on the current management status of the area.

The report will be based to a large extent on a technical workshop which was held on November 1995. Papers from the workshop proceedings will be published in late 1996, while the final status report will be published in 1997. Based on the papers arising from the workshop, the current situation gives cause for cautious optimism for reefal areas. While there are currently no indications of any severe, large-scale reef degradation as a result of human activity, there are a number of important pressures on the reefs which will need to be monitored on an on-going basis. In particular, reef fish stocks as well as nutrients and sedimentation and their potential effects on corals and algae require continued vigilance. Inter-reefal areas however, (especially the inner-lagoon area) are subject to quite heavy pressure from trawling activities. In areas where heavy trawling persists there is the potential for a continued decline in the benthic biota. The status of dugongs and some species of sea turtle, is also an important issue. Dugong numbers in the southern Great Barrier Reef are declining, while stocks of several turtles species are subject to pressures (largely outside Australia) which, although no trends have been demonstrated so far, are considered to be unsustainable. Although most commercial fish stocks appear to be stable, some are exhibiting small declines. It was stressed there were many challenges facing fisheries managers in the coming years, particularly in effective coordination of management effort between the various agencies involved in fisheries within the Great Barrier Reef World Heritage Area.

Review of use trends and management capabilities from the workshop indicate that the Authority must plan for, and manage, increases in tourism and coastal development and maintain traditional day-to-day management activities such as surveillance and enforcement in order to ensure the Great Barrier Reef World Heritage Area is properly managed and protected.

The Great Barrier Reef: multiple-use marine park and world heritage site

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ABSTRACT

This paper provides a review of the different ways in which the Great Barrier Reef has been perceived with particular emphasis on management. It traces the changes associated with its establishment as a Marine Park through to the implicit and explicit expectations associated with becoming a World Heritage Area. Over this same period the World Heritage concept has itself been evolving and this paper tracks the converging outcomes of these two aspects of the Great Barrier Reef.

The initial review considers the establishment and history of the Great Barrier Reef Marine Park as a managed multiple use site and the range of specific objectives identified for its management. This includes reference to the changing demands placed on the Great Barrier Reef over the past 15 years and the identification and recognition of both threats and conflicts. The history of the nomination and listing of the Great Barrier Reef as a World Heritage Site will be reviewed. Specific outstanding universal values associated with the site are identified including reference to the original nomination documents and to the most recent study of World Heritage elements of the Great Barrier Reef. It is clear that two factors are extremely important in establishing the World Heritage value of the Great Barrier Reef. First the way the extraordinary scale of the site contributes to all levels of biodiversity and to the maintenance of ecological processes. Second, the capacity of Australia to meet its international responsibilities and therefore ensure site integrity.

Between the Great Barrier Reef original nomination time (1980) and the present day, there have been considerable variations in World Heritage operational guidelines, in the political context of World Heritage and in the management practices associated with World Heritage. The paper provides a summary of the ways in which this may influence decisions about appropriate use and identify some of the debates which are currently occurring at international, national and local levels.

The final section of the paper attempts to identify mechanisms to accommodate the complex reality of a modern World Heritage environment (social, political and ecological) within the existing management structure for the Great Barrier Reef. The paper throughout draws heavily on the recent review of World Heritage value in the Great Barrier Reef completed by Lucas et al. (1990).

INTRODUCTION

The Great Barrier Reef World Heritage Area was inscribed upon the World Heritage List in 1981. Six years earlier the Federal Government had enacted legislation to establish the Great Barrier Reef Marine Park (GBRMP). The Great Barrier Reef World Heritage Area is the largest World Heritage Area, being about 1.5 times the area of the United Kingdom. Management of the Great Barrier Reef is unlikely to follow the direction that many other listed properties have taken, due to its size and diversity of existing use. Over 85% of WH natural sites throughout the world were already, at the time of listing, highly protected areas (i.e. IUCN Category I or II). Australian sites, in sharp contrast to the sites of other countries, have generally been of much lower protection status. In the time since its inscription both the World Heritage concept and the GBRMP have evolved considerably. The management of the Great Barrier Reef is now entering into a new era, one in which its status as a World Heritage property, demands a re-appraisal of the property's future management.

This paper outlines the background of the GBRMP and introduces the World Heritage concept, prior to reviewing the original nomination of the Great Barrier Reef to the World Heritage List. The findings of a recent consultancy that sought to expand and further articulate the basis for the nomination are briefly summarised. This paper suggests the direction that those responsible for the region's management should consider to ensure its protection, conservation, presentation and transmission to future generations.

The Great Barrier Reef Marine Park

History of the Great Barrier Reef Marine Park
The 1960s was a period of rapid economic change in Queensland, strong markets developed for sugar and beef, the major primary products of North Queensland, and economic development become the priority of the Queensland Government. The Great Barrier Reef was seen as a vast resource waiting to be exploited; oil exploration in the Great Barrier Reef was established; mining of reefs for limestone was proposed; increases in fisheries and tourism were foreshadowed (Kenchington 1990). This was also a time of growing public concern over the effects of unrestrained economic growth on the natural environment. Scientists had begun to discuss the human impact on the environment in books such as *Silent Spring* (Carson 1962), *The Population Bomb* (Ehrlich 1968) and *The Limits to Growth* (Meadows et al. 1972). Australian organisations advocating conservation became established, in particular the Wildlife Preservation Society of Queensland (WPSQ), and later the Australian Conservation Foundation (ACF) and the Australian Littoral Society. Members of the WPSQ first mooted the idea of the Great Barrier Reef 'becoming a great underwater park' in 1963 (Wright 1977:2).

During the late 1960s the threats to the Great Barrier Reef were becoming increasingly apparent. A proposal to mine Ellison Reef, for limestone in 1967, drew opposition from the recently formed conservation groups. In a widely publicised case the Mining Warden refused the application (Wright 1977). Outbreaks of the crown-of-thorns starfish (COTS) (*Acanthaster planci*) were occurring, killing as much of 95% of the living coral on severely affected reefs (Kenchington 1990). The North Queensland trawl fishery was expanding rapidly, and foreign fishing vessels started trawling in Great Barrier Reef waters. Additionally foreign fishers were collecting giant clams, turtles, reef fish and ornamental shells from the region (Kenchington 1990).

These issues drew attention to the lack of an adequate management regime for the Great Barrier Reef, and highlighted the need for Australia to lay claim to its off-shore resources. In 1968 the *Continental Shelf (Living Natural Resources) Act* was passed, giving the Commonwealth Government responsibility for sedentary living resources to the outer barrier of the reef.

However the issue that galvanised public opinion in support of reef conservation was that of oil exploration and drilling. The first well had been drilled on Wreck Island in 1958, with two additional bores in the Capricorn Channel in 1967–68, and a fourth near the tip of Cape York Peninsula in 1969 (Bowen 1994; Wright 1977). By September 1967, 80 920 square miles (nearly 210 000 km^2) of the Great Barrier Reef had been leased for mineral or oil exploration (Wright 1977). Public disquiet grew over the prospect of oil drilling in the Great Barrier Reef following oil tanker accidents, and in particular, the offshore oil leaks from the Santa Barbara oil fields in California during January 1969 (Wright 1977). There were concerns regarding the low level of environmental protection the Queensland Government would most likely require of any drilling operations, and the public was increasingly looking to Canberra for protection of the region. Following increased public pressure and union work bans a moratorium was declared on further drilling in 1970. The Queensland and Commonwealth Governments established a joint Royal Commission to inquire into the issue of oil exploration and production in the Great Barrier Reef region.

In 1972 the social reformist Whitlam Labour government replaced the conservative coalition government. The Whitlam government enacted the *Sea and Submerged Lands Act 1973* which asserted Commonwealth rights, over those of the States, to territorial sea and the continental shelf. The Whitlam government also initiated the Committee of Inquiry into the National Estate which, in its 1974 report, noted a number of concerns regarding the Great Barrier Reef, in particular the impacts of terrestrial inputs, the crown-of-thorns starfish, and oil exploration on the reef. The Committee suggested that an authority be established

'charged first and foremost with the protection of the Great Barrier Reef from damaging activities' (Hope et al. 1974:67). The Royal Commission into oil exploration handed down its findings in 1974, in which the majority finding was that oil exploration could be carried out with stringent conditions in some areas without unacceptable risk, while a dissenting minority report by the Chair of the Commission argued that no exploration or production should take place (Kenchington 1990).

Against this background the Whitlam Government introduced the *Great Barrier Reef Marine Park Bill* into Parliament, with bipartisan support, and was passed into law. The object of the Act is to:

> ... make provision for and in relation to the establishment, control, care and development of a marine park in the Great Barrier Reef Region[1]

The Marine Park Concept

The concept of a marine park was not new, the first marine park being declared at Fort Jefferson in the Dry Tortugas in 1935, and by the 1960s several were established in the United States and British Caribbean territories (Bowen 1994). However these were small marine parks, with an approach not dissimilar to that taken with terrestrial national parks. The GBRMP was set to redefine the concept. The inaugural Annual Report of the Great Barrier Reef Marine Park Authority (GBRMPA), covering the 1976–77 financial year noted that the Great Barrier Reef region was subject to a wide variety of uses, ranging from 'passive' recreational uses through to commercial fishing. The report noted:

> The traditional 'national park' concept is not sufficiently flexible to accommodate many of these activities. A broader approach has been developed for the Great Barrier Reef Region which recognises the diversity of use (GBRMPA 1978:4).

This 'broader approach' adopted is a multiple-use planning framework. In which opportunities for a range of uses from commercial exploitation through to strict preservation are provided. The range of uses are spatially and temporally delineated through zoning plans. The objects the GBRMPA must consider in developing zoning plans clearly enunciate the multiple-use philosophy at the heart of this 'marine park' concept. These objects are:

> (a) the conservation of the Great Barrier Reef;
> (b) the regulation of use of the Marine Park so as to protect the Great Barrier Reef while allowing the reasonable use of the Great Barrier Reef Region;
> (c) the regulation of activities that exploit the resources of the Great Barrier Reef Region so as to minimise the effect of those activities on the Great Barrier Reef;
> (d) the reservation of some areas of the Great Barrier Reef for its appreciation and enjoyment by the public; and
> (e) the preservation of some areas of the Great Barrier Reef in its natural state undisturbed by man [*sic*] except for the purposes of scientific research[1]

Importantly, however, the original aim of establishing the GBRMP was to ensure the protection and conservation of the region. In the second reading speech for the legislation Dr Cass, the Minister for Environment, stated:

> Once the legislation is passed, the Government will be able to declare and protect zones of the reef as national parks or nature reserves... Other zones will be set aside for tourist development, for shipping, fishing and other appropriate uses. However, *conservation and protection of the Great Barrier Reef will be the paramount aim of the Authority in all zones of the Marine Park* [emphasis added] (Australia, House of Representatives 1975, *Debates* vol. HR95, pp. 2680).

[1] *Great Barrier Reef Marine Park Act 1975* (Cwlth), s. 32(7)

This 'paramount aim' appears subsequently to have been somewhat submerged by strong emphasis on the 'multiple use' nature of the GBRMP.

Management regime for the Great Barrier Reef Marine Park
The GBRMP is primarily managed at two spatial scales, a macro scale in the form of zoning plans for each section of the Park, and a micro scale of assessing permit applications for various activities requiring permits under the zoning scheme. Meso scale management through the use of management plans is less developed, with many plans remaining in draft stages for many years. Management planning and permit assessment for the Park is carried out jointly by the GBRMPA and Queensland Department of Environment (QDE), while operational aspects and the day to day on ground management is delegated to a number of Queensland agencies.

Zoning plans are in place for the four sections of the GBRMP: Far Northern, Cairns, Central and Mackay/Capricorn. The vast majority (73%–85% of a Section) of the park is zoned General Use 'A', allowing general use consistent with the conservation of the GBRMP. This has been interpreted as allowing all activities other than mining, oil drilling and spearfishing on SCUBA.

Only a very small area (less than 5%) of the GBRMP is zoned at a level of protection comparable to a terrestrial national park (Marine National Park 'B' Zone) (Whitehouse 1993). Furthermore the areas that are highly protected are unevenly distributed over the habitats of the GBRMP. Similarly the distribution of highly protected areas is uneven throughout the extent of the GBRMP. For example, the seagrass beds on which dugongs depend are not nearly as well protected in the southern Great Barrier Reef, where dugong numbers are declining (Marsh et al. 1995), as in the north, where they appear to be stable (Marsh et al. 1993). A dugong sighted in the Great Barrier Reef Region north of Cooktown is 11 times more likely to be protected by a zone with a higher protection than General Use 'B' than a dugong occurring in the remainder of the Region (Marsh et al. 1995).

In his review of the GBRMPA, Whitehouse (1993) foreshadowed a shift in importance away from large scale zoning plans towards management plans in the planning for the GBRMP. This trend was formalised through amendments to the Great Barrier Reef Marine Park Act in 1995, that give statutory backing to management plans.

The Great Barrier Reef World Heritage Area

The World Heritage Concept

The *Convention Concerning the Protection of the World Cultural and Natural Heritage* (the World Heritage Convention) was adopted by the General Conference of UNESCO at its 17th session on 16 November 1972. It came into force on 17 December 1975, and gained substance on 8 September 1978, when the first properties were inscribed upon the Convention's main instrument, the World Heritage List.

The central theme of the World Heritage Convention is the idea that there are fixed cultural and natural properties of such outstanding value from a global perspective that these sites should be conserved and protected for the benefit of all humanity. The Convention provides the vehicle for the recognition of these properties, and a number of instruments for their protection and conservation.

The primary obligation of States Parties to the Convention is spelled out in Article 4 which places a duty upon a State Party 'to do all it can' and 'to the utmost of its own resources' to ensure

> the identification, protection, conservation, presentation, and transmission to future generations of the cultural and natural heritage referred to in Articles 1 and 2 and situated on its territory (UNESCO 1972, Art. 4)

Properties are inscribed upon the World Heritage List, by the World Heritage Committee, in recognition of their 'outstanding universal value' from the viewpoint of history, art, aesthetics, archaeology, ethnology, science, conservation or natural beauty. The Committee

has developed criteria by which properties nominated for inclusion upon the World Heritage List can be assessed. The criteria and assessment procedures are detailed in the set of *Operational Guidelines for the Implementation of the World Heritage Convention* (World Heritage Committee 1996).

For a property to be inscribed upon the World Heritage List by virtue of its natural heritage the Committee must be satisfied that the property meets at least one of the four natural heritage criteria and the associated conditions of integrity. The criteria relate to the attributes or qualities of the property, while the conditions of integrity refer to the conditions required to ensure those attributes are conserved and protected. For natural heritage nominations the criteria refer to i) geological processes and phenomena, including evolution of the earth; ii) ongoing ecological and ecological processes; iii) aesthetics and natural beauty; and iv) habitats of threatened species and biodiversity (World Heritage Committee 1996).

Nomination and Review of the Great Barrier Reef World Heritage Area
The Great Barrier Reef Region was nominated for inclusion in the World Heritage List in December 1980. The justification for listing is broad and general, primarily focusing on the coral reef ecosystems of the area, with only passing mention of other marine and terrestrial components. The nomination was justified in terms of both cultural and natural heritage criteria. On cultural heritage grounds the nomination stated:

> The area of this nomination contains many middens and other archaeological sites of Aboriginal or Torres Strait Islander origin. There are over 30 historic shipwrecks in the area, and on the islands there are ruins and operating lighthouses which are of cultural and historical significance (GBRMPA 1981:5).

However, the nomination was primarily argued on the grounds of satisfying natural heritage criteria:

> The Great Barrier Reef is by far the largest single collection of coral reefs in the world. Biologically the Great Barrier Reef supports the most diverse ecosystem known to man [*sic*]. Its enormous diversity is thought to reflect the maturity of an ecosystem which has evolved over millions of years on the north east Continental Shelf of Australia.
>
> The Great Barrier Reef provides some of the most spectacular scenery on earth and is of exceptional natural beauty. The Great Barrier Reef provides major feeding grounds for large populations of the endangered species *Dugong dugon* and contains nesting grounds of world significance for the endangered turtle species green turtle (*Chelonia mydas*) and loggerhead turtle (*Caretta caretta*).

The Great Barrier Reef thus meets all four criteria set out in Article 2 of the World Heritage Convention (GBRMPA 1981:5–6).

The nomination document also details how the conditions of integrity are met for the property, stating that 'the area nominated also meets the conditions of integrity in that it includes the areas of sea adjacent to the reef' (GBRMPA 1981:6). Furthermore the management regime envisaged for the Great Barrier Reef World Heritage Area is described including information on the zoning scheme for the Capricornia Section, the only Section proclaimed as the GBRMP at the time of World Heritage nomination. Two threats to the integrity of the Great Barrier Reef World Heritage Area were perceived at the time of nomination, namely a) mining and oil drilling on the reef; and b) the crown-of-thorns starfish.

The technical review of the nomination was carried out by the IUCN, incorporating an expert review by five international experts (IUCN 1981). The review acknowledged the outstanding universal value of the area nominated, remarking that:

> It seems clear that if only one coral reef site in the world were to be chosen for the World Heritage List, the Great Barrier Reef is the site to be chosen (IUCN 1981:2).

This review recognised the importance of the area to the continued survival of dugongs and marine turtles given the pressures upon these species elsewhere, and concluded that the area meets all four of the natural heritage criteria. The IUCN recommended that the area be inscribed upon the World Heritage List.

The evaluation report also highlighted concerns regarding the conditions of integrity for the area. Specifically, attention was drawn to the manner in which management responsibility is divided between the Commonwealth and Queensland Governments, the lack of sufficient legal protection, particularly for the areas lying outside sections considered for a zoning plan, and the lack of a firm temporal commitment to the declaration of other sections of the GBRMP (IUCN 1981).

The evaluation recognised the potential for increased pressures for the exploitation of the area's resources and questioned the fortitude of the governments in maintaining the prohibition of oil drilling, that could damage the reef, in the face of economic pressures. The IUCN recommended that the Committee request periodic reports detailing how 'development pressures are being managed so as to maintain the integrity of the site' (IUCN 1981:2).

The World Heritage Committee at its Fifth Session meeting in Sydney from 26–30 October 1981 decided on 30 October to include the Great Barrier Reef on the World Heritage List. The Committee noted, however, that only a small portion of the area nominated was proclaimed under the Great Barrier Reef Marine Park Act, and requested the:

> Australian government to take steps to ensure that the whole area is proclaimed under relevant legislation (World Heritage Committee 1982:4).

The Outstanding Universal Value of the Great Barrier Reef World Heritage Area
Recently the Great Barrier Reef World Heritage nomination has been revisited with a view to expand and update the justification for the Area's inclusion upon the World Heritage List as a natural heritage property (Lucas et al. 1996). The methodology sought to identify the natural heritage attributes of the Great Barrier Reef World Heritage Area and then consult with a recognised expert for each in order to document the contribution of the attribute to the outstanding universal value of the Great Barrier Reef World Heritage Area. This process covered a range of taxa, habitats, geological aspects and aesthetic qualities for the Great Barrier Reef World Heritage Area.

It became apparent that the 'outstanding universal value', or the World Heritage value, of the Great Barrier Reef World Heritage Area rests upon two primary factors:

- the scale of the Great Barrier Reef World Heritage Area; and
- the high potential for effective conservation management.

More specific attributes are predicated upon these two factors. This was a consistent and recurring theme from the experts, covering the range of physical, bio-physical and aesthetic attributes, that were consulted.

The scale of the Great Barrier Reef World Heritage Area was often seen as the antecedent to some other valued phenomena. The latitudinal extent from low water mark on the mainland coast to past the edge of the continental shelf, and the longitudinal expanse from the tip of Cape York Peninsula to just north of Fraser Island, ensure that a highly diverse suite of habitats and environmental regimes at a range of spatial scales are represented in the one World Heritage Area. This habitat diversity gives rise to a vast range of species and ecological processes, natural beauty and experience opportunities.

Acknowledging that the size of the Great Barrier Reef World Heritage Area underlies its 'outstanding universal value', there is considerable danger, though much superficial attractiveness, in attempting to locate the significance at specific sites. The 'outstanding universal value' of the Great Barrier Reef World Heritage Area is a consequence of many

attributes combining to produce a whole which cannot be reduced, without loss, to disconnected components. Furthermore, while some specific location of particular value can be identified (for example Raine Island), for a number of attributes such specificity cannot be achieved due to the paucity of information.

The second fundamental factor giving rise to the Great Barrier Reef World Heritage Area's 'outstanding universal value' is the relatively pristine state of the Area in comparison to other tropical coral reef ecosystems, and the high potential for effective conservation management. Other systems in the Indo-West Pacific region are under considerably more pressures from extractive uses, while the resources to manage these sites effectively are often limited or lacking. It has become apparent that, if the diversity of tropical coral reef ecosystems and the species they support is going to be conserved into the future, then the Great Barrier Reef World Heritage Area will play the fundamental and pivotal role.

In relation to World Heritage in general and the Great Barrier Reef World Heritage Area in particular, the most poorly understood natural heritage attributes are those concerned with criterion (iii), aesthetics and natural beauty. The lack of consistent methodologies to document, understand and assess these values must not be used as an excuse to ignore them. Furthermore, it is paramount to recognise that aesthetic value is not only about visual amenity, but rather incorporates considerable depth of meaning, understanding and attachment to a place or concept. It is likely that the rich tapestry of meanings that people associate with particular World Heritage Sites, rather than discrete biological or physical phenomena, are the basis for much conflict over what happens to these places.

Managing the Great Barrier Reef Region in a World Heritage Context

There are a number of issues, that while not unique to the Great Barrier Reef World Heritage Area, any new management direction will need to consider. These are the complex jurisdictional issues surrounding the property, the evolution in World Heritage implementation, the size of the property, and its historical genesis as a multiple-use area.

Jurisdictional/Boundaries
The Great Barrier Reef World Heritage Area is not the same as the GBRMP. The World Heritage Area commences at the tip of Cape York Peninsula and extends east to a point beyond the edge of the continental shelf. From here the boundary runs generally south-east to just north of Fraser Island. Here the boundary returns to the Queensland coast and then extends generally northwards at the low water mark to the tip of Cape York Peninsula. The World Heritage Area includes all the Queensland and Commonwealth owned lands and waters within these boundaries.

The vast majority of the World Heritage Area (93%) is, however, constituted as the GBRMP, and its management administered by the GBRMPA accordingly. The remaining areas comprises islands (5%) and Queensland waters outside the GBRMP (2%) (GBRMPA 1994). The majority of the islands are managed as protected areas under Queensland legislation. While a component of Queensland waters are designated as state marine parks and managed along similar lines to the GBRMP under state legislation,[2] a component of the Queensland waters are excluded from such conservation management. These waters are typically around city ports.

The management of the Great Barrier Reef World Heritage Area is particularly complicated as no single agency has the lead responsibility for its management. Moreover the agency with jurisdiction over the majority of the World Heritage Area, has restricted powers to manage activities occurring in the coastal zone, the area where much human activity with the potential to impact upon the World Heritage Area takes place.[3] Furthermore the GBRMPA is not responsible for the management of the major extractive industry, fishing. This is managed by the Queensland Fisheries Management Authority (QFMA) under the *Queensland Fisheries Act 1994*.

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[2]*Marine Parks Act 1982* (Qld)
[3]The *Great Barrier Reef Marine Park Act 1975* (Cwlth), in s. 66(2)(e), gives the Governor-General the power to make regulations for 'regulating or prohibiting acts (whether in the Marine Park or elsewhere) that may pollute water in a manner harmful to animals and plants in the Marine Park'.

The situation is further complicated by the dynamic nature of the marine environment, where seasonal influences may cause sandy shores to change in shape and position, or even disappear in the case of some sand cays (Kenchington 1990). Furthermore, the State and Commonwealth Governments define different low water marks, the Commonwealth taking mean low water, while Queensland uses the low of Indian Springs (Kenchington 1990). In addition, the actual position of low water mark, regardless of its definition may be difficult to place. Thus, the boundary of the Great Barrier Reef World Heritage Area along the coast at low water mark may be open to question, especially across complicated regions such as river deltas, for example, the mouth of the Burdekin River.

Evolution of the World Heritage Concept
The World Heritage Convention was adopted by UNESCO 25 years ago, in the intervening time the operation of the Convention has evolved and its focus changed. Public involvement, particularly that of Indigenous peoples, in World Heritage has increased. The assessment of nominations has become more rigorous and the criteria used were substantially amended following a review in 1992. In particular amendments to the cultural heritage criteria extended the narrowly focused concept of rural landscapes to recognise the past and present role of hunter-gatherer societies in maintaining landscapes, and the continuing association of landscapes and landscape features to indigenous peoples (Titchen 1993). Similarly within Australia the meaning of World Heritage has also changed since the country's first listings of the Great Barrier Reef, Willandra Lakes and Kakadu in 1981.

At the time of the Great Barrier Reef nomination the primary emphasis of World Heritage implementation was the identification and listing of properties on the World Heritage List. The World Heritage Committee now recognises that the future implementation of the Convention will place a greater emphasis on monitoring the state of conservation of listed properties (World Heritage Committee 1992). This change in emphasis, from creating the List to ensuring the continued quality of the List, is mirrored in changing perceptions of the Great Barrier Reef as a World Heritage property.

Listing of the Great Barrier Reef was seen primarily in terms of commemorating the Great Barrier Reef, it is a badge, a plaque on the wall of the GBRMPA office. The obligations of protection and conservation were seen to be delivered by the planning and management regime of the GBRMP. However the assumption that Marine Park management also meets the obligations under the WHC has been recently questioned (e.g. Haigh 1994; Morris 1995a, 1995b). It must also be recognised that along with the increased status which an area receives from being listed as World Heritage, there is also a need to recognise that listing means the property belongs to the world and that this in itself will bring closer scrutiny to its management, especially as that management addresses protection. Furthermore the changes to the cultural heritage criteria provides the opportunity to re-nominate the Great Barrier Reef World Heritage Area as a cultural landscape. The future management of the Great Barrier Reef in a World Heritage context is now at a cross-road, the badge approach is no longer sufficient.

Scale/Size
The Great Barrier Reef World Heritage Area is the largest World Heritage Area listed under the Convention, accounting for more than 32% of the total combined area of natural heritage properties as of December 1993 (IUCN 1994). It is one of only 15 sites greater than one million hectares in size, and one of only two sites greater than ten million hectares in area. The Great Barrier Reef World Heritage Area is nearly two million times larger than the smallest natural World Heritage site, the Vallée de Mai Nature Reserve in the Seychelles, at just 18 ha, and it is nearly one and a half times larger than the United Kingdom.

A World Heritage Area of this size creates some specific problems with regard to management of the site. With smaller World Heritage Area's the whole site can easily be managed as a single highly protected area. As has been noted this is not the case for the Great Barrier Reef World Heritage Area, moreover it is politically and economically unlikely that such a scenario would develop. In recognition of this, management for World Heritage needs to adopt an approach commensurate with the scale of the property. A regional level approach at a scale between broad brush zoning plans and the specific operation permit level needs to be further articulated for the World Heritage Area. Such a planning approach should overtly detail the limits to use for discrete areas of the property.

Furthermore the recognition of World Heritage obligations should be integrated into the planning systems of neighbouring lands.

Multiple Use and World Heritage
At the heart of the issues surrounding the management of the Great Barrier Reef is the discrepancy between the multiple use philosophy underpinning the GBRMP, and some preservationist interpretations of the World Heritage concept. While the large majority of natural World Heritage properties are managed as IUCN category I or II protected areas (Valentine 1994, 1996), World Heritage *per se* does not obligate States Parties to preserve the area as a category I or II protected area. If this were the case then it is doubtful that the Great Barrier Reef would have been listed in the form that it was.

In contrast, the current situation with less than 5% of the Great Barrier Reef World Heritage Area covered by a management regime equivalent to that of a terrestrial national park or higher (Whitehouse 1993) seems to suggest a minimalist approach to the obligations placed on the Commonwealth to ensure the protection, conservation, presentation and transmission of the Great Barrier Reef World Heritage Area to future generations. This problem is further compounded by the varying amounts of protection afforded to different habitats and in different regions. This situation presents two directions for the future management of the Great Barrier Reef in a World Heritage context. One direction would see the World Heritage listed area reduced to those components that are managed along the lines of category I or II national parks. Alternatively the management of the Great Barrier Reef could be explicitly set within a framework of meeting the obligations under the Convention.

The first option, resulting in a serial World Heritage Area similar to one currently under consideration for the Belize Barrier Reef, is clearly not an appropriate approach given the inherent connectivity in marine ecosystem (Bode et al. 1992). Furthermore the Operational Guidelines urge against such a direction suggesting in their conditions of integrity that:

> a coral reef should include, for example, seagrass, mangroves or other adjacent ecosystems that regulate nutrient and sediment inputs into the reef (World Heritage Committee 1996:13)

The second direction is more appropriate, and travel upon this road has already commenced with a number of important initiatives, including the preparation of a 25 Year Strategic Plan for the Great Barrier Reef World Heritage Area, negotiations resulting in a Memorandum of Understanding clarifying the roles of various Commonwealth Departments and Agencies in the management of the Great Barrier Reef World Heritage Area, and the commissioning of a consultancy to articulate the basis for the inclusion of the Great Barrier Reef on the World Heritage List.

Towards a New Management Ethos

Recent changes in the management of the Great Barrier Reef Region as a World Heritage Area
In 1995 the *Great Barrier Reef Marine Park Act* was amended to reflect the World Heritage Listing of the Great Barrier Reef. The amendment may have been prompted by recommendation 1.2 of Whitehouse (1993) in his review of the GBRMPA:

> The objects provisions contained in [section] 5 of the Great Barrier Reef Marine Park Act should be amended to include specifically a reference to the concepts of ecologically sustainable development and ecosystem management, the protection of World Heritage values and the concept of multiple use management of the GBRMP (Whitehouse 1993:178).

The present amendment falls short of the Whitehouse recommendation. The objects provision has not changed. Rather the amendment applies only to the preparation of management plans under Part VB of the Act:

> 39YA.(1) The authority in preparing management plans must have regard to:

(a) the protection of the World Heritage values of the Marine Park;
(b) ...

However it is indicative of a growing concern to explicitly manage the Great Barrier Reef in a World Heritage context. Similarly the GBRMPA has recently negotiated a Memorandum of Understanding (MOU) with other Commonwealth departments and agencies that have responsibilities related to World Heritage in the Great Barrier Reef region, namely the Australian Heritage Commission, the Environment Protection Agency and the Department of Environment Sport and Territories. The MOU identifies the GBRMPA as the lead agency for any actions that may affect the Commonwealth's obligations under the World Heritage Convention in relation to the Great Barrier Reef World Heritage Area. Given that much of the potential impact upon the Great Barrier Reef World Heritage Area is sourced from areas or activities under Queensland jurisdiction, the management of the World Heritage property could be further enhanced by a similar MOU negotiated between the Commonwealth and Queensland Governments.

Other initiatives such as the commissioning of several consultancies investigating World Heritage issues, the preparation of the State of the Great Barrier Reef World Heritage Area Report, and moves to more adequately represent habitats and ecosystem types within the highly protected zones of the Marine Park are further indications that GBRMPA is taking up the challenge of managing in a World Heritage context. In various places and times, the present Chairperson of the GBRMPA has frequently drawn attention to the change in that organisation from seeing World Heritage as a 'badge of merit' to recognising the responsibilities and potentially different way in which management may operate within a World Heritage Area. There is a clear need to identify and implement what may be regarded as best practice in management to match the 'best of the best' status of the Great Barrier Reef. The Australian Regional Committee of IUCN's World Commission on Protected Areas is currently exploring the nature of best practice for protected areas and it is clear that World Heritage sites should be at the forefront of such discussions.

In reviewing the recent historical context of the GBRMP and the Great Barrier Reef World Heritage Area, three qualitatively different eras can be delimited. During the first period we discussed, the 1960s the Great Barrier Reef was seen as a vast natural resource waiting to be exploited. Following this, the 1970s could be characterised as the *decade of actions*. Public disquiet over the future protection of the Great Barrier Reef led to the moratorium of oil drilling in the Great Barrier Reef, the Royal Commission and the passing of legislation to create the GBRMP. The 1980s saw the continuing consolidation and development of the planning framework for the GBRMP, and its inscription upon the World Heritage list. GBRMPA's reputation as a world-wide expert in management of large marine parks grew. This period could be labelled the *badge of honour* years. Finally the 1990s has seen an increasing questioning of the management of the Great Barrier Reef, particularly in the context of World Heritage. This decade, the *decade of responsibilities*, provides a challenge for the managers of the Great Barrier Reef World Heritage Area to recognise and explicitly meet their obligations under the World Heritage Convention. It is interesting to note that public attitudes and values have often been somewhat ahead of governments during these periods. In the next section we discuss some strategies and actions that will assist in fulfilling our responsibilities as a signatory to the Convention.

The Road Before Us

The 25 year Strategic Plan for the Great Barrier Reef World Heritage Area (GBRMPA 1994) provides an agreed framework for the future of the World Heritage Area. The Strategic Plan was developed by a participative planning process involving stakeholders and endorsed by the Commonwealth, Queensland and relevant local governments. The plan is a set of guidelines for the management of the area as a World Heritage property. The 25 year objective for the section of the Strategic Plan which addresses conservation issues is:

> To ensure the persistence of the Great Barrier Reef World Heritage Area as a diverse, resilient, and productive ecological system, while retaining opportunity for a diverse range of experiences and uses consistent with Australian's obligations under the World Heritage Convention (GBRMPA 1994:15).

The Strategic Plan emphasises that all activities within the World Heritage Area must be ecologically sustainable. However, there is a lack of agreement between stakeholders about what this means (Ludescher 1996). This confusion might be lessened by the implementation of standards of 'best practice' for all activities in, and impacting on, the Great Barrier Reef World Heritage Area. This has already been done in some instances. For example, resorts on Great Barrier Reef islands have had to treat their sewage to tertiary standards since 1995. A similar approach could be applied to other activities. For instance, it might be decided that trawler operators would only be licensed to work in the World Heritage Area if they submitted daily catch and effort data directly to managers and their boats were equipped with satellite transponders to enable their position to be monitored accurately, along with devices to reduce by-catch.

Collaboration between marine science, managers and industry is required if industry is to achieve 'best practice'. The 'Limits of Acceptable Change' approach (Oliver 1995) has already been applied with some success. Prior to the dredging for the expansion of the port of Townsville, a panel comprising coral biologists, representatives from the GBRMPA and the Townsville Port Authority defined acceptable threshold limits for coral stress. All parties agreed in advance to the levels of bleaching, an indicator of stress in corals, that would trigger various levels of response. During the dredging program, the lowest trigger level was exceeded on three occasions, but dredging never had to be stopped and no irreversible impacts on corals reefs were recorded. This has given the Townsville community confidence that the port dredging is not destroying their marine environment.

Quality Assurance, through the application of international standards (ISO), is another approach that could be used as a means of demonstrating that various activities are carried out in a measured and responsible fashion (Kirkpatrick 1996; McCreary 1996; Moss 1996). ISO standards provide a framework which allows organisations and industries to identify management needs and to develop their own system to meet a predetermined confidence level. Independent verification of compliance provides all stakeholders with evidence that the management arrangements are appropriate and working and that the activity is ecologically sustainable. The emphasis of this approach would be on risk assessment and minimisation.

In considering future directions for the Great Barrier Reef World Heritage Area, it may be particularly useful to return to some starting principles. First, as noted above, the paramount aim of the GBRMP in all its zones is conservation and protection. Given these responsibilities it may be seen as appropriate for the GBRMPA to more frequently utilise its powers under Section 66 of the Act to regulate activities beyond the borders of the GBRMP where such activities have effects on the protection of the Great Barrier Reef World Heritage Area. Undue emphasis on 'multiple-use' does not provide a sharp enough focus on this commitment. Such a conservation focus could be reinforced by amending the objects provisions of the Marine Park Act to give clear recognition of its World Heritage obligations. This could be best enshrined if the legislation refers to the specific obligations of identification, protection, conservation, presentation, transmission and rehabilitation. It is also important that these objectives be spelled out in the legislation controlling other agencies involved with management within the World Heritage Area (e.g. QFMA, QDoE). The findings of the recent Commonwealth government inquiry into World Heritage has specific support for such actions as well as a continuing stronger Commonwealth role including additional funding (HORSCERA 1996).

One important question relates to the relative roles of Commonwealth and State interests in managing World Heritage Area's in Australia. The clear acceptance of a Commonwealth role, as articulated in the HORSCERA report, is welcomed by us and if implemented will help ensure that the responsibilities accepted by Australia with regard to World Heritage are properly addressed. It is interesting to note the extent to which the US Federal Government has recently found it necessary to intervene to ensure its World Heritage responsibilities are addressed. First by the request to the World Heritage Committee that two of its properties (Everglades NP World Heritage Area and Yellowstone NP World Heritage Area) be entered on the List of World Heritage Properties in Danger. Subsequently by committing itself to a 17 year program costing US$2 billion, to restore the water regime destroyed by development projects in Florida. The US Government has been commended by the World Heritage Committee at its nineteenth session in December 1995. A similar intervention by the US Federal Government has seen the denial of mining in an area nearby, but beyond the

borders of, Yellowstone National Park World Heritage Area. These examples indicate that it is not only in Australia that there may need to be strong interventionist roles for central Governments in meeting their responsibilities. This may be particularly appropriate where State Governments lack the appropriate legislation or other commitment to protecting World Heritage.

It has been recognised that the understanding of criterion (iii), which considers natural beauty and aesthetics, is constrained by a lack of methodological approaches and theoretical understanding. It is also clear that values held by the public play a pivotal role in the acceptance or not of the management regime for the World Heritage Area. The consultancy, which this papers refers to, has focused primarily upon the scientific and conservation values of the Great Barrier Reef World Heritage Area, and their contribution to the outstanding universal value of the Great Barrier Reef World Heritage Area. It is crucial that additional studies are undertaken to further explore the public values held about the Great Barrier Reef World Heritage Area. Only though such studies will the management of the Great Barrier Reef World Heritage Area reflect the aspirations of the community, the owners of the World Heritage Area.

To date there seems to have been little attention to the responsibility for World Heritage presentation, apart from the Great Barrier Reef Aquarium, and future management should give thought to ways of presenting World Heritage in the Great Barrier Reef. There are many opportunities to learn from other World Heritage sites and to develop innovative approaches particularly suited to the Great Barrier Reef (see Lucas et al. 1996). It is worth noting that the presentation of World Heritage is a relatively recent phenomenon in the Great Barrier Reef and even today many visitors may not gain an appreciation of what the listing means during their visit. There is a need for a shared role between the national responsibility to give World Heritage a life in the community and the site specific interpretation of, say, helping people understand that Magnetic Island is part of a World Heritage Area and that residents there share something in common with the citizens of Banff, Canada (for example). Similarly, it is time to recognise the responsibility for rehabilitation specified in the Convention, and to undertake studies which may help develop techniques for identifying the need for and methods to accomplish rehabilitation.

There is also a need to review the extent and nature of 'protected' areas within the Great Barrier Reef World Heritage Area. This process has started but needs to be accelerated. There are currently anomalous mismatches between the protected area status of terrestrial portions of the World Heritage Area and adjacent marine environments. Given the current community sympathy for better protection of the Great Barrier Reef it may be timely to use the political process to enlarge the area of more highly protected zones where there present levels are inadequate and at the same time seek a better match between marine and terrestrial components of the World Heritage Area.

Although the Strategic Plan is being used by some organisations and individuals as the basis for their activities in the World Heritage Area, it has not been implemented in a pro-active and coordinated way as envisaged by the stakeholders who developed it. Unless this is done soon, we believe that it is possible that the World Heritage listed areas in the Great Barrier Reef Region will be reduced to those components that are managed along the lines of category I or II protected areas. This change would be consistent with a preservationist interpretation of the World Heritage concept, but it would fail to recognise one of the key attributes of this particular World Heritage Area, its large spatial scale. Given the connectivity of marine areas, we also believe that such a step would make protection of World Heritage property attributes even more difficult.

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Community involvement in the management of the Great Barrier Reef

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ABSTRACT

This paper will overview the history of community input into management of the Great Barrier Reef (GBR) Marine Park by considering the role of the community in the:

- establishment of the GBR Marine Park;
- work of the GBR Consultative Committee;
- preparation and revision of the Zoning Plans for the Marine Park;
- consultations in the development of research priorities and projects;
- development of the GBR 25 Year Strategic Plan and recognition of the obligations to World Heritage listing;
- day-to-day management of the Marine Park including operations of the Regional Marine Advisory Committees, Aquarium and assessment of development permits and EIAs; and
- highlighting and rectifying deficiencies in current management arrangements.

The authors have sought the experience of community groups through the distribution of a questionnaire to both conservation, community and users groups and direct contact with key individuals and groups. Additionally, the Great Barrier Reef Marine Park Authority and Queensland Department of Environment have been approached for summaries of the documentation prepared for distribution to the community and submissions received by both agencies. However, the involvement of Aboriginal and Torres Strait Islander communities will not be addressed in any detail.

Recommendations on improving community input into all aspects of management of the GBR will be made.

HISTORICAL CONTEXT

Managing human use of the Great Barrier Reef Marine Park has become quite a large business. The 1994/95 Annual Report of the Great Barrier Reef Marine Park Authority states that GBRMPA's total operating expenses for that year were $25,641,439.

Since the Authority was established in the mid-1970s, it has employed a myriad of public servants, scientists and consultants. From time to time, particularly if there is perceived to be a problem, it also comes to the attention of Australians, and in particular Queenslanders, as well as the government ministers and politicians who oversee the legislative side of managing the Marine Park and approve the budget for the management agencies involved.

So where does the public fit in to all of this ? It was, and still is, the Australian public who have defined the long term vision for the Great Barrier Reef to be managed as the world's largest protected area. This all began in the mid-1960s when the first large scale proposals to mine the Reef, firstly for limestone and then oil, came to the attention of the public.

Stopping these mining proposals triggered one of the first major conservation campaigns in Australia which resulted in over 85% of Australians supporting the proposition of no mining on the Reef and bi-partisan political support for the passage of the Great Barrier Reef Marine Park Act through Federal Parliament in 1975.

But all of this is another story, however it is one that should be understood and remembered by those charged with managing the Reef today - namely that the Park relies on community

support for its long term political and financial viability. Its ecological viability depends on how well we manage the balancing act of conservation planning versus resource use.

Defining community involvement

Involving the community in managing the Reef can happen in many different ways. Following is an outline of some of these opportunities and an overview of how they have happened in the Great Barrier Reef context.

Firstly though, it is important to define the term "community". In its broadest sense it means all of us, but for this paper it relates to all non-government organisations and individuals regardless of whether or not they have commercial interests in the Great Barrier Reef. However, because of the breadth of these interests and my own particular experience base, this paper relates most strongly to conservation and general community interests. In particular it only briefly touches on the involvement of Aboriginal and Torres Strait Islander communities.

Actual involvement in the management process falls into three broad categories, namely consultation, participation and community based management (Figure 1). These represent an increasing scale of direct dialogue and interaction between decision makers and the community.

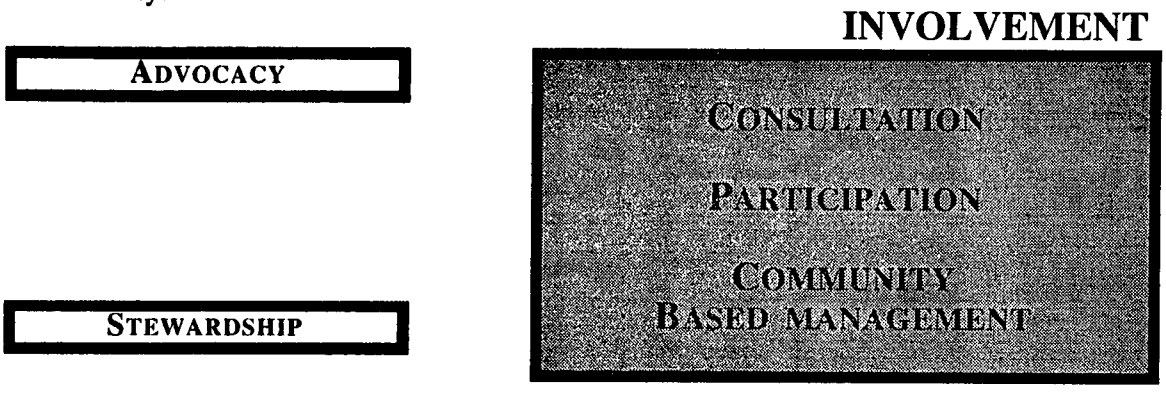


Figure 1. Categories of community involvement.

Consultation occurs when the views and experiences of the community are sought - this can be done opportunistically through informal processes, or in a planned and methodical way such as seeking submissions on zoning and management plans. For the community, consultation does not necessarily equate to directly influencing the outcomes of decisions.

Participation implies more direct interaction between decision makers and the community, than happens through consultation. Invariably this is targeted at "key stakeholder" groups or "leaders in the community" with specific interests in the long term viability of the Reef. For the Great Barrier Reef, the regional Marine Resource Advisory Committees are a relatively recent initiative providing opportunities for better participation, while development of the 25 year Strategic Plan for the World Heritage Area is probably the best example of broad ranging, key stakeholder participation.

Over the past decade there also appears to be an increase in informal discussions and consultations between management agency personnel and representatives of particular sectoral interests. These discussions are largely undocumented and rely on personal networking and contacts by GBRMPA staff in particular. How they translate into changed management practices is not apparent, but they do have the capacity to influence how, and why decisions are made.

Community based management is where there is an active partnership established between members of the community and management or research agencies. The Low Isles Protection Society and the Whitsunday OUCH (Order of Underwater Coral Heroes) group are good examples of this happening on the Reef.

However two important community roles, namely advocacy and stewardship, continue regardless of whether or not there are opportunities for participation, consultation or community based management.

Advocacy is all about specific interest groups in the community making the rest of the community, and in particular politicians and senior public servants, aware of their views, concerns and priorities for managing the Reef. Often the media is used as a key mechanism for disseminating these views.

Stewardship relates to that ongoing sense of responsibility in individuals that they personally, and the community as a whole, have an obligation to ensure that human use of the Great Barrier Reef does not jeopardise its fundamental integrity. This stewardship ethic manifests itself in many different ways through seeking participation and involvement in planning and operational Reef management activities to ensuring that when they visit the Reef that their "footprint" is as light as possible.

Underpinning and enhancing community involvement is the ongoing education and communication initiatives of the Authority, other government agencies and various sectors. The management agencies have an important role in continually providing information that updates the community's knowledge base. This also entails being receptive to input from the community and learning from local, regional, national and international experience and perspectives. Likewise the work of user groups who are seeking to minimise the impact of their operations must be valued and disseminated.

Opportunities for community involvement in management of the Great Barrier Reef

Figure 2 lists the major milestones in community involvement relating to the implementation of the Commonwealth government's *Great Barrier Reef Marine Park Act 1975*. This piece of legislation was a milestone in itself as it takes precedence over all other legislation that could influence resource use and human impacts on the Reef. It also established the zoning plan process which explicitly provides for two exposures for public comment of zoning plan documentation. Consequently, this Act has established standards for public involvement in the planning process that others have aspired to.

1975	*Great Barrier Reef Marine Park Act* passed by Federal Parliament.
1976	Great Barrier Reef Marine Park Authority began operating.
~ 1977	- Establishment of the Great Barrier Reef Consultative Committee. - Various advisory committees and working groups of the GBRCC.
1987	GBR Aquarium opened to the public.
1990	First regional Marine Resources Advisory Committees established.
~ 1991	Development of the 25 Year Strategic Plan for the GBR World Heritage Area commenced.
1994	Release of the 25 Year Strategic Plan.
1994/95	Establishment of the Cooperative Research Centres.
1996	11 regional Marine Resources Advisory Committees operating.

- GBRMPA liaison officers work with fishing, tourism and agricultural sectors and aboriginal communities.

Figure 2. Milestones in community involvement.

Established under the 1975 Act, the Great Barrier Reef Consultative Committee was the first forum providing the opportunity for non-government interests' involvement in Reef management. The Committee's members are appointed for their expertise but represent a range of interest groups including government and non-government, and commercial and not-for-profit. The Chair is elected by the members of the Committee. From time to time it has set up advisory committees and working groups to address specific issues of concern such as tourism charges and exclusive use of reefs. Probably its most important function has been a little recognised one. Namely, it brings together individuals who are leaders in their sector to discuss the common issues of managing use of the Reef while ensuring its conservation. Although this "information transfer" role has not been quantified in any way, we believe it has been catalytic in better informing all sectors of the environmental consequences of their actions, and of the conservation and resource values of the Reef.

Up until the late 1980s, much of the work of the Authority and the major opportunities for community involvement came through the progressive development of zoning plans for the entire Marine Park. It is interesting to note the numbers and source of submissions on the zoning plans over this period (Table 1).

In her PhD thesis, Jacki Alder notes, "The issues raised in submissions during the public participation phase for the first Cairns Section Zoning Plan focused on what form of zoning should be applied to particular areas and how to ensure that specific uses such as recreational and commercial fishing would have minimum restrictions .... the submissions for the public participation program for the second Cairns Section Zoning Plan now focused on zoning details and management of specific issues which appeared to be having a visible impact such as moorings and diving." (Alder, 1995). This analysis indicates that the community is now looking to the Zoning Plan process and the more localised Area Management Plans to address resource allocation issues at a more detailed level.

For the Townsville area, the Great Barrier Reef Aquarium which was opened in 1987 is probably the public face of the Authority. The vision for the Aquarium was to provide "a land based facility to enable the public, at low cost and in comfortable surroundings, to see and appreciate the wonders of the Great Barrier Reef, thereby gaining community support for its management and conservation" (Kelleher, 1988). The Great Barrier Reef Volunteer Association of Townsville underpins the staffing and education role of the Aquarium having contributed an estimated 30,000 hours of volunteer time over 5 years (Whitehouse, 1993).

The past six years has seen a definite shift from consultation to participation in the "culture" of involvement of the community in Reef management. Examples of this include the formation of the regional Marine Resources Advisory Committees along the GBR coastline and the development of the 25 Year Strategic Plan for the Great Barrier Reef World Heritage Area.

There are now 11 RMRACs with members coming from local marine and coastal user groups. Their establishment is facilitated by GBRMPA and Queensland Department of Environment (QDoE), however they are run by local representatives, and operate on a consensus basis. The aims of the committees are:

to formalise communication links between managers and user/interest groups;
to provide a communication channel between managers and user/interest groups;
to provide advice on marine resource issues to legislative and advisory representatives;
assist with increasing awareness of general public and user groups regarding marine resource issues and their management; and
to pursue and endorse the concepts of viable and sustainable use.

The development of the 25 Year Strategic Plan was tackled in a different fashion with some 60 stakeholder groups including tourist operators, fishing interests (both commercial and recreational), scientists, Aboriginal and Torres Strait Islanders, Federal, State and Local government agencies, the agricultural sector (principally the sugarcane industry) and conservation interests being intensively involved in preparing a draft strategy (Raymond & Craik, undated). A 25 year vision was agreed upon, and short-term and long-term objectives

Table 1.Overview of Submissions received during development of Zoning Plans for Sections of the Great Barrier Reef Marine Park. [1]

	% of submissions				
Major User Groups	Cairns Section 1983 [2]	Far Northern Section 1984	Central Section 1985	Southern Section 1987	Cairns Section 1991
Recreational:					
- Fishing		3	32	22	30
- Spearfishing		-	4	4	8
- Diving		-	11	19	9
- Boating		-	4	4	3
- Shell collecting		1	3	6	1
- Other		9	3	-	-
Commercial:					
- Charter boat		5	7	6	7
- Fishing		46	27	18	26 ?
- Diving		-	-	-	3
- Tourism		2	1	1	3
- Aquarium fish collecting		3	2	1	5
Conservation	7	12	3	7	5
Total No. of Submissions	202	116	414	287	1209

Notes:
1. The information for this Table came from various GBRMPA documents that summarised the source and content of the submissions received when the various Sections of the GBR Marine Park were being zoned. There are inconsistencies between each document in the way the submissions were analysed hence this Table represents an approximate overview of the categories. In particular one category of submissions, namely research / scientific was not consistently identified as a separate category. As well submissions from Aboriginal and Torres Strait Islander were not cited although it is likely that submissions from these stakeholders were made in other formats.
2. The categories used for the analysis of the submissions received in 1983 were quite different to those used in later analyses, and so could not be reliably interpreted for inclusion in this Table.

and strategies to achieve the vision were developed in the areas of conservation, resource use, communication, research and monitoring, integrated planning, Aboriginal and Torres Strait Islander interests, management processes and legislation. This document was then released for public comment. When an agreed text was reached, over 70 organisations then endorsed the Plan. The Authority is now reviewing progress in implementing the Plan.

Additionally, two other GBRMPA activities are influencing opportunities for community involvement. These are the appointment of specific interest groups liaison officers and collaboration with the Cooperative Research Centres.

GBRMPA now employs liaison officers to work with the fishing, tourism and agricultural sectors and aboriginal communities and agencies. Obviously, dedicated staff should mean better collaboration with these interest groups. With the CRCs the Authority is participating with commercial users and researchers in research priority setting and follow-up monitoring. Again, this should result in stronger, and more regular collaboration with these interests.

For the preparation of this paper a questionnaire was distributed to a number of community groups and individuals seeking their experience with, and opinions of the opportunities available to contribute to managing the Great Barrier Reef Marine Park. Twenty-one questionnaires were distributed and 13 responses were received. Not surprisingly, all respondents had made submissions on zoning plans, national park plans and local area management plans at various times. Many had commented on environmental impact assessments and other development planning documents. A number either are, or have been involved in various project-based work in collaboration with GBRMPA or the QDoE. Very few had received any project grant funding to assist them in the majority of this work.

The most positive feed-back was in relation to the regional Marine Resource Advisory Committees. Of the respondents involved with RMRACs, all noted the value of working regularly with other interest groups from their region. However, notes of caution were made about whether or not the RMACs could achieve consensus on the harder issues, and whether or not their advice is heeded by GBRMPA and more particularly by government in Canberra and Brisbane.

Issues influencing community involvement

While management agencies can provide opportunities for community involvement and in most circumstances any group or individual who really wants to get involved should be able to find opportunities to do so, there are certain external factors that influence the overall likelihood and success of community involvement.

In her thesis Jacki Alder summarises the factors affecting the capacity of community groups to be involved. " The common limitations of funding, staff resources and expertise also apply to NGOs involved in MPAs. Other factors specific to MPAs include:

> a reluctance of many NGOs to work in MPAs because they are not familiar with marine environments, and for many it appears to be a hostile one;
> the costs of undertaking programs in marine environments are higher; and
> prevailing weather conditions can restrict the time of the year that programs can be implemented." (Alder, 1995).

Our experience has shown that for NGOs the limitation in staff resources is particularly pressing and generally results in a high turn-over of personnel and loss of institutional memory as well as relevant expertise. Thus, any investment in dialogue and contacts is constantly eroded.

Alder (1995) also notes that "the history of NGOs' advocacy role has made some managers reluctant to involve NGOs in management programs. This reluctance can be removed through workshops and liaison programs between the two groups. Workshops and programs can explore the role of NGOs in management and where partnerships in managing the resources can be forged." We would add that this reluctance also exists for many scientists.

RECOMMENDATIONS

For the Great Barrier Reef we have had the time to learn how to take positive advantage of the interest, energy, knowledge and experience resident in the community. With the benefit of hindsight, how then can we collectively do better in getting the community involved.

Firstly, we should enhance what is working well now.

- Continue with the Regional Marine Resource Advisory Committees and ensure that the resources needed are available.
- Follow through with the implementation of the 25 Year Strategic Plan for the World Heritage Area.

- Continue with the schedule of revisions to the Zoning Plans and preparation and review of site specific management plans while facilitating maximum community participation in their development and implementation.
- Continue with the networking and contacts and identify existing opportunities for managers and researchers to meet with the community.
- Seek out opportunities like the Low Isles Protection Society and OUCH to increase community based management projects. Perhaps the Coastcare grants scheme can be used creatively to achieve this.

Additional areas where effort and resources should be directed include,
- Appointment of a "conservation / community" liaison officer.
- Provision of regular (annual or six monthly) opportunities where community representatives, managers and scientists get together.

Information flows between managers, scientists and the community are essential. Scientific information is an enormously important tool in protecting the Reef, but it must be accessible and understandable to people who may be well informed, but who haven't had the opportunity to gain a PhD in the biological, physical, social and economic sciences. Perhaps an annual travelling "road show" of key GBRMPA, QDoE and CRC personnel would play a useful role.

Finally, many agencies seeking to consult and involve the community make the mistake of not providing adequate feed-back on how the community's views and contributions have been used. At various times, the GBRMPA and other Reef management agencies have all been guilty of this, some more so than others. It is extremely important that, when the community has gone to the effort of providing submissions or participating in the work of the agency, there is a reasonable amount of feed-back to these groups and individuals. Again, this is part of the process of maintaining contact and information flows.

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