THE GREAT BARRIER REEF

SCIENCE, USE AND MANAGEMENT

A NATIONAL CONFERENCE

PROCEEDINGS

VOLUME 2

NOVEMBER 25-29 1996
AT JAMES COOK UNIVERSITY
OF NORTH QUEENSLAND
TOWNSVILLE, QUEENSLAND

THE GREAT BARRIER REEF SCIENCE, USE AND MANAGEMENT

A National Conference

PROCEEDINGS

VOLUME 2

25–29 November 1996
James Cook University of North Queensland
Townsville, Queensland, Australia

This conference was jointly sponsored by:

CRC Reef Research Centre

GREAT BARRIER REEF
MARINE PARK AUTHORITY

ISBN 0 642 23024 2 (v. 2).

Published July 1997
by the Great Barrier Reef Marine Park Authority

The opinions expressed in this document are not necessarily those of the Great Barrier Reef Marine Park Authority or the Cooperative Research Centre for Ecologically Sustainable Development of the Great Barrier Reef.

Accuracy in calculations, figures, tables, names, quotations, references etc. is the complete responsibility of the author(s) of individual invited papers.

National Library of Australia Cataloguing-in-Publication data:

The Great Barrier Reef, science, use and management:
a national conference : proceedings.

Bibliography.
ISBN 0 642 23023 4 (v. 1).
ISBN 0 642 23024 2 (v. 2).
ISBN 0 642 23022 6 (set).

1. Coral reef ecology - Queensland - Great Barrier Reef - Congresses. 2. Conservation of natural resources - Queensland - Great Barrier Reef - Congresses. 3. Marine parks and reserves - Queensland - Great Barrier Reef - Management - Congresses. 4. Great Barrier Reef (Qld.) - Congresses. I. Great Barrier Reef Marine Park Authority (Australia).

551.42409943

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This Conference was supported by:

CRC Reef Research Centre
Great Barrier Reef Marine Park Authority
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Association of Marine Park Tourism Operators
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Proceedings compiled by Jim Campbell and Christine Dalliston (GBRMPA)

GREAT BARRIER REEF
MARINE PARK AUTHORITY

Great Barrier Reef
Marine Park Authority
PO Box 1379
Townsville Queensland 4810

Telephone: (077) 500 700
Facsimile: (077) 726 093

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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.

Volume 1 of the Proceedings contained keynote and invited papers. Volume 2 contains a selection of contributed papers, which were represented at the conference by posters prepared by the same authors. Abstracts are included, in a separate section, for other posters. A full list of posters presented at the conference, and their authors, is listed at the back of this volume, as is a list of delegates.

The work of the Organising Committee (Jan Crossland, David Yellowlees, Terry Done, Don Alcock, Jon Brodie, Peter Valentine, Kirstin 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

Section 1

Contributed Papers

SESSION 1

Land use influence and nearshore processes and pressures

The distribution of sediments and nutrients throughout the Whitsunday Islands inner shelf region, Great Barrier Reef

Steve G Blake
Environmental Geochemistry Group, Research School of Earth Sciences, Australian National University ACT 2600
Present address: Environmental Science Section, Environmental Resources Information Network, Department of the Environment, Sport and Territories, Canberra ACT 2601

ABSTRACT

Various physico-chemical parameters are described and quantified along a seven site gradient of riverine discharge in the Whitsunday Islands inner shelf region of the Great Barrier Reef. A gradient of decreasing suspended solids concentrations, turbidity, $\delta^{13}C$ values, percentage terrigenous matter, total organic matter and silicate away from the Proserpine and O'Connell Rivers is observed. However, offshore repositories of some metals (Cu, As, Zn, Cr and Mn) and TP mainly exist in the leeside protected embayments in the southern and central Whitsunday Islands region and within the protected mainland embayments. Strong macro-tidal currents in the Repulse Bay and southern/central Whitsunday Islands region maintain much of the clay-sized material in suspension in the water column, the suspended load being deposited only in the quiescent settings of leeside embayments (southern and central Whitsunday Islands regions) and also wherever the meso-tidal currents are strongly reduced in velocity (northern regions).

Sediment grain size controls the distribution of metals, nutrients and organic matter. Nutrients (P and N) and organic matter concentrations occur in higher abundances in the marine environment than is found on land, indicating that this is their main depositional site. The long distance transportation of nutrients (especially P) from the catchment sources has a significant influence on the geochemistry of the marine sediments of the Whitsunday Islands inner shelf region. In contrast, metals are typically found in lower concentrations offshore, however discrete repositories are still seen to exist in the marine environment associated with depositional settings.

Macroalgae increasingly tend to dominate the benthic community composition in areas characterised by high nutrients/suspended solids concentrations, often at the expense of both hard and soft corals. Such a phase-shift to macroalgal dominance has occurred at the Repulse Islands in Repulse Bay. Turbidity (light limitation) is preferentially selecting for certain species in these 'harsher' environments (e.g. the Repulse Islands). However, at the majority of sites in the Whitsunday Islands region not characterised by such chronic turbidity, ecological processes are likely to be more important in shaping the benthic community patterns than are physico-chemical ones.

INTRODUCTION

A major threat to the inner shelf regions of the Great Barrier Reef is considered to come from land-based sources, specifically those coastal catchments adjoining the Great Barrier Reef where agriculture (both grazing and cropping) is practised (Johns et al. 1988; Yellowlees 1991; Moss et al. 1992). Generally, the approach taken to date has been to analyse water quality in the rivers and in the offshore receiving waters. This 'cause and effect' approach relies on both the maintenance of long-term time series of water quality and also the capture of discrete 'events' such as cyclonic rainfall-induced floods. Geochemical studies provide information on terrestrial sediment provenance and dispersal patterns.

The Proserpine region, settled in 1860, has a long history of sugarcane cultivation commencing in the late 1870s, a cane processing mill being established there as early as

1897 (Proserpine Historical Museum Society 1988). Fertilisers have been used extensively on sugarcane plantations since the mid-1940s in north Queensland and the quantities of fertiliser utilised have been on the increase ever since. Estimates of current usage indicate that approximately 13 000 tonnes of fertiliser (mostly urea and phosphatic blends) are added per year in the Proserpine region alone. The estimate for the Proserpine–Plane catchments are 21 000 tonnes of nitrogen (N) and 3000 tonnes of phosphorus (P) per year (Steven 1995). Sugarcane and pastoral land for cattle grazing dominate the two catchments' land usage, with nearly 20% (17 500 hectares) of the Proserpine catchment's total area under sugarcane cultivation.

The results of coral reef mapping in the Whitsunday Islands region have previously been described by van Woesik (1992) and Blake (1994). In general, the fringing reefs are observed to become more diverse and are seen to display more luxuriant growth forms the further northwards and eastwards you progress away from Repulse Bay. Coral/algal mapping was undertaken at seven sites along a transect moving away from the river mouths in 1993 by van Woesik, Tomascik and Blake (paper submitted). The accompanying physico-chemical information collected along the seven site transect is the subject of this paper. The aim of the study was to test whether there exists a discernible gradient of riverine discharge effects throughout the Whitsunday Islands region away from the mouths of the two rivers (Proserpine and O'Connell) which discharge into Repulse Bay.

MATERIALS AND METHODS

Field sampling

The field phase of the project commenced in January 1993 in conjunction with the coral/algal community mapping when water samples, bottom grab samples and sediment cores were collected, split and sub-sampled from 7 study sites to study several water column parameters (detailed in table 1), the surface and down-core distribution of grain-size, metals, nutrients and organic carbon (including $\delta^{13}C$ isotopes). The seven study sites are (with increasing distance away from the river mouths): The Repulse Islands; Cow and Calf Islands; Pine Island; Long Island; North Molle Island; Armit Island; Double Cone Island.

The sediments in the cores were sub-sampled at 10 cm intervals. A suite of 156 surface grab samples were collected in order to detect the offshore extent of river flood plumes and the geochemistry of the Proserpine and O'Connell River catchments. Both the sediment cores and the grab samples were snap frozen immediately on recovery. Water sampling was continued at the seven study sites at bi-monthly intervals until July 1994. Nutrient, turbidity and suspended solids sampling of the water column at the study sites was also undertaken in the region between 1988 and 1992 and is fully described in Blake (1994). Inter-Ocean S4 current meters were located at the base of the reef slope at each of the 7 study sites for a period of approximately one month. The current meters were located 1 metre above the sea-floor mounted on current meter stands. The current meters were programmed to record current speed, current direction and water depth twice an hour.

Laboratory sampling

The following determinations were undertaken on the sub-sampled core sediments and the grab samples:

(a) Total N and P, total organic matter and mud content were determined from the bulk samples

(b) Trace metals (Al, Cr, Mn, Fe, Ni, Cu, Zn, As, Cd and Pb) using a two-step sequential analysis technique on the < 0.063 mm fraction

(c) Grain-size and calcium carbonate content

(d) $\delta^{13}C$ isotopes and organic carbon content

(e) Accelerator mass spectrometry (AMS) ^{14}C dating and conventional ^{14}C dating of the down-core charcoal fragments and small and large shells respectively

(f) Pore water Total N and P and sediment water content, pH and Eh

$\delta^{13}C$ and organic carbon determinations were also made on representative surface sediment samples in the vicinity of the Proserpine and O'Connell Rivers sediment plume pathway to delineate terrigenous dispersal in an offshore direction (Chivas et al. 1983; Chivas 1991). $\delta^{13}C$ and organic carbon determinations were processed at the Stable Isotope Laboratory, Research School of Earth Sciences, Australian National University. Water column dissolved inorganic nutrient concentrations were measured at the Australian Institute of Marine Science and the New South Wales Environmental Protection Authority. Suspended solids (SSC) and chlorophyll *a* determinations were made at the Australian National University according to the methods of Strickland and Parsons (1972). Sediment metal and nutrient concentrations were determined in the AWT Hydro-Sedimentology Laboratories, Sydney.

RESULTS

Sediment, nutrient, metal and current data

The results from the study are summarised in table 1 as mean concentrations/levels. The numbers of samples averaged to derive the mean values in table 1 are listed where n = the number of samples per site. Suspended solids concentrations (SSC) are measured in mg/L (n = 54). Turbidity is measured in NTU (n = 54). Chlorophyll *a* is measured in µg/L (n = 54). Dissolved inorganic nutrients are measured in mM (n = 54). Sediment metal data is based on the fine fraction (< 0.063 mm) only (n = 4). Sediment nutrient data are based on bulk samples (n = 4). All sediment metal and nutrient data are expressed in mg/Kg. All pore water nutrient data are measured in mg/L (n = 4). Current velocity values (both mean and maximum) are expressed in cm/sec (n = 1344). Sedimentation rates are in mm/yr (n = 4).

These data indicate that the highest levels of suspended solids and turbidity are found in the Repulse Bay region. This finding is supported by the silicate results which indicate the most terrestrial input is directly into the Repulse Bay region. The organic carbon, $\delta^{13}C$ stable isotope, percentage terrigenous versus carbonate and the sediment metals data indicate that the terrigenous sediment derived from the Proserpine and O'Connell Rivers is in fact accumulating at a greater rate in the southern and central Whitsunday Islands regions as opposed to Repulse Bay. This conclusion is supported by the sediment total P and sedimentation rate data, the highest rates occurring in the protected leeside island embayments of Long Island and at North Molle Island. The macrotidal currents in Repulse Bay are not as conducive in allowing direct sediment deposition and uninterrupted accumulation as occurs in the protected mainland and island embayments to the north of Cape Conway. The highest current velocities (both mean and maximum values) occur at Site 1 (Repulse Islands) and Site 5 (North Molle Island). Sites 2, 3 and 4 displayed very similar current velocities. Sites 6 and 7 displayed the lowest current velocities.

Sediment TKN values vary little throughout the study region but are generally highest in those regions where tidal currents are weakest. Relatively enhanced concentrations of NO_3 exist in the Repulse Bay and North Molle Island regions where tidal currents are the strongest. The results indicate that the sediments are probably the main source of dissolved N species and that tidal currents are likely to be responsible for promoting this process. Chlorophyll *a* levels are seen to increase where dissolved inorganic N levels are high and correspond with low SSC and reduced turbidity such as occurs at Long Island and North Molle Island. This same trend has previously been described in the region (Blake et al. 1994). Elevated chlorophyll *a* levels are not seen at the Repulse Islands, Cow and Calf Islands and at Pine Island probably as a result of the reduced light penetration due to enhanced turbidity (Walker 1981; Kirk 1983; Grobbelaar 1985).

The Repulse Islands communities

At the Repulse Islands a few small stunted coral colonies are growing on the shallow rocky slopes. There is a high macroalgal cover (65–70%) comprising large fleshy species, whilst the hard coral and soft coral cover account for 4% and 7% of the total space respectively. Visibility on SCUBA is normally between 0.1–0.3 m. Hard coral species recovered to date have been very small encrusting forms exhibiting stunted morphologies. Massive *Porites* spp. core samples collected display a hummocky growth form combined with a very dark skeleton, indicating sediment incorporation during growth. The density bands are very close together which suggests very slow growth at this location. Forty-one species of scleractinian and alcyonarian corals have been identified from the Repulse Islands.

The number of genera recorded at the Repulse Islands was low compared with sites to the north but was not statistically significantly lower. Genera belonging to the Families Faviidae (especially), Dendrophylliidae, Siderastreidae and Poritiidae dominate the hard coral community composition of the Repulse Island Group. The following species are particularly abundant at the Repulse Islands: *Montipora* spp., *Turbinaria frondens*, *Goniastrea favulus*, *Goniastrea australensis*, *Pocillopora damicornis*. All these species are known for their

Table 1. Summary of water column, surficial sediment, down-core nutrient/ metal and current velocity results from the seven study sites. All values are site means.

	Repulse Islands	Cow and Calf Islands	Pine Island	Long Island	North Molle Island	Armit Island	Double Cone Island
SSC	9.7	7.0	6.2	4.8	3.3	2.3	2.1
Turbidity	7.3	5.2	4.7	3.7	2.5	1.8	1.6
Chl *a*	0.88	0.86	0.83	1.07	1.21	0.40	0.31
$Si(OH)_4$	5.44	5.11	4.97	4.12	3.05	2.08	1.93
PO_4	0.20	0.20	0.19	0.19	0.20	0.19	0.17
NO_3	0.21	0.19	0.19	0.18	0.26	0.15	0.19
NO_2	0.05	0.10	0.07	0.06	0.07	0.02	0.02
NH_4	0.97	1.81	0.73	0.62	1.22	0.65	0.62
Mud %	28.1	32.2	23.1	33.42	30.2	27.9	12.7
TOM %	9.5	7.8	7.7	6.6	6.0	4.4	2.8
H_2O %	30.55	29.35	30.70	35.27	30.24	27.96	26.00
pH	8.0	7.2	7.4	7.3	7.9	7.1	7.4
Eh	37.0	-230.0	95.2	-29.5	73.8	97.4	110.4
TKN Pore Water	6.83	8.36	7.61	7.74	5.93	3.26	2.11
TP ·Pre Water	0.27	0.33	0.30	0.32	0.13	0.04	0.03
Al	55440.27	48010.10	52058.91	49645.83	52051.85	40328.20	34351.52
Cr	53.94	56.71	55.04	58.63	56.81	49.40	38.87
Mn	335.98	347.88	326.94	332.20	332.84	296.68	291.54
Fe	28005.69	25103.82	26242.50	27552.14	25765.49	19152.34	14558.31
Ni	22.47	22.96	23.05	48.04	22.15	17.98	17.66
Cu	20.58	18.41	40.33	45.94	37.25	21.14	18.55
Zn	54.74	54.73	51.16	75.71	49.66	40.70	36.01
As	4.54	7.52	4.97	5.79	4.27	4.94	2.57
Cd	3.10	3.76	3.48	3.20	3.38	3.36	3.45
Pb	11.49	11.08	11.13	17.88	11.62	9.19	10.26
TKN	407.41	422.98	535.78	463.66	403.27	292.89	282.03
TP	938.22	1011.57	854.09	1032.46	826.51	771.07	613.70
$\delta^{13}C$ (1 M)	-16.85	-19.23	-17.31	-18.09	-16.17	-16.54	-16.37
% OC (1 M)	1.07	0.35	0.26	0.79	0.79	0.74	1.77
$\delta^{13}C$ (0.5 M)	-19.21	-19.04	-18.08	-18.76	-16.32	-17.18	-16.42
% OC (0.5 M)	1.64	0.44	0.30	0.91	0.90	1.39	1.99
% Terrig.	59.6	70.2	65.2	55.7	51.0	49.4	44.5
% Carb.	39.0	29.8	34.8	44.3	49.0	50.6	55.5
Mean current vel.	33.0	26.8	25.0	26.0	37.8	9.8	10.9
Maximum current vel.	81.3	63.7	59.2	61.4	91.2	48.1	49.7
Sedn. rate	0.4–0.6	0.3–0.7	0.3–0.6	0.8–1.1	0.4–0.8	no data	no data

hardiness (via active and passive sediment rejection strategies) in muddy environments subjected to large tidal ranges (Veron 1986; Stafford-Smith and Ormond 1992).

Two elevated fossil micro-atolls present at the Repulse Islands have diameters up to 1.5 m and have been ^{14}C dated at 2320 ± 70 BP and 2770 ± 70 BP respectively (ANU Quaternary Dating Research Centre). The abundance of these well formed micro-atolls combined with their large size may be indicative of less harsh conditions within the bay approximately 2500 BP. These dates also indicate a high sea-level stand approximately 1 m above present lasting until 2500 BP in agreement with the dates reported in McLean et al. (1978), Polach et al. (1978), and the Chappell (1983) and Larcombe et al. (1995) sea-level curves constructed from fringing reef micro-atoll data for north Queensland.

CONCLUSIONS

(1) A gradient of decreasing SSC, turbidity, $\delta^{13}C$, percentage terrigenous matter, total organic matter and silicate away from the rivers exists in the Whitsunday Islands region. However, offshore repositories of some metals (Cu, As, Zn, Cr and Mn) and TP mainly exist in the leeside protected embayments in the southern and central Whitsunday Islands region and within the protected mainland embayments. Strong tidal currents in the Repulse Bay and southern Whitsundays region maintain much of the clay-sized material in suspension in the water column, the suspended load being deposited only in the quiescent environment of protected embayments in the leesides of islands, adjacent to the mainland in protected embayments and also wherever the tidal currents are strongly reduced in velocity.

(2) TP occurs in highest abundance within the clay-dominated, muddy, organic matter-rich protected embayments of the Whitsunday Islands inner shelf region where the highest sedimentation rates are occurring.

(3) TKN is likewise found in highest proportions in the main Whitsunday Island Group, especially where the weakest tidal currents occur.

(4) As, Cu, Zn, Cr and Mn combined with TP concentrations are providing the best indication to date that eroded soil and dissolved trace metals from the Proserpine catchment are entering the marine environment.

(5) Sediment grain size itself controls the distribution of metals, nutrients and organic matter. Nutrients (P and N) and organic matter concentrations occur in higher abundances in the marine environment, indicating that this is their main depositional site. The long distance transportation of nutrients (especially P) from the catchment sources has a significant influence on the geochemistry of the marine sediments of the Whitsundays inner shelf region. In contrast, metals are typically found in lower concentrations offshore, however discrete repositories are still seen to exist in the marine environment.

(6) At the Repulse Islands the scleractinian corals are limited to encrusting a rocky slope in an environment of very high tidal current velocities, a very high tidal range and associated high ambient turbidity. Small robust, isolated and stunted colonies, principally belonging to the Family Faviidae (covering < 4% of the substrate) are co-existing with a high fleshy macroalgal biomass (covering 65–70% of the substrate).

(7) Turbidity (light limitation) is preferentially selecting for certain species in the 'harsher' environments (e.g. the abundance of faviids and montiporids at the Repulse Islands). However, at the majority of sites in the region not characterised by such chronic turbidity, ecological processes are likely to be more important in shaping the benthic community patterns than are physico-chemical ones.

DISCUSSION

Little mention is made in the literature on the role of sedimentation or turbidity to the eutrophication process, despite the association of high sedimentation, turbidity and nutrient enrichment in situations of documented eutrophication (Smith et al. 1981). Habitat loss/ destruction due to soft substrate build-up associated with chronic sedimentation prevents colonisation by coral planulae and provides one of the primary limiting factors to the establishment of coral planulae (Johannes 1975; Hubbard 1986; Acevedo et al. 1989). It is hypothesised that very high turbidity can act in synergy with direct sedimentation effects in reducing the suitability of a site for establishment and growth to some coral species, enabling others a competitive advantage (Fisk and Harriott 1989; Hopley et al. 1992; Stafford-Smith and Ormond 1992).

ACKNOWLEDGMENTS

This work was funded by the CRC Reef Research Centre (as part of Task 1.3.4) and the Research School of Earth Sciences (RSES), Australian National University in Canberra. The CRC Reef Research Centre was established in 1993 under the Australian Government's Cooperative Research Centres Program. I wish to thank the staff at the AWT Hydro-Sedimentology Laboratory in Sydney for their assistance with the processing of the down-core sediment metal and nutrient samples. Assistance in processing the organic carbon and $\delta^{13}C$ samples was provided by Ms Michelle Jenkins (ANU Vacation Scholar) under the supervision of Dr Michael Bird (RSES).

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Spatial variation in stream water quality in a humid tropical catchment: long profile and tributary stream patterns

DT Neil

Department of Geographical Sciences and Planning, The University of Queensland Qld 4072

ABSTRACT

Spatial patterns of stream water quality (turbidity and conductivity) in the Tully River catchment were investigated in relation to subcatchment characteristics. These parameters were converted to suspended sediment concentration (SSC) and total dissolved solids (TDS), respectively, using empirically derived calibration curves. Water samples were obtained from the Tully River at 17.5 (2.5 km above tidal limit), 57 and 72 km upstream on 15 occasions. In addition, 50 paired SSC observations were made for the 17.5 and 57 km upstream sites, and 47 paired TDS observations at these sites. Samples were also obtained from 46 tributary streams on 15 occasions of varying streamflow conditions.

Mean SSC and TDS increased downstream, by 318% and 16%, respectively, between 57 and 17.5 km from the river mouth. This increase is associated with a change in land use from 1.5% area cleared for grazing upstream of 57 km to 8% cleared for cropping and 12% cleared for grazing upstream of 17.5 km. Land use (% area cleared) is the catchment characteristic which best predicts both SSC and TDS in tributary catchments.

INTRODUCTION

Spatial variations in catchment characteristics determine patterns of water quality which in turn determine net exports from the catchment. Although the contribution of humid tropics catchments to the total input of both freshwater and sediments to the Great Barrier Reef lagoon is relatively small (Neil and Yu 1995) some of the most intensive land use in the Great Barrier Reef catchment occurs in this region. Therefore, it is important to establish, at a catchment scale, the contribution of land use to sediment yield from the humid tropics region. The paper examines the spatial relationships between water quality and catchment characteristics in the Tully River, a humid tropical catchment discharging to the Great Barrier Reef lagoon, with particular reference to the land use factor.

METHODS

Study area: The Tully River, in the humid tropics of north-east Queensland, has a catchment area of 1685 km^2, mean annual rainfall is estimated at 3 000 mm and mean annual stream flow at 3.7 x 10^6 ML. Montane and plateau areas retain a rainforest cover on late Palaeozoic granites and volcanics. Land use in the catchment, predominantly improved pasture, sugar cane and banana growing, is largely confined to flood plains. The Tully River discharges into Rockingham Bay. Continental (high) islands in the Bay have small areas of fringing reef and reefs of the Great Barrier Reef lie a further 30 km eastward.

Sampling and Analysis: Dip (grab) samples, from 10 cm depth, were obtained during the periods November 1987 – March 1988 and March–April 1990 (long profile analysis) and during November 1987 – March 1988 (tributary stream analysis). Because this study is largely concerned with the quantity and behaviour of fine sediments which may be transported to sensitive coastal ecosystems, the use of dip sampling from the top of the water column is appropriate. For long profile analysis, water samples were obtained from the Tully River at Adopted Middle Thread Distance (AMTD i.e. distance upstream) of 17.5 (2.5 km above tidal limit), 57 and 72 km on 15 occasions. A total of 50 paired SSC observations and 47 paired TDS observations were made for the 17.5 and 57 km AMTD sites. The locations of long profile water quality sampling points along the Tully River are shown in figure 1. Forty-six sites on tributaries of varying catchment characteristics were sampled on 15 occasions during the 1987–88 sampling period, using a sampling scheme similar to that of Walling and Webb (1975). Flooding rendered most tributary sites inaccessible during the 1990 sampling period. Relationships between stream sediment concentrations and the characteristics of subcatchments of the Tully River were investigated using regression analysis. Catchment characteristics were interpreted from aerial photographs, soil, geology, topography and historical maps, and field checking. Nephelometric turbidity was calibrated against SSC as non-filterable residue on 0.45 µm filter papers. Conductivity was converted to total dissolved solids (TDS) using an empirically derived calibration curve. Calibration curves were based on samples from the Tully River and its tributaries.

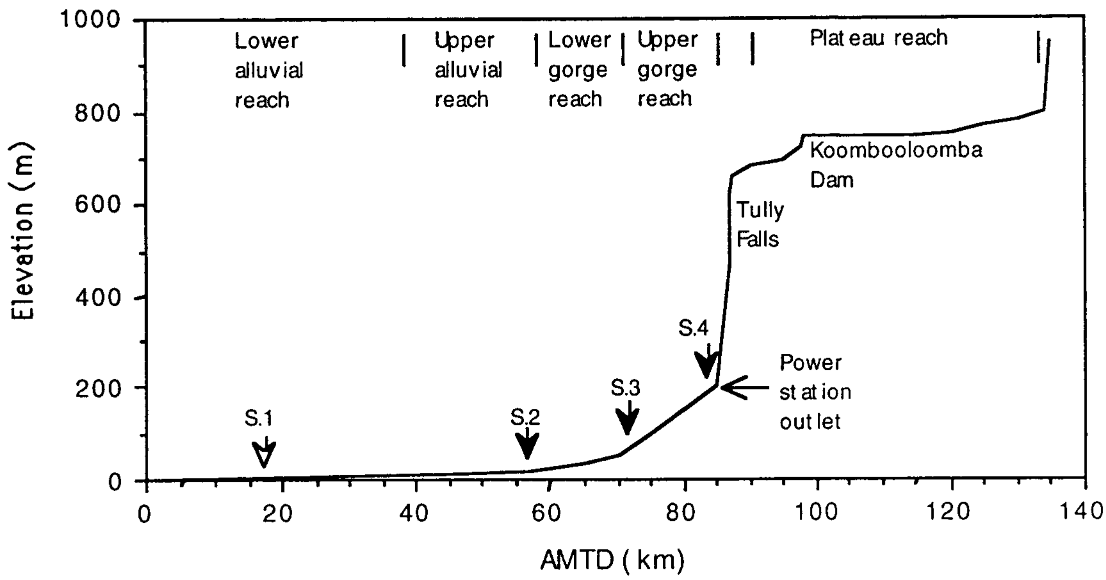
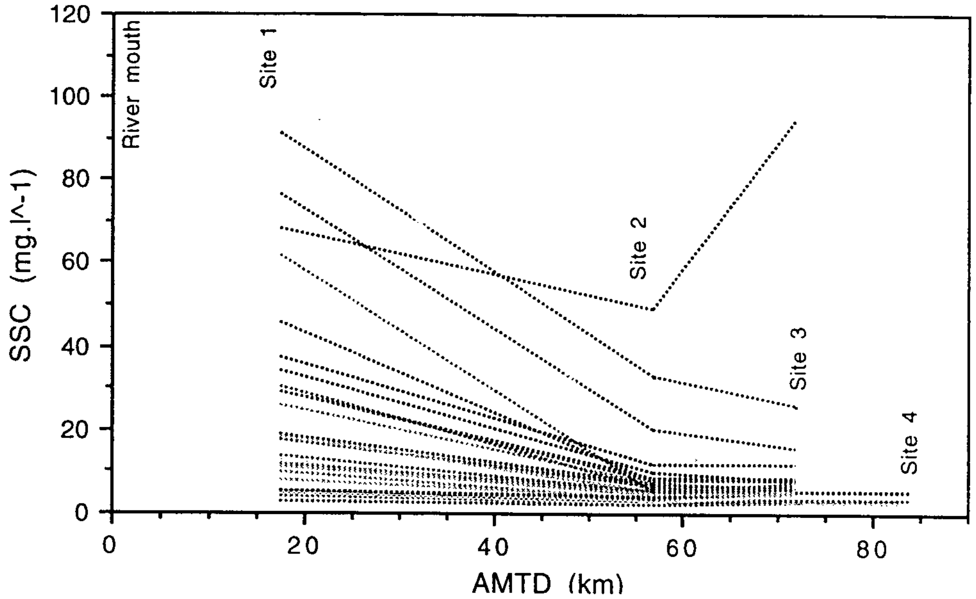


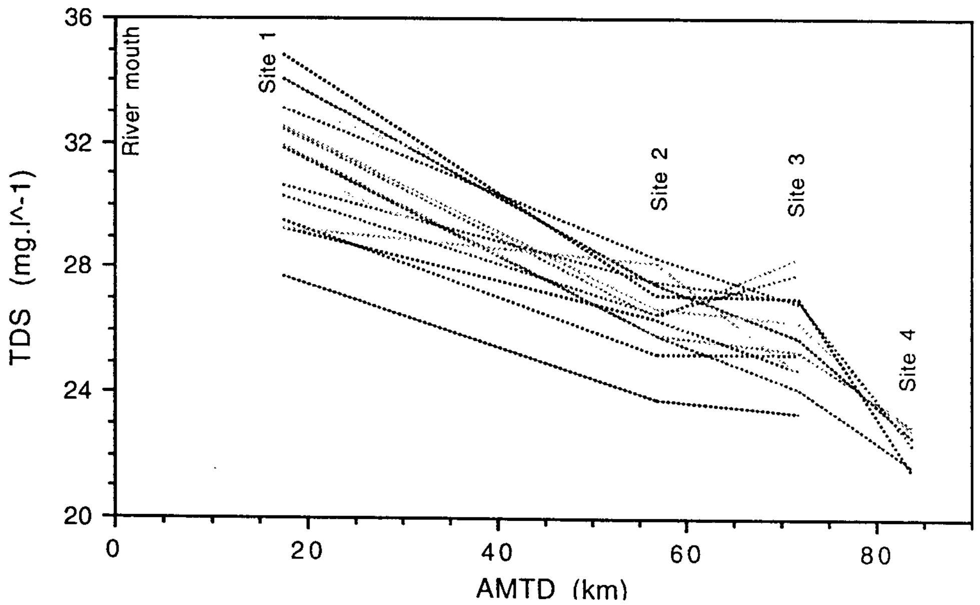
Figure 1. Longitudinal profile of the Tully River and sampling site locations

RESULTS AND DISCUSSION

Long profile patterns: The trends in SSC and TDS with distance upstream are illustrated in figures 2 and 3 for sampling stations on the Tully River (Sites 1–4). A quite consistent pattern of increased concentrations for both parameters is observed with distance downstream. In the case of SSC there is a generally monotonic increase downstream, with a marked increase between Site 2 and Site 1 (figure 2). TDS is similar, although increasing most sharply from Site 4 to Site 3 (figure 3). The increase between Site 2 and Site 1 is a result of such factors as land use change (cropping, grazing and associated accelerated stream bank erosion) and flushing of particulates and solutes out of swamps in low lying areas of the floodplain during runoff events. Lower solute levels upstream are also likely to be a consequence of lower atmospheric accession rates to inland parts of the catchment (Neil 1994). A paired 't-test' indicates that both the SSC and TDS are significantly ($p \leq 0.05$) greater at Site 1 than at Site 2. Between 57 and 17.5 km AMTD (Site 2 to Site 1), mean SSC increased by 318% ($n = 50$ paired observations). Mean TDS increased by 16% ($n = 50$ paired observations) between these two sites.

The pattern of long profile SSC variation evident in the Tully river is the reverse of that reported by Richey et al. (1986) for the Amazon. In that case, the maximum SSC occurred at the station furthest upstream (c. 2500 km, in the Andes foothills) with a decline downstream. Such a pattern would be expected under natural conditions in the Tully in response to the steep terrain of the upper reaches. However, Douglas (1967) reports higher (about double) suspended sediment loads in the lower reaches than in the upper reaches of the Barron River, and Davies and Millstream Creeks, north Queensland. This he attributes to land use change in the lower reaches, a pattern consistent with that in the Tully River. The 318% SSC increase and 16% TDS increase are associated with a change in land use from 1.5% area cleared for grazing upstream of Site 2 (57 km AMTD), to 8% cleared for cropping and 12% cleared for grazing upstream of Site 1 (17.5 km AMTD). Similar SSC patterns have also been reported elsewhere in eastern Australia (e.g. Loughran et al. 1986). It is likely that, in catchments of similar topography to the Tully, long profile suspended sediment concentrations decline downstream under natural conditions and the reverse may occur when land use intensification occurs on the floodplain. Catchment lithology is generally seen as the major determinant of streamwater chemistry (Currey 1970; Banens 1987), although land use (Walling and Webb 1975) and rainfall (Yu and Neil 1993) may be a factor within catchments and, where solute concentrations are low, atmospheric accession may play an important role in some coastal catchments (Douglas 1968; Cornish and Binns 1987). The solute data suggest that all of these factors apply in the Tully catchment.





Figures 2 (top) and 3 (bottom). Long profile variation in SSC (figure 2) and TDS (figure 3) in the Tully River

Tributary patterns: The relationship between stage and the median SSC observation for sites within the alluvial plain terrain classes is shown in figure 4a, and for montane catchments in figure 4b in relation to stage at one of the sites. This site was chosen as an index of stage height as its configuration permits accurate stage measurement and stage at this site is well correlated with that at the other sites. SSC increases with flow, as expected. The terrain classes fall quite clearly into two groups – the alluvial plain catchments and the montane catchments, with the former having higher SSC throughout the streamflow range. The SSC of the two montane groups is similar at low flows. As stage increases the granitic catchments appear to have marginally higher sediment concentrations than do those on rhyolite.

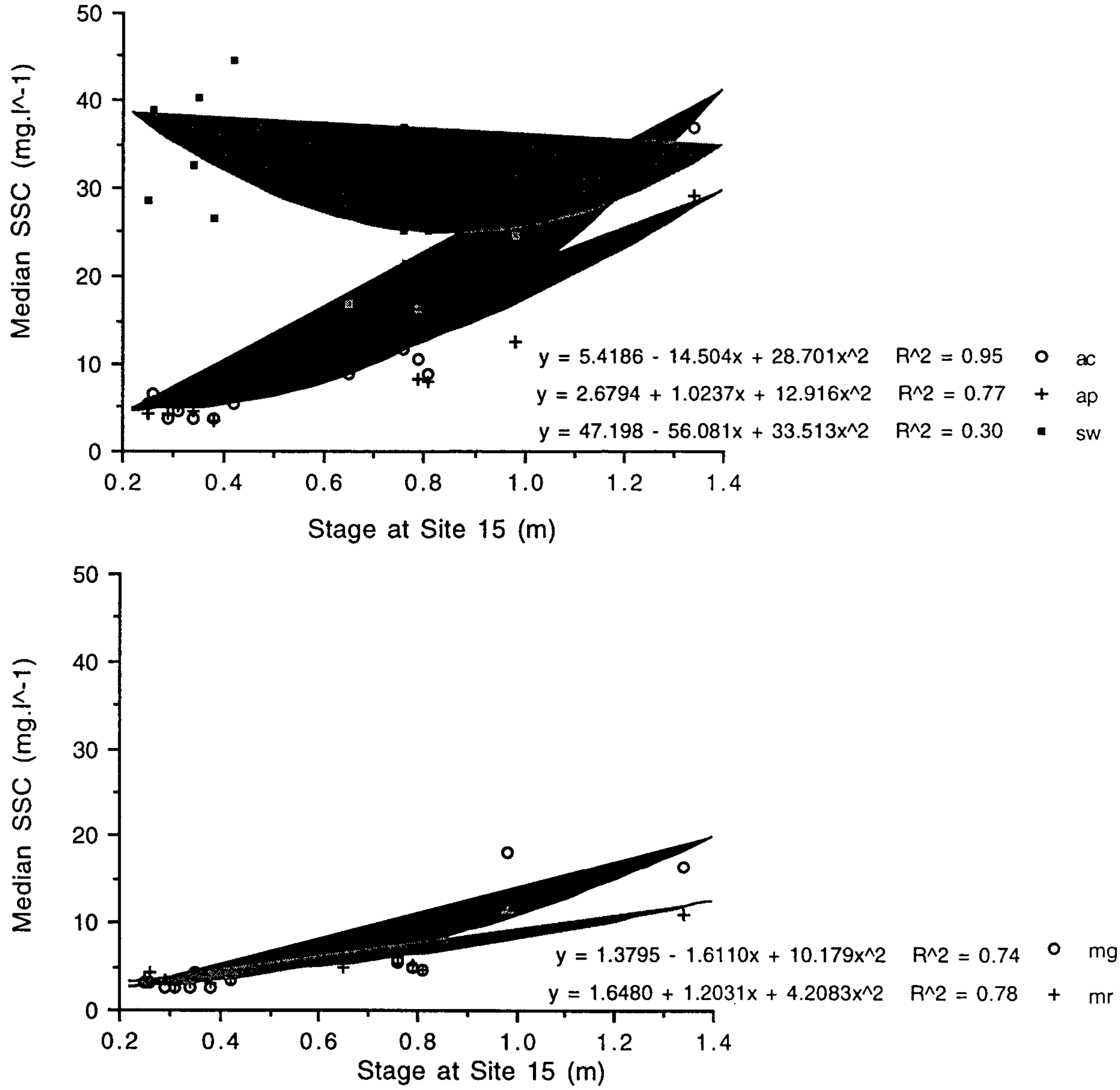


Figure 4. SSC in relation to stage (Site 15) for four terrain types (15 obsv. x 46 streams; **a** (top) ac - alluvial plain cropland, ap - alluvial plain pastureland, sw - alluvial plain swampland; **b** (bottom) mg - rainforested montane granite, mr - rainforested montane rhyolite)

The poorly drained swampy catchments have relatively high sediment loads at low stream flows. It is likely that high levels of productivity are maintained in these warm, shallow, relatively stagnant swamps and these productivity levels are enhanced by the aerial application of fertiliser, predominantly superphosphate. Some sediment resuspension probably occurs due to trampling by livestock. Consequently, at low discharges there is a steady export of, largely organic, particulates. During runoff events, however, organic particulates are rapidly flushed from the system and inorganic soil erosion products then predominate, indicated by the decline in SSC with increasing streamflow and then an increase to approximately the same level as other pasture subcatchments at higher flows. High particulate loads observed at low flows from these catchments are unlikely to have any significant effect on the overall sediment yield of the catchment. Comparison with topographically similar sites where drainage works have been carried out indicates that land use change may have reduced particulate loads from some areas of the catchment at low flows. The relationship between suspended sediment concentrations in tributary streams and the proportion of land cleared in each subcatchment is significant ($p \leq 0.05$) for 13 of the 15 series of observations. For all significant relationships the slope was positive, confirming a general increase in the particulate concentration with area cleared. The relationship between % area cleared and median SSC at each of the 42 sites (the 4 swampland catchments are omitted from this analysis as their hydrological and sediment transport characteristics are clearly atypical) is significant ($p \leq 0.05$)):

$$SSC = 3.581 + 0.079. \text{ \% area cleared}; \quad R^2 = 0.310 \text{ [Equation 1]}$$

Other catchment variables were tested, including catchment area, relief, percent slope and length of unsealed roads.km^{-2} in the catchment. In general, less than half the variance explained by the % area cleared is explained by these variables. Neither do they significantly improve the relationship between SSC and % area cleared. In virtually every case, the sign of the slope coefficient is contrary to that which would have been expected, and supports the general conclusion that land use is regionally more significant than natural catchment characteristics in determining suspended sediment concentrations.

For cropland on alluvium terrain, the mean area cleared is 36 $\pm$ 20 %. Suspended sediment concentration is significantly correlated ($p \leq 0.05$) with % area cleared for this terrain type:

$$SSC = 2.442 + 0.090. \text{ \% area cleared}; \quad R^2 = 0.506 \text{ [Equation 2]}$$

There is no significant relationship between % cleared and SSC for the eight sites in the pasture on alluvium terrain class. Although there is no clear evidence of the effect on SSC of land use change to pasture on the alluvial plain, an increase by a factor of 2 seems a realistic estimate. There is an insufficient range of % area cleared in the two montane terrain classes to estimate the effect of land clearing therein.

Apart from the general trend in relation to discharge (TDS is inversely related to streamflow), the TDS data for this broad-scale spatial survey follow a generally similar pattern to that evident for SSC. The solute loads for the two montane, forested terrain types are always lower than for the alluvial plain catchments, for a given discharge. At low discharges the alluvial plain swamplands have much higher solute concentrations than for cropland or pasture. This is attributed to the same conditions of drainage from eutrophic swamps as contributed to the high SSC levels in these catchments at low discharges. At increasing discharges, cropland solute concentrations exceed those from pastureland and swampland solute concentrations are similar to those from pasture. Montane catchments have lower solute concentrations than those on the alluvial plain at all stages observed.

Of the catchment characteristics evaluated, the % area cleared is the best correlate of solute concentration. This relationship (Eqn. 3) is significant ($p \leq 0.05$).

$$TDS = 30.788 + 0.107. \text{ \% area cleared}; \quad R^2 = 0.31 \text{ [Equation 3]}$$

The other catchment variables tested were poorly correlated with solute concentration and, with the exception of catchment relief, do not significantly improve the relationship between TDS and % cleared. A decline in solute load with increased relief is likely to be the result of greater overland flow relative to throughflow, and to decline in atmospheric accession with elevation (Neil 1994). There is a similarity between SSC and TDS as they relate to area cleared within terrain classes. For the alluvial cropland there is a significant ($p \leq 0.05$) relationship between TDS and % area cleared at high flows and for the median of stage for the 15 sets of observations, but at low flows the relationship is not significant. There is no relationship between % cleared and TDS in the alluvial pasture terrain class. Interpretations generally similar to those for SSC patterns may be made of these results. Higher solute loads occur in streams on the alluvial plain than from the montane catchments because of the greater proportion of streamflow derived from throughflow in the former terrain. On the alluvial plain, solute concentrations at low flows are similar for both terrain classes. As streamflow increases, with a greater proportion derived from surface runoff processes, solute loads from cropland exceed those from pasture, probably as a result of the higher levels of soluble fertilisers applied to the cropland. These interpretations are tentative and require detailed process studies to confirm them.

From long profile analysis it was shown that mean SSC consistently increased downstream, by 318% between 57 and 17.5 km AMTD. Mean TDS increased by 16% between these two sites. These increases are associated with a change in land use from 1.5% area cleared for grazing upstream of 57 km AMTD to 8% cleared for cropping and 12% cleared for grazing upstream of 17.5 km AMTD. Of the catchment characteristics evaluated in the tributary stream analysis, land use (% area cleared) is the best predictor of both SSC and TDS. The results suggest an increase in SSC by a factor of 4.7 for a lowland catchment 100% cleared for cropping, or by 3.2 for 100% cleared catchments in general. TDS increases 35% for a

100% cleared catchment. Highest SSC and TDS both occur in alluvial plain swamplands at low flows, although this aspect of water quality contributes little to the total sediment and solute yield of the catchment which is largely controlled by concentrations at high flows, at which times land use effects dominate. These results contribute to the discussion of downstream effects of land use in the Great Barrier Reef catchment by:

i. demonstrating the relative importance of land use compared with other catchment characteristics on a regional scale. Within the tributary stream analysis, subcatchment landuse was consistently the catchment characteristic best correlated with both water quality parameters analysed. Furthermore, land use was generally the only parameter which was significantly related to water quality. Characteristics such as the area, relief and lithology of tributary catchments were apparently overshadowed by the contribution of land use.

ii. indicating the magnitude of the land use effect for a humid tropical catchment. Standardising to a 20% cleared catchment (as the Tully was at the time of data collection; and assuming that land use intensification in such a standardised catchment occurred on floodplains, not hillslopes) the land use associated increase in median SSC estimated from the long profile analysis is by a factor of 2.1 and from the tributary stream analysis is 1.4.

ACKNOWLEDGMENTS

The support of the Australian National University and the Australian Institute of Marine Science and the advice of Prof. J. Chappell are gratefully acknowledged.

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Water quality monitoring in Australia

David Tait[1] *and Charles Lewis*[2]
[1] *Aquatech Environmental Consultants, 42 Jaeger Circuit, Bruce ACT 2617*
[2] *Environment Protection Agency, 40 Blackall Street, Barton ACT 2600*

ABSTRACT

Water Quality Monitoring in Australia is a study of Australia's water quality monitoring effort – covering all water types e.g. fresh and marine surface water, groundwater, effluents and drinking water. The project has two major products:

- *Water Quality Monitoring in Australia* (WQMA) Report, with an annex covering Australia's Exclusive Economic Zone.
- *Water Quality Monitoring in Australia* Database.

The project was funded by the Federal Environment Protection Agency with additional funds from the State of the Environment Reporting Unit of the Department of the Environment, Sport and Territories, and carried out by Aquatech Environmental Consultants.

The paper will describe the main findings and recommendations of the report and annex, with emphasis on relevance to the Great Barrier Reef. The paper will also introduce the *WQMA Database,* which is undergoing pre-release or β testing, and demonstrate its usefulness as a research and management tool, with an emphasis on the Great Barrier Reef region.

The report makes seven main recommendations regarding:

- the distribution of funds within water quality monitoring programs
- the coordination of water quality monitoring activities
- the reporting and analysis of long-term monitoring data
- increasing community involvement in water quality monitoring
- provision of regular updates of water quality monitoring in Australia
- integration of water quality monitoring into the National Water Quality Management Strategy and into Total Catchment Management approaches
- provision of a nation-wide (including the Exclusive Economic Zone) water quality monitoring system

The database includes details on the water quality monitoring activities of more than 200 organisations covering all parts of Australia, including the Exclusive Economic Zone. The database is arranged by organisation: each organisation may administer from one to many monitoring programs; each monitoring program may cover one or many 'variable sets' (i.e. group of water quality determinands that are measured); each variable set may be monitored at one or more monitoring sites. The geographic location of each monitoring site is included (if provided by the monitoring organisation), facilitating searches on 'who is monitoring what, where?'

INTRODUCTION

The Environment Protection Agency commissioned a study by Aquatech Pty Ltd to produce a comprehensive assessment of water quality monitoring across Australia, as a basis for the development of a more uniform and efficient approach. Additional funds were provided by the State of the Environment Reporting Unit of the Department of Environment, Sport and Territories to upgrade the database from the study. The *Water Quality Monitoring in Australia* (WQMA) Report was released by the then Minister for the Environment, Sport and Territories, Senator Faulkner, in October 1995.

METHODS

The main study focused on water quality monitoring for drinking waters, inland, estuarine and coastal waters and effluents within the following categories:

- drinking water reticulation systems
- drinking water supply reservoirs
- lakes and dams
- rivers and creeks
- general riverine environment
- urban stormwater
- groundwaters
- estuaries
- coastal waters
- industrial water supply and process effluent
- agricultural run-off.

The study involved the distribution of a questionnaire to about 2000 organisations around Australia and there were follow up interviews with the most significant organisations. The study has been extended to cover Australia's marine waters including the Exclusive Economic Zone (EEZ), Territories and Antarctica. This extended study will be reported in detail later, but some information is provided in this paper.

RESULTS AND DISCUSSION

Over 200 organisations responded with information on monitoring programs for drinking waters, inland, estuarine and coastal waters and effluents and later, 18 organisations responded with further information on marine programs.

The report found that there are around 1800 water quality monitoring programs in Australia for drinking waters, inland, estuarine and coastal waters and effluents worth about $100 million each year (programs can vary considerably in size and scope). About 65% of monitoring is by State, Territory or local governments. The rest is by the Commonwealth, community organisations, universities and private companies. Additionally there were 22 marine monitoring programs costing about $10 million each year.

Summary statistics on monitoring programs are shown in tables 1–3

Table 1. Number of water quality monitoring programs across Australia for drinking waters, inland, estuarine and coastal waters and effluents

Category	Numbers of (non EEZ) water quality monitoring programs across Australia for drinking waters, inland, estuarine and coastal waters and effluents (in 1993), conducted by governments, universities and research organisations, private companies and community organisations
Industrial water supply and process effluent	447
Drinking water reticulation systems	290
Rivers and creeks	251
Drinking water supply reservoirs	192
Lakes and dams	169
Groundwaters	48
General riverine environment	83
Estuaries	69
Coastal water	63
Urban stormwater	58
Agricultural run-off	27
Total	**1796**

The Aquatech study generated the WQMA Database on monitoring organisations, programs, sites and parameters measured. This database is undergoing pre-release or β testing by some potential users in agencies.

Table 2. Examples of numbers of water quality monitoring programs for drinking waters, inland, estuarine and coastal waters and effluents and marine waters

State or Territory	Number of non EEZ water quality monitoring programs for drinking waters, inland, estuarine and coastal waters and effluents conducted by state, territory or local government (in 1993)	Number of water quality monitoring programs in EEZ conducted off coastlines of states and territories and for islands and Australian Antarctic Territory (1995)
New South Wales	346	5
Victoria	340	3
Queensland	243	4
Northern Territory	85	1
Tasmania	69	4
South Australia	37	1
Western Australia	25	1
Australian Capital Territory	20	-
Australia's Islands	-	* 1
Australian Antarctic Territory (AAT)	-	#3
Total	**1165**	**22**

*potable water
#drinking water and sewage discharges

The consultant also provided answers to about 25 questions posed in the specifications for the consultancy, for example on, organisations conducting water quality monitoring, mechanisms for coordination, indicators of water quality and guidelines being used, quality assurance and control procedures, databases and availability of data on water quantity.

Table 3. Reasons for the existence of monitoring programs

Reasons for the existence of a particular water quality monitoring program	Per cent of non EEZ water quality monitoring programs for drinking waters, inland, estuarine and coastal waters and effluents (1993)	Per cent of EEZ water quality monitoring programs conducted off coastline of states and territories and for islands and Australian Antarctic Territory (1995)
Statutory or legislative	24	10
Operation or process optimisation	23	25
Licence requirement	19	10
Academic, educational or research	16	35
Total catchment management	12	-
Pilot study	6	20
Total	**100**	**100**

The existing distribution of resources within components of monitoring programs was estimated through discussions with program managers from about 50 key water management agencies. About 60% of budgets went to laboratory analysis, with the remaining 40% spread over the other components of programs, which was often insufficient for needs. The proposed distribution of resources (see Recommendation 1 below) was also based on these discussions. Program managers felt monitoring programs needed more resources devoted to field determinations with portable equipment, statistical analysis of results, and dissemination of results to the scientific and general communities. Redistribution of some funds (up to about a third) from laboratory analysis to the other components was the best option as overall budgets are unlikely to increase.

The main report and annex list many references on water quality monitoring.

SUMMARY OF RECOMMENDATIONS of the Water Quality Monitoring Study

1 Redistribution of funds within water quality monitoring programs
To achieve greater effectiveness and efficiency within water quality monitoring programs, redistribute funds internally in line with the following approximate breakdown:

- preparation and planning to meet program objectives – 15%
- sampling and field analyses – 15%
- laboratory analyses – 40%
- data storage, analysis and interpretation – 15%
- report preparation and dissemination – 15%

Redistributing funds within programs reduces the emphasis on laboratory analyses and would entail training personnel for new skills, redesign of programs, greater use of field analyses, and the reporting of information to the general community. The outcome would be better designed and operated programs that produce more and better information for water resource management.

2 Increased coordination
Select a government agency in each State and Territory, and the Commonwealth, to:

- coordinate water quality monitoring activities within their area of jurisdiction; and
- coordinate the flow of information generated from monitoring to the general community and the technical community.

Better coordination, for example through agency coordinators, a one stop shop and continued support for the 'Streamline' database would reduce the overlap between monitoring programs, encourage collaboration between organisations and improve information flow to water managers.

3 Increased reporting and analysis of long-term monitoring data
To promote increased analysis, interpretation and reporting of long-term water quality monitoring data, as part of the state of the environment reporting process, select and analyse water quality monitoring databases.

This would also involve developing agreed standards for databases and linkages with geographical information systems. Much of the water quality monitoring data collected over the years needs further examination and analysis to enable better conclusions such as determination of long-term trends, establishment of baseline data for Environment Impact Assessment (EIA) and better monitoring program design. A program to implement this Recommendation would be best implemented through collaboration between agencies.

4 Increased community involvement
Continue to increase the amount and extent of community involvement in water quality monitoring, including further integration of community monitoring with agency monitoring.

Community based monitoring has become increasingly important in recent years through State based schemes such as Streamwatch (NSW) and Ribbons of Blue (WA) and the Commonwealth's Waterwatch. It is important that this continue, to build up links between community groups, government and private sectors, to facilitate on ground action for remediation, to promote education in water quality issues, to develop databases and to achieve national consistency in data gathering and reporting.

5 Provision of a regular update of water quality monitoring in Australia
To coincide with state of the environment reporting periods, provide at appropriate intervals e.g. every four years, an update of water quality monitoring in Australia.

6 Integration of water quality monitoring into the National Water Quality Management Strategy (NWQMS) and into Total or Integrated Catchment Management approaches
Ensure that the concept of water quality monitoring as an 'information system' is an integral part of the NWQMS and Total Catchment Management approaches.

This could include development of protocols and indices of water quality and would encourage the use of water quality monitoring information in state of the environment reporting, and in the operation of Total Catchment Management committees.

7 Provision of a nation-wide water quality monitoring system
Provide a nation-wide water quality monitoring system, by selecting about 100 currently monitored sites for each of the four main environmental waters types (rivers, lakes, estuaries/coastal and groundwaters), the results to be used in state of the environment reporting. Continued funding of the Monitoring River Health Initiative involving biological indicators of water quality is also recommended.

The recommendations in the annex on monitoring in the Exclusive Economic Zone are likely to generally mirror those in the main report, but include two relating specifically to marine waters i.e. design and implementation of a cost effective nationally coordinated marine monitoring program.

Adoption of the above recommendations would improve water quality monitoring in an area such as the Great Barrier Reef region. The region's monitoring would also form an important part of any national marine monitoring program (see also 'Use of the WQMA Database in the Great Barrier Reef region' below).

Overview of the WQMA Database

Arranged by organisation
The information in the database is arranged by organisation:

- Each organisation has a number of monitoring programs – there can be one or more programs per organisation, and each program belongs to one organisation.
- Each program has a number of variable sets (a variable set is a set of variables that are monitored, such as: pH, conductivity, phosphorus and nitrogen) – there can be one or more variable sets per program. Thus, each variable set belongs to one program and one organisation.
- Each variable set has a number of sites (a site is a location where monitoring takes place, and usually has a name, a latitude and a longitude) – there can be one or more sites per variable set. Thus, each site belongs to one variable set, one program and one organisation.

This complexity is inherent in the nature of the data, i.e. in the way water quality monitoring is organised (figure 1).

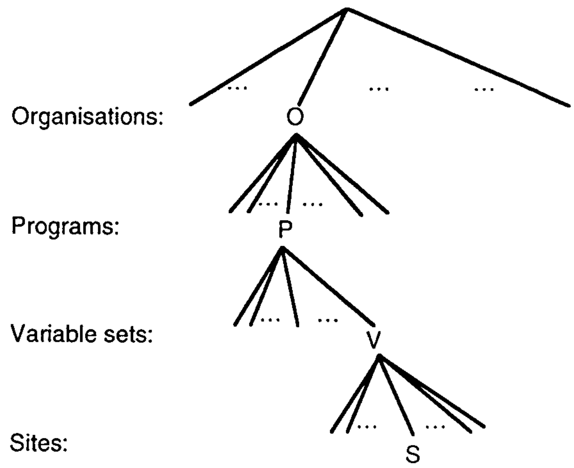

Figure 1. Organisation of data in the WQMA Database

Looking at the data

The information (or data) in the database on the selected organisation is read from the Viewer window (figure 2). This window opens automatically when the database starts. It has four scrollable lists covering organisations, programs, variable sets and sites down the left hand side, and four text boxes for displaying information about the selected organisations, programs, variable sets and sites down the right hand side. The Viewer window is only for looking at the data and does not allow data to be changed.

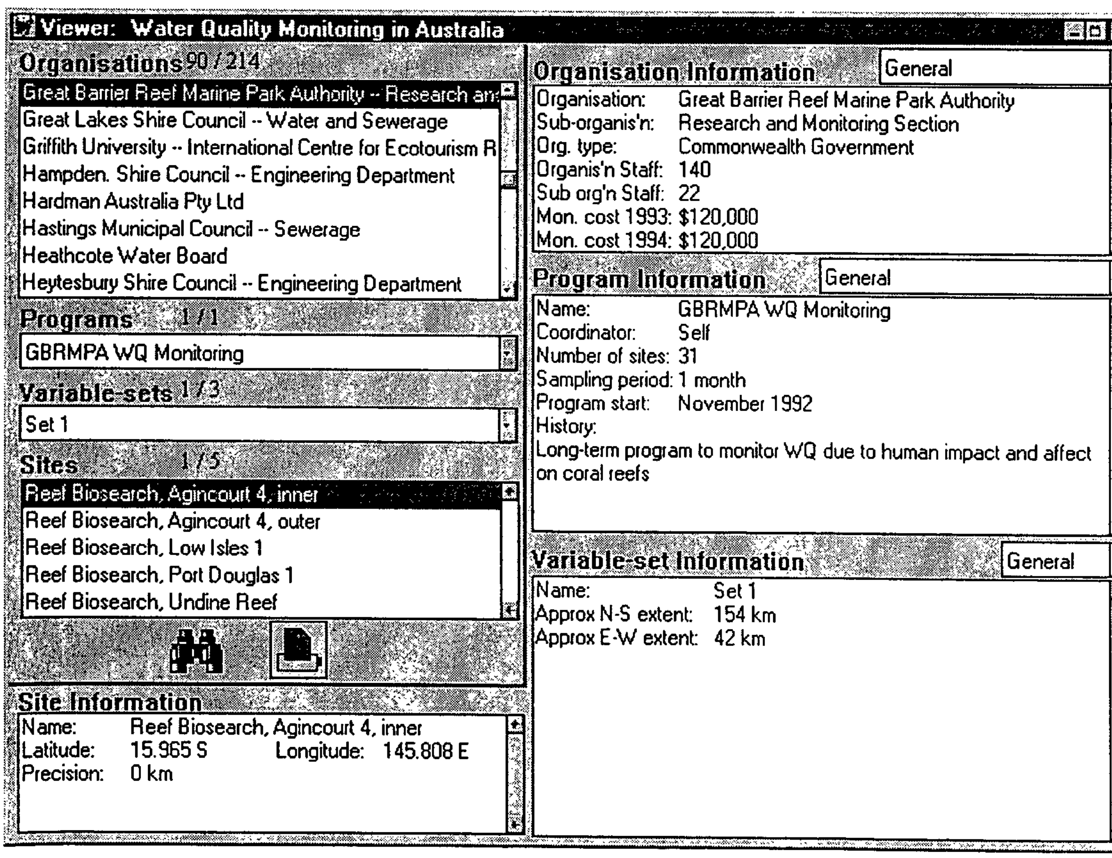

Figure 2. The main 'Viewer' window of the WQMA Database

Searching the Database

Organisations, programs, variable sets and sites are listed by searching the database using your selected criteria, which can include more than one category per box. The Search window (figure 3) is activated by clicking the binocular icon on the Viewer window. About twenty types of searches can be done by organisation name, contact name, state, variables, site location, etc.

Printing

Any information from the database can be printed to paper. Single-clicking on the printer icon in the Viewer window, or choosing Print from the File menu, brings up the Print window and clicking OK, prints out the required information.

Use of the WQMA Database in the Great Barrier Reef region

The database will be of value to all involved in water management issues in the Great Barrier Reef region. It offers a 'one-stop-shop' for locating and identifying water quality monitoring data in the region or in other regions of interest. The data can be partitioned into categories such as organisation, geographical location, water type and analytical variables. For researchers, agencies and community groups, this information can be important when reviewing monitoring activities, changing existing research or monitoring programs, or when considering development proposals which may impact on water quality.

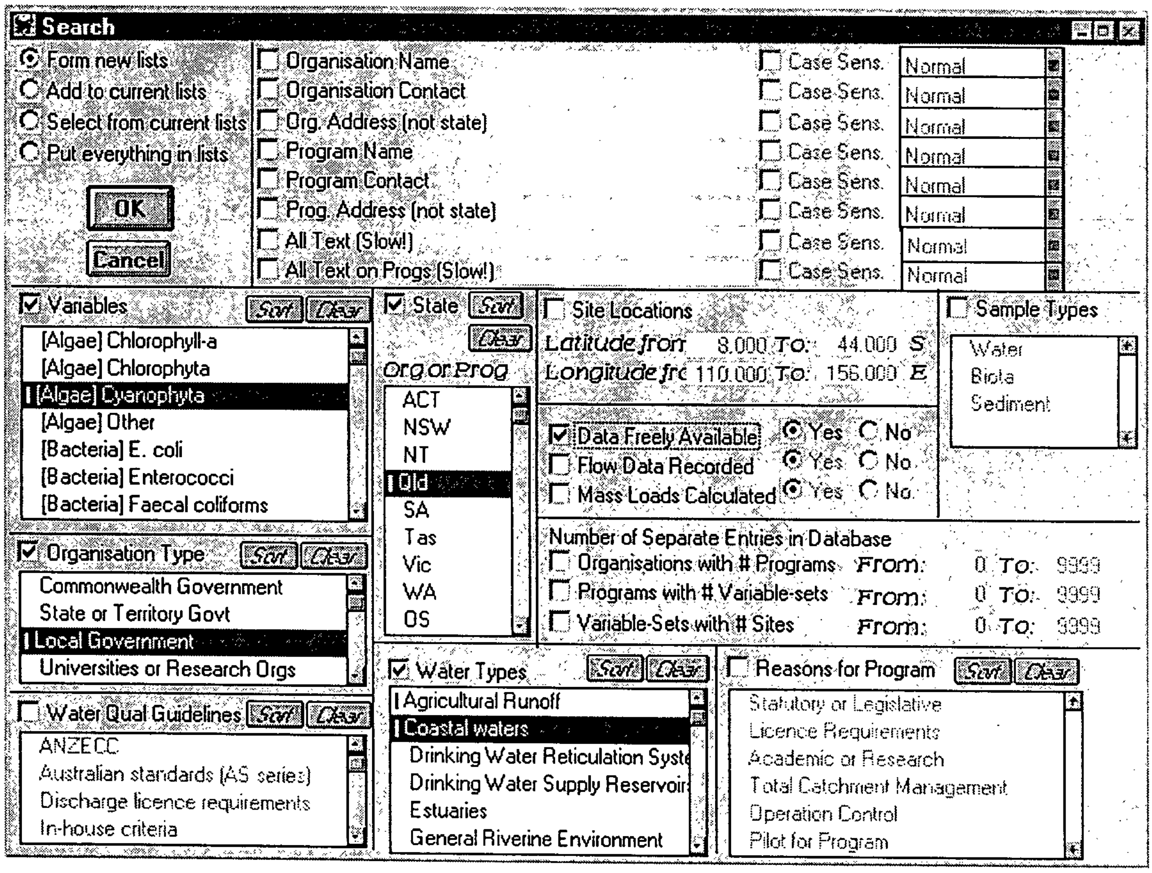

Figure 3. The WQMA 'Search' window, with criteria set up for the query: 'List all local government organisations in Queensland that monitor *Cyanophyta* in agricultural run-off or coastal waters, and that allow free access to data.'

The protean nature of 'wet tropical coast' flood plumes in the Great Barrier Reef lagoon – distribution and composition

Jeremy Taylor[1] *and Michelle Devlin*[2]
[1] *Department of Earth Sciences, James Cook University Qld 4811*
[2] *Australian Institute of Marine Science, PMB No. 3, Townsville Qld 4810*

ABSTRACT

Episodic flood events are a common feature on the north Queensland coast of Australia. Following periods of intense rainfall on the neighbouring coastal catchments flood plumes can flow into the Great Barrier Reef lagoon. These plumes can introduce a significant amount of terrestrially derived sediment and nutrients to the Great Barrier Reef lagoon over a relatively short period of time. However, the distribution and composition of the flood plumes can be quite protean in nature.

While the dominant factor in the development of a flood plume is rainfall, data collected from several events demonstrates that flood plumes can vary in distribution with similar quantities of rainfall. Physical factors such as wind speed and direction can influence plume distribution significantly. In 1994 a coalesced plume from several rivers reached the mid-shelf reefs, aided by light northerly winds; in contrast, in 1995 a similar rainfall event yielded a plume that was constrained to the coast in part due to strong south-easterly winds.

Measurements collected during plume events include salinity, total suspended solids, chlorophyll *a* and nutrients (N, P and Si). Flood plume monitoring is reactive by nature and due to the variability associated with the distribution of a plume no fixed stations were established for monitoring plume events. However, data collected shows that the timing of sampling is critical to quantify the amounts delivered to the Great Barrier Reef lagoon.

INTRODUCTION

Perceived changes to the levels of nutrients and sediment discharged to the Great Barrier Reef lagoon from mainland run-off has undergone significant debate in recent years (Yellowlees 1991; Larcombe and Woolfe 1995). Attention has mainly been divided between estimating export fluxes and budgets from coastal catchments and lagoon waters (Hunter 1993; Furnas et al. 1995; Mitchell and Furnas 1996) to the study of the effects of elevated nutrients and sediment on biota (Stafford-Smith and Ormond 1992; Steven and Larkum 1993). Recent work has shown that a large proportion of nutrients delivered to the Great Barrier Reef lagoon from the 'wet tropical coast' region (Herbert River–Daintree River) is via rivers during flood events (Hunter 1993; Furnas et al. 1995; Bramley and Johnson, in press).

Episodic flood events, often associated with tropical cyclones, are a common feature on the 'wet tropical coast' of Queensland. Following periods of intense rainfall on the neighbouring coastal catchments, river run-off enters the Great Barrier Reef lagoon as flood plumes. The extent of these flood plumes has been noted previously (Rainford 1925; Orr 1933) but studies of plumes are scarce (Wolanski and Jones 1981; Davies and Hughes 1983; Wolanski and van Senden 1983) with a paucity of data on the sediment and nutrient content of these plumes (Brodie and Mitchell 1992; Devlin et al. 1996; Taylor, in press). Available data suggests that the distribution and composition of the flood plumes can be quite protean in nature especially between 'wet' and 'dry' catchments (Brodie 1996).

Flood events in 'wet tropical coast' catchments followed rain depressions associated with cyclones Sadie (1994), Violet (1995) and Ethel (1996). Flood plumes emanating from the rivers were mapped using aerial surveys to ascertain the extent of plume coverage (personal observation and J Brodie, pers. comm.). Because flood plume monitoring is reactive by nature, no fixed stations were established for sample collection. Figure 1 shows the surface extent of the flood plumes for the three events with sample locations. Measurements collected during plume events include salinity, total suspended solids, chlorophyll *a* and dissolved and particulate nutrients (N, P and Si). Sampling methods are described in Devlin (in press) and Taylor (in press).

The dominant factor in the development of a flood plume is rainfall as this induces river run-off which subsequently discharges its suspended load to the marine environment. Data collected from several events demonstrates that flood plumes can vary in distribution with similar quantities of rainfall (table 1). Physical factors such as wind speed and direction can influence plume distribution significantly (table 2). In 1994, a rain depression associated with cyclone Sadie produced extensive rainfall in the coastal catchments, the individual river plumes coalesced and aided by light winds and small seas reached the main reef tract. In contrast, similar rainfall events in 1995 and 1996 yielded flood plumes that were constrained to the coast in part due to strong south-easterly winds and larger seas.

Table 1. Catchment size and mean discharge with average rainfall for recent flood events

River	Catchment size (km^2)	Mean Annual Discharge ($ML \times 10^3$)	Average Rainfall during Flood Event[1] (mm)		
			26 Jan – 1 Feb 1994	22 Feb – 1 Mar 1995	4 Mar – 10 Mar 1996
Daintree	2125	1023[2]	355	417	1405
Barron	2175	884[2]	455	370	414
Russell–Mulgrave	1475	1617[2,5]	835	1140	774
Johnstone	2495	2642[3]	707	905	670
Tully	1685	3039[5]	754	706	890
Herbert	10131	3440[4]	577	304	198

[1] Devlin et al. (1996);[2] QDPI Water Resources (1995); [3] Hunter, H.M. (1993); [4] Hausler, G. (1991); [5] Mitchell, A.W. and Furnas, M.J. (1996)

Table 2. Characteristic wind speed and direction in the Great Barrier Reef lagoon during plume movement with associated cyclones

Year	Associated Cyclone	Wind Speed (Knots)	Wind Direction
1994	SADIE	10	NW – NE
1995	VIOLET	20 – 25	SE
1996	ETHEL	20	SE

The areal distribution of the flood plumes can be quite different depending on the prevailing conditions, but can be easily mapped from the air. However, the volume of the plume and composition can only be obtained by sampling. Reasonable estimate of the volume of the plume can be obtained using salinity. It is estimated that the plumes sampled are less than 3 m thick (unpublished data).

The composition of the plumes can be quite variable between years and between catchments as shown in figure 2 for surface salinity and dissolved inorganic phosphorus. Individual catchments were not collected on the same day and by the same method and therefore some caution needs to be taken with interpretation. As would be expected, there is a general trend of increasing salinity with distance from river mouth for all years. Dissolved inorganic phosphorus shows the opposite trend of decreasing with distance from the river mouth.

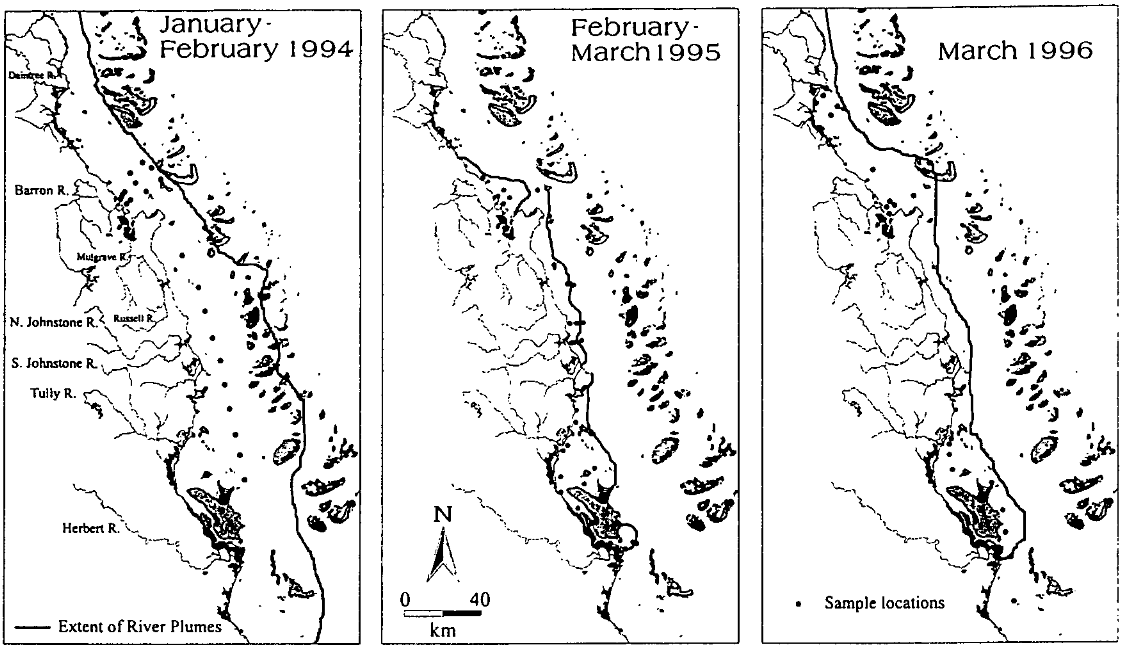

Figure 1. Extent of major flood plumes in the Great Barrier Reef lagoon for 1994, 1995 and 1996

Because plumes do not remain as discrete bodies, there is some overlap of plumes that makes tracing an individual plume difficult.

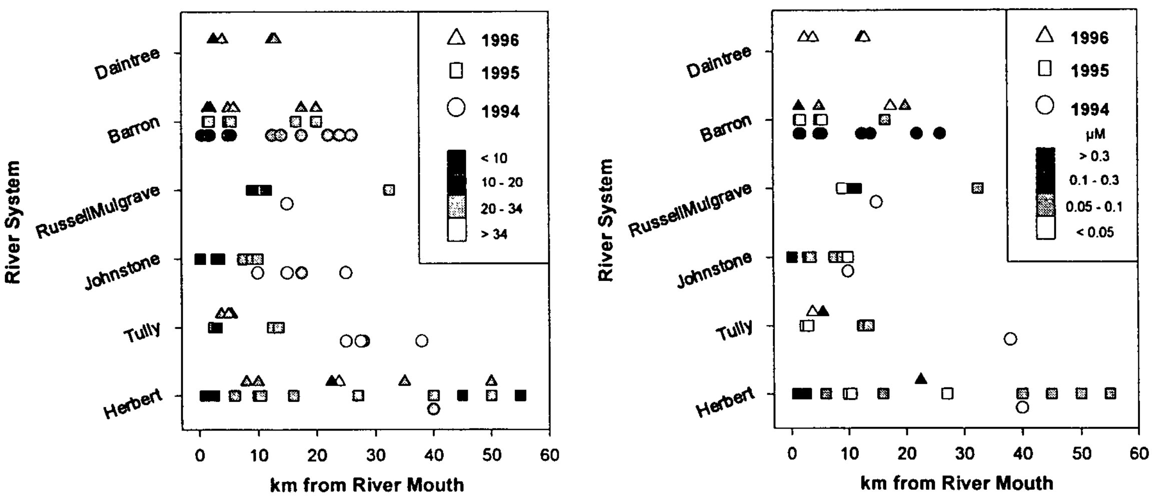

Figure 2. Surface salinity and dissolved inorganic phosphorus variability for different catchments and years

This can be seen in the Herbert plume with samples 40–55 km from the mouth appearing anomalous in 1995; there is probably some overlap with the run-off from the Murray River and coastal streams.

Data collected shows that the timing of sampling is critical to obtaining reliable estimates of material exported in the flood plumes (figure 3). Two sites were sampled at three depths, two days apart, with a highest values nearer the surface and a significant decrease in silicate concentration between sampling occasions.

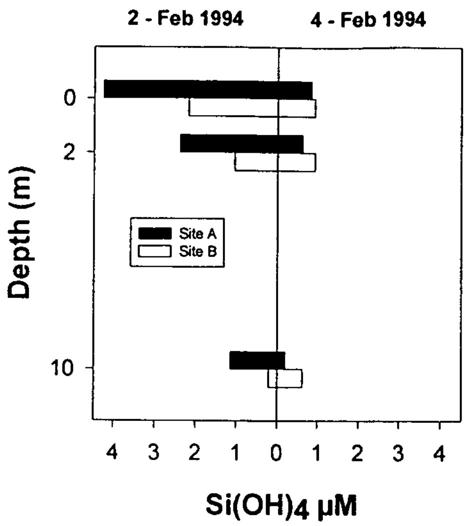

Figure 3. Silicate variability with depth and time at two sites in the Barron River plume 1994 (A in main plume; B near front of plume)

Variability in plumes sampled is high on several space and time scales with little other data currently available. Further work is required on sampling flood plumes to ascertain the spatial and temporal distribution and composition of terrestrially derived material contained in the plumes. This is especially important considering rivers are the dominant input of terrestrial nutrients and sediment to the Great Barrier Reef lagoon and flood plumes the dominant transport mechanism to lagoon waters.

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Detection of anthropogenic and natural mercury in sediments from the Great Barrier Reef lagoon

G Stewart Walker[1] and Gregg J Brunskill[2]
[1] *CRC Reef Research Centre, James Cook University Qld 4811*
[2] *Australian Institute of Marine Science, PMB No. 3, Townsville Qld 4810*

ABSTRACT

A research program is investigating the analysis of sediment and coral cores as a means of detecting changes in past and present land use. Cores of sediment of up to 4 metres in length have been analysed from sites expected to be influenced by flow from the Burdekin, Herbert and Tully Rivers in north Queensland. The recent development of a new sensitive analytical method has allowed the detection of mercury in sediment cores. Background levels of mercury, and spatial and temporal excursions from those levels have been detected. Cores from Hinchinbrook Island, Bowling Green Bay and Upstart Bay have been found to have different profiles of mercury concentration.

INTRODUCTION

Knowledge of mercury predates historical records (Goldwater 1972) and natural mercury-rich deposits have been utilised by many cultures. Much of the early history of mercury was land-based. However, the analysis of mercury in marine sediments came to prominence in the mid-1950s when the release and accumulation of methyl mercury compounds from factories in Minamata Bay, Japan caused neurological disorders and deaths (D'Itri 1972). As a consequence of this disaster and other similar pollution events in Japan (D'Itri 1972), Sweden (Friedberg and Vostal 1974) and Canada (D'Itra and D'Itra 1977), much work was undertaken to establish analytical methods for the reliable analysis of mercury concentrations in sediments, fish and human matter. The levels of mercury in these instances and in other regions where heavy industrial pollution causes a large rise in contaminants are relatively high – c. 2000 ppm (parts per million) (Kaiser and Tolga 1980). Analysis of background levels of mercury which may be c. 60 ppb (parts per billion) (Sadiq 1992) requires much more sensitive analysis and careful attention to potential contamination of samples or solutions.

The recent development of a new sensitive analytical method (Walker et al. 1996) has allowed the analysis of sediment cores for the detection of background levels of mercury, and spatial and temporal excursions from background levels. Cores of up to 4 metres in length have been taken at various sites near river deltas, from Hinchinbrook Island, Bowling Green Bay and Upstart Bay.

Seven potential sources of mercury in the sediments of the area of investigation have been suggested (Walker 1995):

1. mining using the amalgamation of mercury and gold or silver – 1870–1890;
2. agricultural use of organomercurial herbicides and fungicides – 1940–present;
3. natural levels of mercury in soils and rocks from which sediment was formed;
4. natural events such as thermal upwelling from ocean fault lines or discharge from volcanic eruptions;
5. shipwrecks with mercury as a cargo giving rise to high-level localised input (Loney 1984);
6. sewage outfalls;
7. a combination of lesser sources – coal and oil combustion (coal from a merciferous belt can have mercury in concentrations as high as 300 ppm), marine fungicide, domestic paints etc.

ANALYSIS

Cores of sediment have been collected from a number of sites off the north Queensland coast. A Kasten corer was deployed from the AIMS vessel MV *Harry Messel* to yield cores of sediment of 1–4 m in length. Cores were logged and cut into sections of 2 cm vertical depth from 0 to 20 cm, and into sections of 4 cm depth from 20 cm to the end of the core. Subsamples were taken for other analysis including ^{210}Pb for dating. In subsequent trips samples were taken specifically for mercury analysis in acid-washed glass containers which were frozen within an hour of being sampled.

The analytical method used was a acid digestion followed by a combination of Inductively Coupled Plasma Atomic Emission Spectroscopy and Inductively Coupled Plasma Mass Spectrometry (Walker et al. 1996). Accurate amounts of wet defrosted sample are weighed into 30 cm^3 pyrex reactor tubes. Five ml of 70% HNO_3 and 1.8 ml of 35% HCl were added. Tubes were heated to 100°C and maintained for one hour.

Five ml of 5% $K_2Cr_2O_7$ solution was added to stabilise the solution and prevent volatilisation of metallic mercury. Analysis was carried out by reacting each solution in a Cold Vapour Generator (Varian CGA 76) with equal volumes of a solution of 45% NaOH and a reducing solution of Stannous Chloride (31g $SnCl_2$ in 35% HCl and water) according to a published method (Haraldsonn et al. 1989). Analysis of mercury vapour was achieved by either an Inductively Coupled Plasma Atomic Emission Spectrometer (Varian Liberty 220) or an Inductively Coupled Plasma Mass Spectrometer (Varian Liberty).

Absolute detection limits for standard solutions of mercury chloride or mercury nitrate were found to be 2 ppb for the ICP–AES and 25 ppt for the ICP–MS.

Other analysis undertaken include, water content, carbon (total), carbon (carbonate), nitrogen, sulphur, ^{210}Pb and other main or trace elements.

RESULTS

Each core has been found to have a different profile of mercury concentration.

Missionary Bay, Hinchinbrook Island (Core 638) has a uniformly low level of less than 10 ppb (equivalent to 50 pmoles (10^{-12}) of mercury per gram of sediment (dry weight)) between 3.4 m and 0.44 m. From 0.44 m to the surface an elevated mercury concentration up to 40 ppb (200 pmolesg^{-1}) was found.

A core from Upstart Bay (1250) has background levels around 15 ppb (70 pmoles/gram) from 0.8–2.92 m depth, but higher concentrations of mercury were found within the top 0.8 m with maximum levels of 100 ppb (500 pmoles/gram) occurring around 0.5 m.

In contrast, a core from Bowling Green Bay has background levels of 12 ppb (60 pmoles/gram) from 3.08–3.82 m. A sharp rise from 12 ppb (60 pmoles/gram) to 500 ppb (2500 pmoles/gram) occurs over only 0.4 m. An exponential-type reduction in mercury concentrations is observed in the sediment from 2.52 m to the surface. This is seen as characteristic of a single addition event with limited back-mixing and exponential forward reworking. Modelling studies are underway to mimic the conditions that would have given rise to this signal.

DISCUSSION

Results presented in this paper represent the initial output from a new project. At present it can be concluded from the present data that:

- mercury occurs in sediments in the regions investigated;
- the background levels of mercury – as low as 2 ppb – can be detected;
- in one location a sharp deviation from background to a level 25 times background occurred over a short depth at around 3 m depth;
- the sharp gradient of increase in mercury indicates an input of substantial amounts of mercury over a short period;
- the slope of the increase suggests limited backmixing occurred;

- the exponential 'decay' of the mercury signal indicates a succession of remixing of layers of sediment;
- in other locations, within a radius of 50 km, mercury has only been found at higher concentrations in the most recent sediments, indicating an anthropogenic effect.

We suggest the large input of mercury found in core 1260 from Bowling Green Bay is a consequence of transport of mercury used in the amalgamation process of gold mining in the Charters Towers/Ravenswood area between 1870 and 1890. Support for this hypothesis comes from ^{210}Pb dating which suggests a date of earlier than 1900 for this region of the core, and weather reports that indicate an abnormally high rainflow in the corresponding period (Isdale 1996).

The increase in mercury concentrations observed in recent sediments in Upstart Bay and Missionary Bay are an anthropogenic effect. It is possible that the high concentrations of mercury might correlate with the increase in population of the area or increasing amounts of organomercurial fungicide used as a result of the expansion of sugar plantations. The fungicide used by the sugar industry (methoxyethylmercuric chloride, Shirtan™ or Aretan™, CH_3-O-CH_2-CH_2-Hg-Cl) was banned in Canada and USA in 1971 (Handbook of Pesticides 1975).

Levels of mercury from a low-level diffuse source such as agriculture would be expected to produce lower levels of mercury. A study in 1978 was done to ascertain if mercury was contaminating the water supply but failed to detect a significant amount of mercury in groundwater from the Burdekin region (Brodie 1978). However, rough calculations (Walker unpublished) suggest that from 1960s through to the present as much as 500 kg equivalent of metallic mercury has been added to sugar fields around the Burdekin river each year on cane setts dipped before planting. The potential for accumulation of mercury is obvious.

CONCLUSIONS

Mercury exists in sediment from the study area. Levels of mercury are generally low and typical of an unpolluted site except for a large and sharp mercury spike in core 1260 from Bowling Green Bay and a gradual rise in mercury in the most recent sediment of core 1250 from Upstart Bay and core 638 from Missionary Bay.

Further studies should address the distribution of mercury in this region. More information from analyses of other elements will aid the interpretation of the mercury results. Speciation to identify what form (or forms) the mercury exists in will be a priority.

ACKNOWLEDGMENTS

We thank the CRC Reef Research Centre for providing funds for this research; Dr Terry Done, Frank Tirendi and Steve Boyle of the Australian Institute of Marine Science for providing access to facilities for digestion and ICP–AES; Dr. Mike Ridd and Rob Cirrocco, Advanced Analytical Centre, James Cook University, for access to ICP–MS; Bill Kwiecien, Queensland University of Technology, for assistance in setting up ICP–AES; and Varian Limited, Mulgrave, Victoria, for supplying a Mercury Vapour/Liquid Separator for the VGA76.

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SESSION 2

Pressures and effects on the Great Barrier Reef lagoon

Macroalgal distributions on the Great Barrier Reef: a review of patterns and causes

Laurence McCook[1] and Ian R Price[2]
[1] Australian Institute of Marine Science, PMB No. 3, Townsville Qld 4810 and CRC Reef Research Centre, James Cook University Qld 4811
[2] Department of Tropical Plant Sciences, James Cook University Qld 4811

ABSTRACT

Despite the long recognised importance of algae on both healthy and degraded coral reefs, there has been a lack of information about algal distributions on the Great Barrier Reef. This paper reviews research on the patterns and causes of macroalgal distributions on the Great Barrier Reef, including both published studies and current research. There is little previous work on distribution patterns, but a recent series of surveys provides a background description of distribution patterns. Hard data on the causes of Great Barrier Reef algal distributions are only just emerging. Recent work includes manipulative experiments with *Sargassum*, and ecological and physiological tests of nutrient effects on a range of algae. Despite this emerging body of data, we argue that there is still a critical lack of information on the roles and significance of Great Barrier Reef algae, especially in the context of reef degradation. In particular, despite claims to the contrary, we argue that there is a lack of data on the history and causes of abundant algae on inshore fringing reefs of the Great Barrier Reef. Both the emerging picture of algal distributions and the uncertainty remaining have important implications for reef managers and stakeholders.

INTRODUCTION

Benthic algae are crucial elements of both healthy and degraded coral reef communities. They are major contributors to reef growth and development and to primary production and nitrogen fixation (reviews by Hatcher 1988, 1990; Cribb 1990). Reef degradation due to eutrophication or reduced herbivory commonly involves replacement of hard corals by macroalgae (seaweeds: Smith et al. 1981; Maragos et al. 1985; Kinsey 1988; LaPointe 1989; LaPointe and O'Connell 1989; Carpenter 1990; Hughes 1994).

Despite their importance to reef status and ecology, there is a critical lack of information on algal distributions and ecology on the Great Barrier Reef. Survey of the published literature shows that algae have received far less research effort on the Great Barrier Reef than fish or corals (McCook and Price, in press). We review here the available information on the patterns and causes of benthic algal distributions on the Great Barrier Reef, including work currently underway. We then assess the available evidence for temporal shifts in macroalgal abundance, especially on inshore fringing reefs. We argue that the baseline information needed to recognise an unnatural bloom of benthic algae on the Great Barrier Reef is only just emerging. The ability to predict, interpret and manage changes in reef biota will depend on increased understanding of patterns and causes of algal distributions.

Distribution patterns

The macroalgal flora of the Great Barrier Reef region is low in endemism, but high in diversity, reflecting the exceptional latitudinal extent of the Great Barrier Reef, the diversity of reef and substrate types and water conditions, and the consequent habitat diversity. We have estimated that there are 400–500 species of macroalgae on the Great Barrier Reef, although an accurate estimate will require much more survey and taxonomic work. There are few published accounts of algal distributions with any degree of taxonomic resolution and these are largely restricted to intertidal or shallow subtidal zones of a few, isolated islands (often research stations; review by McCook and Price, in press, table 1). This contrasts with the situation in the Caribbean, where taxonomic and composition data have been available for many years.

In order to redress the lack of adequate baseline information on algal distributions, we have surveyed 583 sites on 77 reefs in the Cairns and Central Sections, estimating abundance for around 125 taxa of macroalgae, as well as community and environmental parameters. The most detailed data are for 12 Central Section reefs, including data for 3 times of year, for two cross-shelf series of reefs, surveying 3 zones (slope, crest and flat) for each of three sites on the south-eastern side of each reef. These data will provide descriptions of large-scale variation, both across the shelf and between series (north-south), and variation between and within reefs, between zones, and critically, between seasons.

Only a brief overview of the results can be presented here. Most importantly perhaps, the surveys showed that turf algae, blue-green algae (Cyanophyta), nongeniculate crustose coralline algae and *Halimeda* were widespread and abundant (McCook et al., in press). Cross-shelf differences are dramatic quantitatively but not simple or easy to define in terms of individual species. The brown algae (Phaeophyta) are more diverse and abundant (especially *Sargassum*) inshore whereas the flora of offshore reefs is dominated by green algae (Chlorophyta, especially *Caulerpa*, *Chlorodesmis* and *Halimeda*) and red algae (Rhodophyta, especially crustose corallines). However, red algae are also common inshore and some brown algae also occur offshore. The cross-shelf patterns are also confounded by within-reef zonation, latitudinal and other large-scale variations and occasional distributional outliers (such as individuals of *Sargassum* or *Padina* on outer-shelf reef fronts). On offshore reefs, contrary to the widespread perception, fleshy seaweeds, especially red algae, are commonly dominant on reef flats, and surprisingly common and diverse on reef fronts. Moreover, inshore reefs with abundant *Sargassum* and turbid water may also have high cover of healthy hermatypic corals, again in contrast to widespread perception.

There are strong seasonal changes in composition and abundance of algal vegetation, in contrast to dominant benthic fauna such as corals. Not only is *Sargassum* highly seasonal in abundance on inshore reefs, but on mid- and outer-shelf reef flats, the abundance of blue-green algae, red algae such as *Spyridia filamentosa, Laurencia* spp., *Galaxaura* spp. and *Liagora* spp., and green algae such as *Boodlea* spp., also varied greatly with season.

By distinguishing between macroalgal abundances and taxa expected in different reef areas at different seasons, multivariate analyses of these data should allow classification of reefs based on algal composition. The only other large-scale data on reef algal distributions and abundance comes from long-term monitoring studies (LTM) (e.g. Oliver et al. 1995), but these data have little taxonomic resolution (McCook and Price, in press). There is potential to use our survey descriptions to significantly enhance the power of the LTM surveys to detect and interpret changes in algal abundances. For example, if low resolution LTM surveys indicated increased algal abundance on an offshore reef, a simple sampling procedure could allow comparison with expected compositions for different reef types, based on our surveys.

Large-scale descriptions of inter-reefal flora are also emerging from recent surveys of vegetation in deep water, soft-bottom areas of the northern Great Barrier Reef, using towed video cameras (R. Coles and W. Lee Long, QDPI Cairns, pers. comm.). Although these surveys show that rhizoid-anchored macroalgae are very abundant in these areas, the surveys focus on seagrasses and currently lack the resources to quantify macroalgae with any degree of taxonomic resolution (Coles and Lee Long, pers. comm.).

The surveys described above can only provide preliminary descriptions of algal distributions on the Great Barrier Reef, given limitations on spatial and seasonal coverage, and especially given limitations on field identification of algae. We have summarised the resources available for identifying Great Barrier Reef algae (McCook and Price, in press, table 2), and noted a critical lack of both expert taxonomic floras and field identification guides. The lack of field identification guides has been ameliorated with the recent publication of a naturalists guide to seaweeds of Queensland (Cribb 1996). However, this work is not comprehensive, and does not allow unequivocal identifications. Although Phillips and Price (in review) have recently completed a critical compilation of the brown algal species recorded for Queensland, there remain no comprehensive taxonomic treatments for the brown, green and blue green algae, for non-turfing species or for the central and northern regions of the Great Barrier Reef.

Causes of macroalgal distributions

There is also little published information on the processes which determine the patterns of algal distribution on the Great Barrier Reef, at any scales, although there are a number of relevant studies currently underway. Factors which influence the distribution of marine species, especially of algae, include resource availability (e.g. nutrients, light, substrate); stress gradients and disturbance regimes (e.g. wave exposure, temperature, emergence, cyclones, freshwater); recruitment and dispersal; and species interactions, including competition and herbivory (e.g. Underwood and Denley 1984; Chapman 1986). Table 1 summarises publications and studies underway which address the roles of these different factors. Attention has focused on possible effects of water quality (primarily sediments and the nutrients nitrogen and phosphorus) and herbivory, since work in other reef areas has demonstrated that increases in sediment or nutrient inputs or reductions in herbivory can lead to shifts from coral to algal dominance (references in Introduction).

On the Great Barrier Reef, recruitment, productivity and abundance of algal turfs (as 'epilithic algal community') have been shown to depend strongly on herbivory (Hatcher and Larkum 1983; Sammarco 1983; Wilkinson and Sammarco 1983; Scott and Russ 1987; Klumpp and McKinnon 1989, 1992) and to some degree on nutrients (Hatcher and Larkum 1983; Russ, unpubl. data). Of these studies, only Russ's work addresses the causes of large-scale distributions, suggesting roles for both herbivory (Scott and Russ 1987) and water quality (unpubl. data) in the cross-shelf differences in turf algal vegetation. Other work has focused on chemical mediation of competition (de Nys et al. 1991) and herbivory (Steinberg et al. 1991).

More recently, several studies have indicated that herbivory has a stronger direct impact on the distribution of larger macroalgae than does water quality. Transplant experiments demonstrate that fish herbivory significantly reduces the survival of *Sargassum* both on offshore reefs and on inshore reef slopes, whereas differences in water quality had no direct effect on survival or on tissue nutrient levels. It appears that the absence of *Sargassum* on most mid-shelf reefs and on many inshore reef slopes is due to an interaction between herbivory and low dispersal, and not due to any nutrient limitations (McCook 1996, in press). Several other experiments have addressed the direct impacts of sediments or nutrients on *Sargassum*. Manipulation of sediments on a fringing reef showed that *Sargassum* was directly inhibited by sediment deposition, despite being generally more abundant on reefs with greater sediment loads (Umar et al., unpubl. data). Preliminary experiments in large aquaria suggested that *Sargassum* growth and recruitment were directly inhibited by long-term, high level nutrient enhancement, perhaps due to overgrowth by epiphytes (McCook et al., in press). However, more detailed experiments show *Sargassum* growth in isolation to be stimulated by moderate nutrient enhancement but inhibited at higher levels. Importantly, *Sargassum* shows rapid uptake and growth in response to pulsed delivery of nutrients. This could allow the alga to grow in areas which experience only brief periods of high nutrient supply, such as resuspension during storms (Schaffelke and Klumpp, in press; similarly Russ, unpubl. data, for turfs).

Nutrient effects on reef biota have also been recently examined in the collaborative ENCORE experiment, which used a factorial combination of nitrogen and phosphorus supplements in small microatolls at One Tree Island. Neither algal turfs nor coralline algal rhodoliths showed strong direct effects of enhanced nutrient input (Larkum et al., in press; Larkum and Koop, in press). Dennison et al. (unpubl. data) used the ENCORE experiment to compare (^{15}N) ammonium uptake among various macroalgal and coral species. Interestingly, uptake rates were highest in the red alga *Laurencia intricata*, which has very wide cross-shelf distribution patterns (e.g. McCook and Price, unpubl. data).

It is important to note that the available data form a very incomplete picture, and by no means preclude effects of nutrients or sediments on algal distributions. Direct nutrient effects are likely to be complex and species-specific and to depend on period and intensity of enhancement, epiphyte growth etc. Water quality is also likely to have major indirect effects on algal distributions, perhaps by affecting herbivorous fish abundances or substrate availability through coral mortality. Further, interactions between different factors are likely. By trapping sediments, algae may render a site less suitable for coral recruitment. Finally, several studies have shown that chronically stressed reefs may show little degradation due to eutrophication or herbivore depletion until damaged by natural disturbances, such as storms or freshwater floods (e.g. Hughes 1994; Kinsey 1988). The critical impact of the chronic stress may be in preventing recovery from natural disturbance, allowing algae to persist and inhibiting coral recovery. Thus natural disturbance which normally leads to a successional sequence from algae to coral may be blocked, resulting in a long-term phase shift and degradation.

Table 1. Summary of ecological research, published or underway, relevant to the causes of macroalgal distributions on the Great Barrier Reef. Descriptions of work currently under way is based on information requested from the various authors ('in prep.' November 1996; black dots indicate study directly addresses the factor; asterisks indicate study has related information). Data on distribution patterns or taxonomy are not included, but are tabulated in McCook and Price (in press).

Author	Scale and/or Area	Approach or Technique	Taxa	Herbivory	Nutrients	Sediments	Recruitment/ Dispersal	Competition
Scott and Russ 1987	Cross-shelf	Settlement plates and cages	Algae esp. turfs	•	*	*	•	
McCook et al., in press, unpubl.	Cross-shelf - >between zones, seasons	Surveys; correlations; chemistry	Algae	*	*	*	*	
McCook and Price, in prep.	Among fringing reefs; 50 km	Settlement plates	Algae				•	
Russ, in prep.	Cross-shelf	Settlement plates, cages, cyclone	Algae esp. turfs	•	*	*	•	
Coles and Lee Long, in prep.	Large scale: 100s km, deep water inter-reefal	Towed video surveys	Soft-bottom taxa (Chlorophyta)		*	*		
Elmetri and Bell in prog.	Cross-shelf; Laboratory	Correlations with growth rates, phosphatase	Macroalgae		•			
Hatcher and Larkum 1983	Offshore reef µatolls	Cages and nutrient enhancements	Turfs	•	•			
Sammarco 1983, Wilkinson and Sammarco 1983	Damselfish territories	Settlement plates, cages, nitrogen fixation measurements	Turfs, Cyanophyta	•	*		*	
Klumpp and McKinnon 1989, 1992 etc.	Within mid-shelf zones, damselfish territories	Trophodynamics	Turfs etc	*	•			
Larkum and Koop, in press	Offshore reef µatolls	Nutrient manipulation: ENCORE	Turfs		•		*	
Purcell, in prep.	Within mid-shelf reef	Correlations	Turfs	*		•		
Fugelli and Johnson in prog.	Offshore reefs	Nutrient manipulation, surveys, physiological ecology	Turfs	•	•		•	*
Steinberg et al. 1991	Cross-shelf	Transplants; Chemistry	Sargassum; other browns	•				

Author	Scale and/or Area	Approach or Technique	Taxa	Herbivory	Nutrients	Sediments	Recruitment/ Dispersal	Competition
McCook 1996	Cross-shelf; 50 km	Cages; transplants	Sargassum	•	*	*		
McCook et al., in press	Aquaria	Nutrient manipulations	Sargassum; Padina		•		•	
Schaffelke and Klumpp, in press, in prep.	Culture, aquaria, fringing reef flats	Nutrient manipulations; physiological ecology	Sargassum		•			
McCook, in press	Within fringing reefs; 50 m	Cages; transplants	Sargassum	•	*	*	•	
Umar et al., in prep.	Fringing reef flats	Sediment manipulations	Sargassum			•	•	
McCook in prog.	Among and within fringing reefs	Canopy removal	Sargassum / other benthos				•	•
Drew 1983	Cross-shelf	Physiological ecology	Halimeda	*	*			
Wolanski et al. 1988	Offshore reefs, medium scale	Oceanography, correlation	Halimeda		*			
de Nys et al. 1991	Fringing reefs, small scale	Chemistry, transplants	Plocamnium (Rhodophyta)					•
Costanzo and Dennison, in prep.	Inshore, Whitsundays, Moreton Bay	Physiological ecology	Gracilaria (Rhodophyta)		•			
Dennison, Drew and Stewart, in prep.	Offshore,	Nutrient manipulations	Laurencia (Rhodophyta)		•			
Chisholm 1988	Within mid-shelf reef	Physiology	Crust. corallines (non geniculate)					*
Larkum et al., in press	Offshore reef µatolls	Nutrient manipulation: ENCORE	Crust. corallines (non geniculate)		•			
Ringeltaube and Johnson, in prep.	Within Heron Reef	Surveys, settlement plates, grazer and algal removals, transplants, shading	Crust. corallines (non geniculate)	•			•	•

Long-term changes in abundance of macroalgae on inshore reefs: what is the evidence?

The abundance and composition of macroalgal vegetation on inshore reefs has been suggested as a symptom of widespread decline of those reefs (e.g. Endean 1976; Bell and Elmetri 1995), apparently in response to large increases in anthropogenic inputs of sediments and nutrients (Moss et al. 1992; Pulseford 1991; Brodie 1995). However, given the proximity of these reefs to natural terrestrial inputs, it is likely that they always had different flora from the offshore reefs. We here review the evidence for and against recent increases or shifts in status of inshore reefs, with emphasis on the macroalgae. Evidence either for or against widespread shifts in reef biota is very limited and equivocal. As there is even less data specifically for macroalgae, we conclude that there is no clear indication whether the abundance of algae on fringing reefs is natural or anthropogenic.

The Great Barrier Reef Expedition of 1928–29 collected quantitative transect data, photographs and descriptions of reef flats at Low Islets, including the only detailed survey of algal composition prior to 1960 (Stephenson et al. 1931; McCook and Price, in press). Resurvey of these sites led Bell and colleagues to suggest a long-term decline in coral cover, with a concomitant increase in macroalgae and other non-reef builders (e.g. Bell and Elmetri 1995). However, these data refer to only a limited area on a single reef flat, and provide no indication of intervening dynamics. Photographs of other reef flat areas at Low Islets indicate that at least part of these reefs are in good condition (Wachenfeld, in press). Even where changes in coral cover have occurred, assessment of algal changes awaits detailed resurvey of algal composition (currently under way by J. Phillips, Univ. Qld, pers. comm.).

Historical descriptions and photographs of Green Island, Dunk Island, Magnetic Island, and reefs in the Whitsunday region, as well as Low Islets, led to suggestions of widespread declines in inshore reefs over the last 50 to 100 years (Endean 1976; Bell and Elmetri 1995). However, photographic comparisons by Wachenfeld (in press) of 14 reefs, including Green Island, Magnetic Island, and the Whitsunday Islands suggest that such declines are not prevalent. These photographic comparisons are problematic, as they do not necessarily represent general dynamics (Wachenfeld, in press). Although more reliable quantitative data are available for the last two decades, their significance is also equivocal. At Brampton Island, comparison of data from 1986 (Van Woesik 1992) and 1995 (Burns et al. 1995), along with anecdotal reports from resort staff, suggest a decline in coral cover and increased abundance of algae such as *Sargassum*. Similarly, environmental assessments at Magnetic Island from 1989–1995 suggest an increase in macroalgae, although these results are confounded by differences in sites, seasons and survey techniques (Sinclair Knight Merz 1995). On Pandora Reef, near Townsville, Done (in press) found that although macroalgae dominated in 1980, corals have actually displaced *Sargassum* over the following 15 years. Ayling (in press) presented quantitative data for changes in cover for 7 fringing reefs from Cape Flattery to the Keppel Islands for 4 to 10 years. Although reef flats were typically dominated by macroalgae, with low coral cover, he recorded high (> 50%) coral cover on reef slopes, with no evidence of decreases, even at Magnetic Island between 1989 and 1993 (cf. Sinclair Knight Merz 1995).

Detection and interpretation of widespread and long-term changes in algal composition are limited not only by the paucity of quantitative data, but also by several confounding factors. Comparisons of single before and after points on a time series give no indication of intervening dynamics, and may give false impressions of long-term change or lack of changes (e.g. Underwood 1991). Shifts from coral to algal abundance may be a natural phase of reef dynamics, in which damage to corals results in temporary dominance by macroalgae, followed by recovery of corals. If reef degradation involves failure to recover after disturbances, then widespread decline in response to anthropogenic factors may be expressed piecemeal, and so be difficult to detect and interpret. Further, it cannot be assumed that evidence of decreases in coral cover necessarily means increased macroalgal cover. Cover of corals and *Sargassum* are not simply negatively correlated on fringing reef flats (McCook, unpubl. data).

Finally, evidence that reef biota are currently stable in the short-term does not preclude past (or future) shifts. Terrestrial inputs have probably increased throughout the last hundred years (Pulseford 1991), and there is very little information on the rates of terrestrial input likely to cause changes at different reef sites. Thus, shifts could conceivably have occurred and stabilized long before most of the data reviewed above were collected. We conclude that, in the absence of high quality historical ('pre-impact') surveys of sufficient coverage, definitive description of 'natural' inshore algal flora is not possible.

Implications for reef science, management and development

Even this brief review of the available information on Great Barrier Reef algal distributions has a number of significant implications for reef scientists, managers and tourist operators. Given the importance of macroalgae on both healthy and degraded reefs, it is imperative that we improve our ability to distinguish between the two states.

The description of algal species distributions and abundances emerging from our surveys (McCook et al., in press) should allow the identification of an multivariate, inshore species 'suite'. Whether the composition of inshore algal vegetation is anthropogenic or natural, the appearance of similar vegetation on offshore reefs would most likely represent degradation. The surveys show that individual species distributions are not simple or clearcut, suggesting that individual species would be poor indicators of reef status. In contrast, an 'inshore species suite' or region of multivariate space, based on quantitative abundance of a wide range of taxa at a range of seasons, should provide a much more robust measure of reef status. Although such surveys require some expertise in field identification of algae, they are relatively fast and technically simple, and so should be feasible and cost-effective as management tools. Since algal vegetation may change more rapidly than corals, algal surveys may allow more rapid detection of changes in benthos.

Although knowledge of the detailed causes of algal distributions remain far from complete, the emerging results have several significant implications. The importance of herbivory is consistent with results from other reef regions and highlights the importance of protecting herbivorous fish populations on all reefs (e.g. Hughes 1994; McCook 1996). The management implications are less clearcut for the lack of nutrient effects in the field, especially given the strong effects in physiological studies. The ability of *Sargassum* to obtain sufficient nutrients on offshore reefs indicates that nutrient levels on offshore reefs are already sufficiently elevated, naturally or anthropogenically, for *Sargassum* growth. If natural, this might imply that nutrient effects on algal distributions are not a management concern. If offshore nutrient levels are anthropogenic, macroalgal invasion of offshore reefs may be an imminent possibility, perhaps in response to disturbances or declines in coral or herbivore populations.

Similarly, although the emerging picture suggests that large fleshy algae such as *Sargassum* may rarely invade reefs without prior disturbance to corals, we still have little information on the impact and community dynamics of macroalgal beds once established. Even where macroalgal abundance is not the direct cause, but the consequence of coral decline, we need more information on the factors which may lead to stable maintenance of algal dominance, or to the successional re-establishment of abundant corals.

Probably most critical to reef management is the still considerable lack of knowledge about Great Barrier Reef algal distributions. Whilst work is underway in a number of significant areas, there are still many issues which are not being addressed. This lack of information is compounded by the complexity of spatial and temporal patterns and scales, taxonomic diversity and uncertainty, and the likelihood of indirect effects and of interactions between natural and anthropogenic factors. It is likely that simple, definitive answers are not feasible for some issues (e.g. identifying natural algal flora for inshore reefs). Definitive interpretation of patterns of algal distribution as natural or anthropogenic is thus difficult and unwise, and easily discredited. Rather, an approach which attempts to assess the risks and consequences, of different interpretations and management responses, should provide a better direction for science, management and publicity. Given the increasing reports of abundant macroalgae on degraded reefs world-wide, the lack of strong evidence for degradation does not justify assuming that reefs are pristine.

ACKNOWLEDGMENTS

We would like to thank the various researchers who provided details of their research for inclusion in table 1. We are grateful to T. Done, M. Price and B. Schaffelke for discussion and comments on the manuscript. This is AIMS publication number 855, produced with the support of the CRC Reef Research Centre.

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SESSION 3

Pressures on reefs, islands and cays

Reef-top hydrodynamics at Heron Island

MR Gourlay and Jennifer LF Hacker
Department of Civil Engineering, The University of Queensland Qld 4072

ABSTRACT

Reef-top hydrodynamics at Heron Island are dependent on tide, wind and wave conditions. During tropical cyclone Rewa, in January 1994, some concrete blocks, weighing 1.2 tonnes, were moved up to 12 m towards the boat harbour by current and wave action on the reef-top. Reef-top sediments were also deposited in the boat harbour during this event.

Instruments were installed in March 1996 to measure wave and current conditions causing sediment loss from the island and reef-flat into the boat harbour and thence off the reef. Two wave-rider buoys have been deployed, one to the north of Heron Reef and one to the south, at the entrance to Wistari Channel. Two automatic current recorders and two wave staffs have been installed on the reef-flat. The Bureau of Meteorology operates an automatic weather station at Heron Island.

Increased wind and wave conditions result in wind- and wave-setup on the reef-top, particularly during low tides. This setup, or increase in water level, can completely change the pattern of reef-top currents around Heron Island. During relatively calm conditions the reef-top currents oscillate with tidal conditions, but when there are conditions of strong winds and/or large offreef waves, these tidal reversals may be completely suppressed, resulting in strong currents directed towards the boat harbour for the full tidal cycle.

INTRODUCTION

Heron Island, in the Capricorn group of reefs, is located approximately 80 km east-north-east of Gladstone at the western end of a large lagoonal platform reef (figure 1). A well-patronised tourist resort and university research station are located on the island. In order to facilitate access, a boat harbour has been constructed at the western end of the reef. A gap through the reef-rim was blasted in 1947 and the boat harbour was first dredged in 1967, followed by further enlargement in 1987 (Gourlay and Jell 1993).

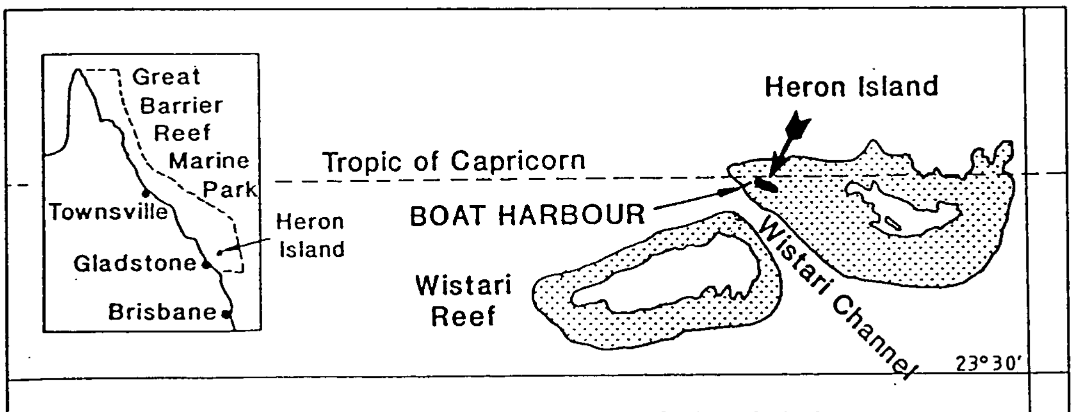

Figure 1. Location of Heron Island and boat harbour

Reef-top hydrodynamics are dependent on tide, wind and wave conditions. During conditions when there is little wind and offreef waves are small, currents on the reef-top are entirely controlled by the rise and fall of the tide. The maximum tidal range at Heron Island is 3.3 m. On the other hand, wind and/or wave setup are generated on the reef-top at times when it is windy and/or there are large offreef waves (Gourlay 1993). The presence of the boat harbour has a marked effect on reef-top current directions at Heron Island.

The reef-rim at Heron Reef is slightly higher than the rest of the reef-top, as is the case with most reefs. Therefore, the construction of a boat harbour through the reef-rim caused water to drain off the reef-top through the harbour entrance channel at low tide resulting in a changed pattern of reef-top currents at the western end of the reef and flow into the harbour for the greater part of the tidal cycle. This flow has resulted in the deposition of sediments in the harbour and entrance channel. Sediments which are deposited in the boat harbour cannot be moved back up onto the reef-top and the presence of the boat harbour leads to the progressive depletion of sand from the island and the reef-top. Low bund walls formed from concrete blocks were constructed on either side of the boat harbour in 1993–1994 to restore reef-top water levels to their former levels.

Sediments have been deposited in the boat harbour during the strong wind and wave action accompanying tropical cyclones. For example, in January 1994, during tropical cyclone Rewa, approximately 250 m^3 of sediment was deposited in the north-eastern corner of the harbour. Additionally, approximately 30 concrete blocks, each measuring 1.2 x 0.6 x 0.6 m and weighing 1.1–1.2 tonnes were moved across the reef-top towards the harbour. Some blocks were moved as much as 12 m (Gourlay 1995).

METHODS AND MEASUREMENTS

The following instruments were installed in March 1996 to measure wave and current conditions (figure 2).

- **Wave rider buoys.** Two wave rider buoys have been deployed close to Heron Reef. One is located to the north of the reef and the other at the south-eastern entrance to Wistari Channel. The wave rider buoys measure wave height and wave period for 25 minutes every hour and transmit the data to an onshore computer.

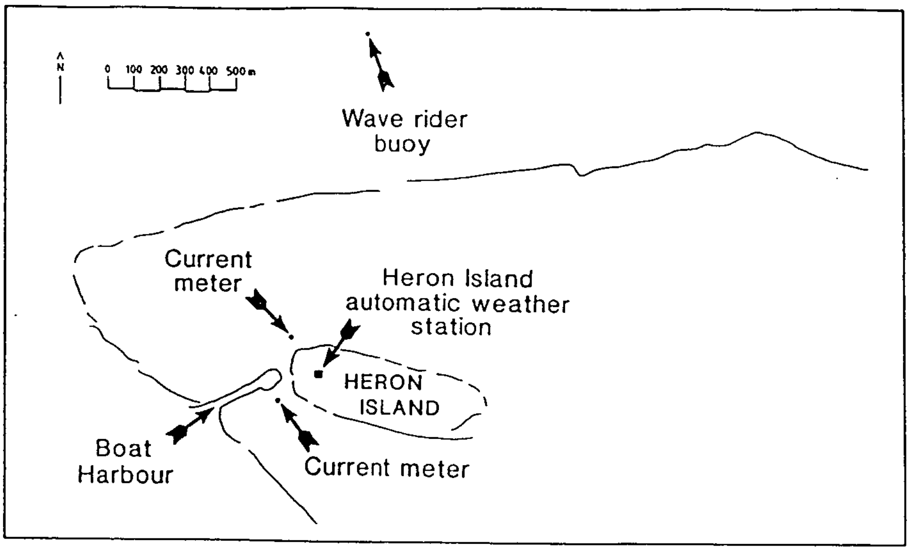

Figure 2. Heron Reef, location of northern wave rider buoy and current meters

- **Current meters.** Two S4 current meters have been installed on the reef-top, in the vicinity of the boat harbour (figure 2). They measure current speed and direction and water depth every 10 minutes. Occasionally, at low tide, the water level falls below their sensors. Data is stored within the instrument and requires downloading every six weeks.

- **Wave staffs.** Two wave staffs have also been installed on the reef-top to measure wave heights on the reef-top, but there have been problems and only a small amount of data has been collected.

There is an automatic weather station on Heron Island operated by the Bureau of Meteorology. Hourly data including wind speed and direction have been made available.

RESULTS

Time series of data have been acquired on a continuous basis from the wave rider buoys and the current meters since their deployment in March 1996. The resultant data set is large and preliminary results only are presented. Two cases are considered:

Case 1. In the first case, on 29 June 1996, the weather was fine, winds were light, varying between 1 and 4.5 m/s, south-easterly until noon, then veering north-easterly to northwesterly later in the day. The offreef wave heights were small, less than 0.3 m.

The resultant pattern of currents measured at the northern current meter demonstrates a series of current reversals which are dependent on the state of the tide (figure 3). For simplicity the tidal cycle has been divided into four intervals, labelled A, B, C and D which correspond to the diagrams beneath.

During interval A, the tide is coming in through the boat harbour, the tide level is rising (top graph) and the currents are flowing away from the boat harbour, that is north-eastwards for the northern meter and south-eastwards for the southern meter (lowest graph and diagram A). This continues until approximately half-tide level is reached (1.5 m) when the current at the northern current meter reverses to flow southwestwards towards the boat harbour as the incoming tide comes in over the whole reef-rim (Interval B). When the tide turns, the current again reverses at the northern meter and again flows in a north-eastwards direction out over the reef-rim (Interval C). Then, when half-tide is reached again, the currents at both locations reverse and are directed towards the boat harbour (Interval D). The current is strongest (0.35 m/s) at the northern meter during interval D.

Case 2. The second case occurred during the period 25 to 29 July 1996, when there was a strong wind warning current for most of the period. Large waves, significant wave height, Hsig,[1] rising to 3 m, were measured at the northern wave rider buoy on 27 and 28 July (figure 4, graph (d)). At the same time, there were fresh to strong breezes (near gale at times), initially north-easterly on 27 July and veering northwesterly on 28 July (figure 4, graphs (e) and (f)). These wind and wave conditions caused total suppression of the 'normal' tidal reversals at the northern current meter on 27 and 28 July and partial suppression for much of the rest of the period (figure 4, graph (c)). During the time when the current reversals were suppressed, a stronger than normal current, up to 0.7 m/s, was measured and this flowed in a southwestwards direction, towards the boat harbour (figure 4, graphs (b) and (c)). Currents of this magnitude should be capable of transporting sediment of up to coarse sand size across the reef-top. N.B. Wind directions are the directions **from** which the wind blows, whereas current directions are those **towards** which the current flows.

The tide level curve for the period 25 to 29 July 1996, graph (a), records that tide levels on the reef-top were higher than normal during this event. On 27 July 1996, the tide level did not fall below 1.0 m LWD, whereas on 25 and 29 July 1996, it did fall below this value. This shows that there was wave- and wind-setup on the reef-top of at least 0.1 m on 27 July 1996.

CONCLUSIONS

Currents measured on Heron Reef in the vicinity of the boat harbour exhibit an intricate pattern of reversals when controlled by the tide alone. At the northern current meter, there are four reversals during one tidal cycle. Under conditions of strong winds and large offreef waves, this 'normal' current reversal pattern is suppressed and currents on the windward side of the island are directed towards the boat harbour for the duration of the event.

This preferred current direction at such times is capable of transporting reef-top sediments into the boat harbour, causing depletion of sediment reserves and erosion of Heron Island.

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[1] Significant wave height is defined as average of highest _ of zero up-crossing wave heights in a given record. This is the standard statistical representation of wave height used by coastal engineers.

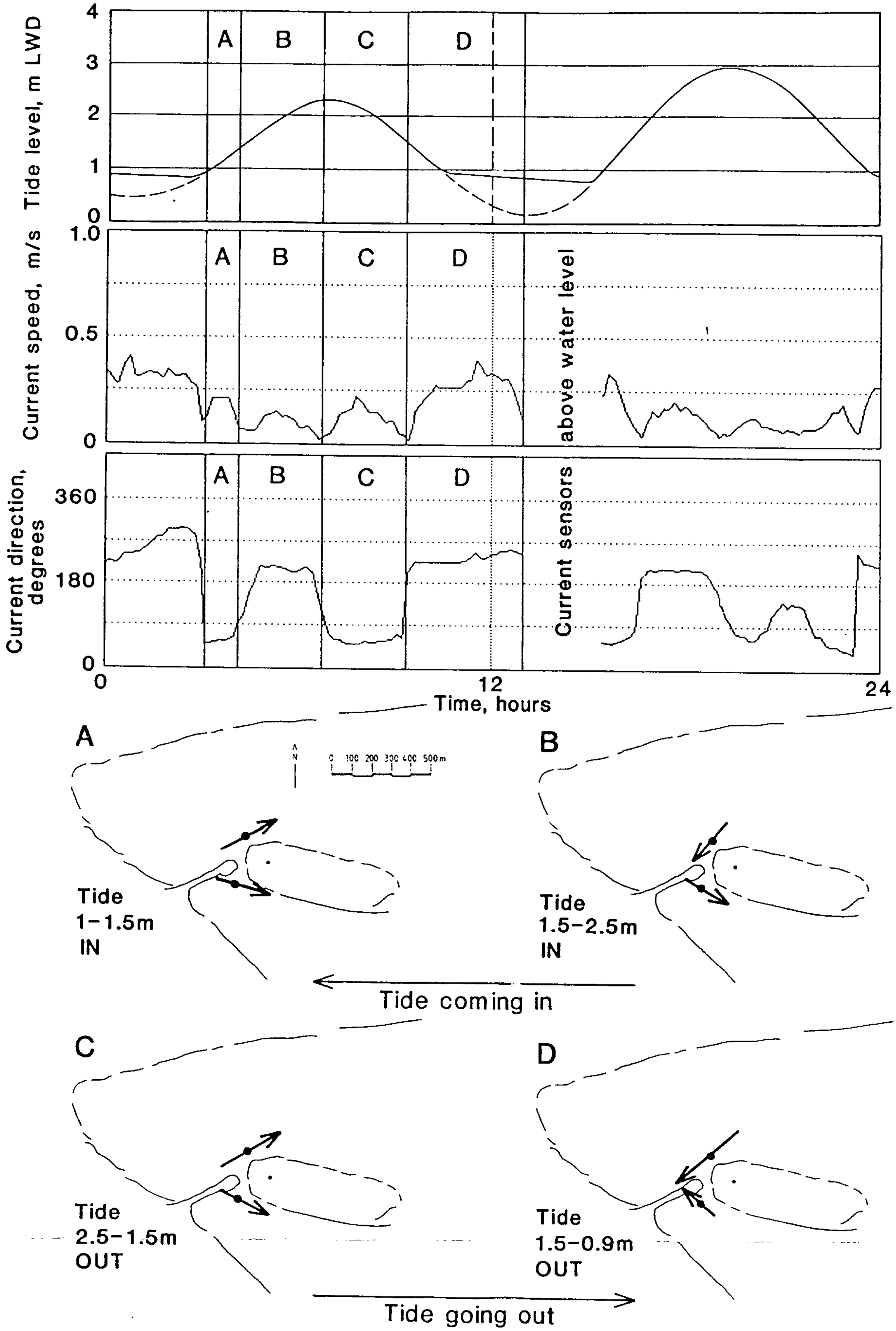

Figure 3. Tide levels and reef-top currents, speed and direction, on 29 June 1996. Graphs are for the northern current meter, courtesy of Beach Protection Authority, Queensland.

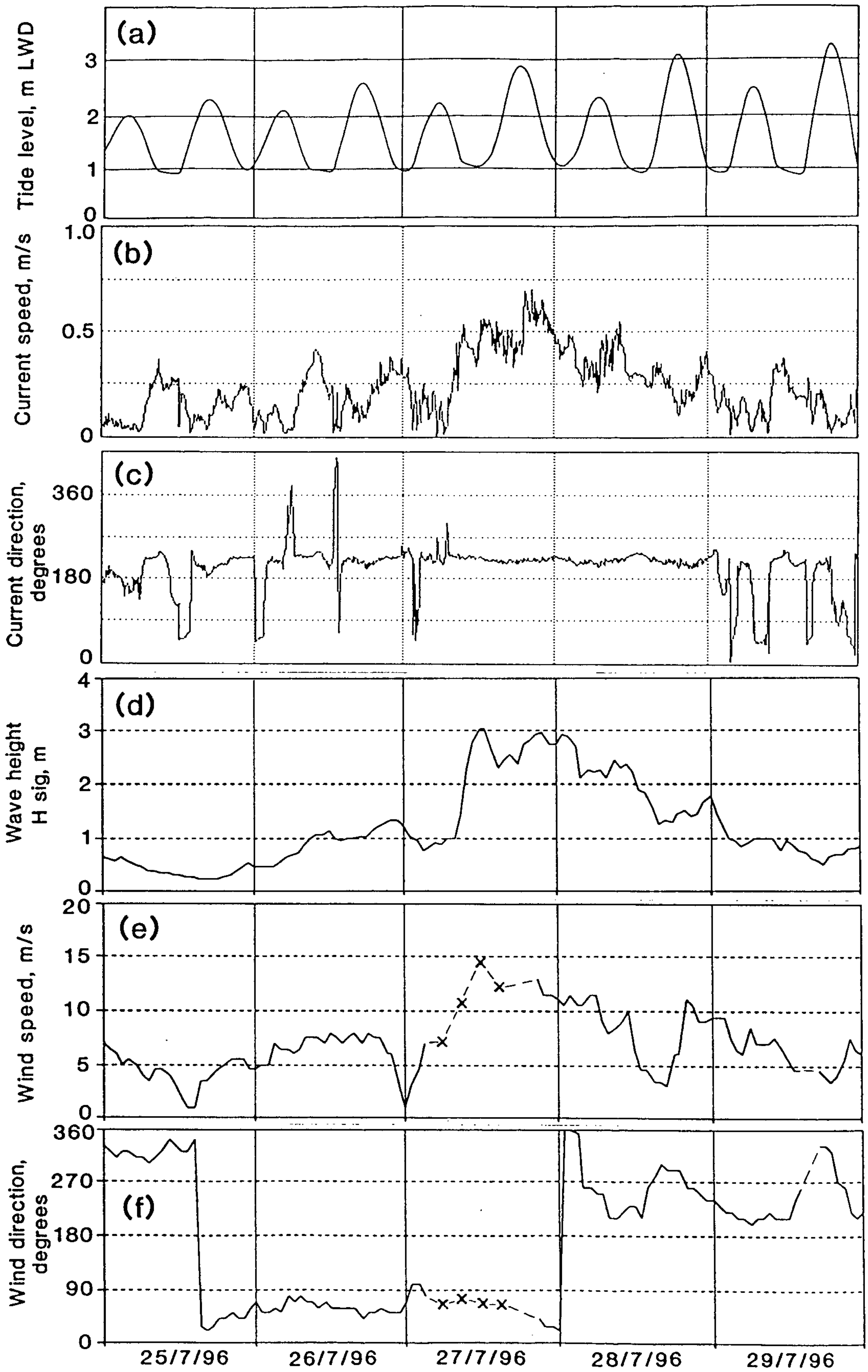

Figure 4. Tide levels, reef-top currents, speed and direction, wave height and wind speed and direction for 25 to 29 July, 1996. Tide level, current and wave rider buoy data, courtesy of Beach Protection Authority, Queensland; wind data, courtesy of Bureau of Meteorology.

ACKNOWLEDGMENTS

This project is being undertaken as part of a monitoring project (funded by the Great Barrier Reef Marine Park Authority) for the Heron Island Boat Harbour. Instrumentation has been provided and serviced by the Queensland Department of Environment (Beach Protection Authority and Queensland Government Hydraulics Laboratory) and the CRC Reef Research Centre at James Cook University of North Queensland. Significant assistance, including 'in kind' support for transport and accommodation, has been provided by P&O Heron Island Resort, Heron Island Research Station and the Queensland Department of Environment. The Bureau of Meteorology, Brisbane Regional Office, supplied the meteorological data. Peter McMillan, Department of Civil Engineering, The University of Queensland, has provided technical and logistical support. Reg Stonard assisted with figure preparation. The authors acknowledge that none of this work would have been possible without this assistance.

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Harbour bund wall construction at Heron Island: coral response

Jennifer LF Hacker and MR Gourlay
Department of Civil Engineering, The University of Queensland Qld 4072

ABSTRACT

The boat harbour at Heron Island was originally constructed in 1967 and enlarged in 1987. Consequent drainage off the reef through the harbour entrance channel during periods of low tide levels reduced the water-level on the reef-flat in the vicinity of the boat harbour.

Between October 1993 and February 1994, low bund walls were constructed of concrete blocks along both sides of the boat harbour to raise the water level on the reef-flat during low tides and to inhibit sediment flow into the harbour. Water levels on the reef-flat during low tides were measured before, during and after construction. Measurements of coral growth in response to raised water levels near the boat harbour have also been made.

Water levels on the reef-top are affected by ambient wind and wave conditions as well as tides. The presence of the bund walls raised the water level on the southern side of the harbour by up to 0.12 m and on the northern side by up to 0.14 m. As a result of this rise in water-level, the reef-top coral species have shown prolific vertical growth, with some *Acropora* colonies growing by 145 mm in the two years following bund wall construction. Vertical growth is also evident in the slower growing *Porites* species. Some changes in species dominance have been noted in two belt transects, one on either side of the harbour.

INTRODUCTION

Heron Island, in the Capricorn group of reefs, is located approximately 80 km east-north-east of Gladstone (figure 1). A boat harbour has been constructed at the western end of Heron Island to facilitate access. A gap in the reef rim was blasted in 1945 and the boat harbour was first dredged in 1967, followed by further enlargement in 1987 (Gourlay and Jell 1993).

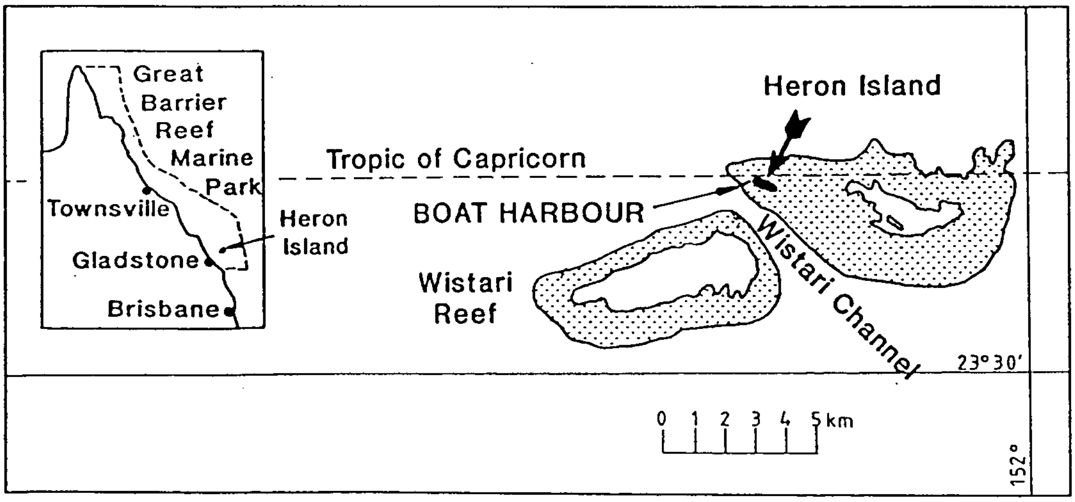

Figure 1. Location of Heron Island and Heron and Wistari Reefs showing location of boat harbour

In common with most platform reefs, the reef-rim at Heron Reef is slightly higher than the rest of the reef-top. Consequently the construction of a boat harbour through the reef-rim allowed water to drain off the reef through the harbour entrance channel at low tide. This had two important adverse effects.

- It reduced the water-level on the reef-top during low tide which had a deleterious effect on much of the reef-top biota.
- It changed the pattern of reef-top currents, causing them to flow into the harbour for the greater part of the tidal cycle. This resulted in deposition of sediments in the harbour and entrance channel.

In order to address these adverse effects, the harbour bund walls were constructed between October 1993 and February 1994. The bund walls are low concrete block walls, one either side of the boat harbour (figure 2). The walls are formed of 1.2 tonne interlocking concrete blocks 1.2 x 0.6 x 0.6 m, set in concrete. The elevation of the upper surface of the blocks is 0.86 m above Heron Island Low Water Datum (LWD) which is approximately the original low-tide water level on the reef-top prior to bund wall construction.

MEASUREMENT METHODS

Tide levels were measured in the boat harbour and at six locations on the reef-flat, three on either side of the harbour (Sites TW 1–6, figure 2). The level of the tide was measured in 50 mm diameter polycarbonate wells installed on the reef-top. This level was determined relative to Heron Island Low Water Datum (LWD) using an automatic level. Tide levels were measured in September 1993, before bund wall construction; in April 1994, after bund wall construction and again in June 1996, two years after construction.

Measurements of coral response following the raising of the low tide water level caused by bund wall construction included the following.

- Measurement, in 1996, of the amount of vertical growth above the previous, pre -1994, limit of growth of *Acropora* spp. colonies along a 500 m transect north of the harbour (sites TW 4 to wave staff, figure 2). These levels were also related to Heron Island Low Water Datum.
- Measurements, at four monthly intervals, of the elongation of three branchlets in three *Acropora* spp. colonies, one south of the harbour (site TW 2), the other two north of the harbour (sites TW 4 and 5). Branchlets were initially tagged in July 1994.
- Measurements, at yearly intervals, of growth, including both height and areal extent, of three complex *Porites* sp. colonies south of the harbour (figure 2). Initially, heights were measured relative to microatoll level, but subsequently, levels were taken by direct measurement using an automatic level.
- Visual assessment of coral cover on the reef-top within 200 m of the boat harbour from aerial photographs taken on 14 October 1993, 29 January 1994, 25 April 1994, 20 December 1994, 17 November 1995 and 3 April 1996.
- Measurement, at yearly intervals, of two belt transects, one either side of the boat harbour (figure 2). Numbers and size of colonies of the seven dominant species and other organism types were recorded (*Acropora* spp., *Porites* spp., *Montipora digitata*[2], *Goniastrea retiformis*[1], *Chlorodesmis* spp., *Tridacna* spp. (Mollusca) and Holothuriidae (Echinodermata)). Both transects were one metre wide, the northern one was 20 m long and the southern 25 m long.

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[1] Coral identification, R Berkelmans, GBRMPA

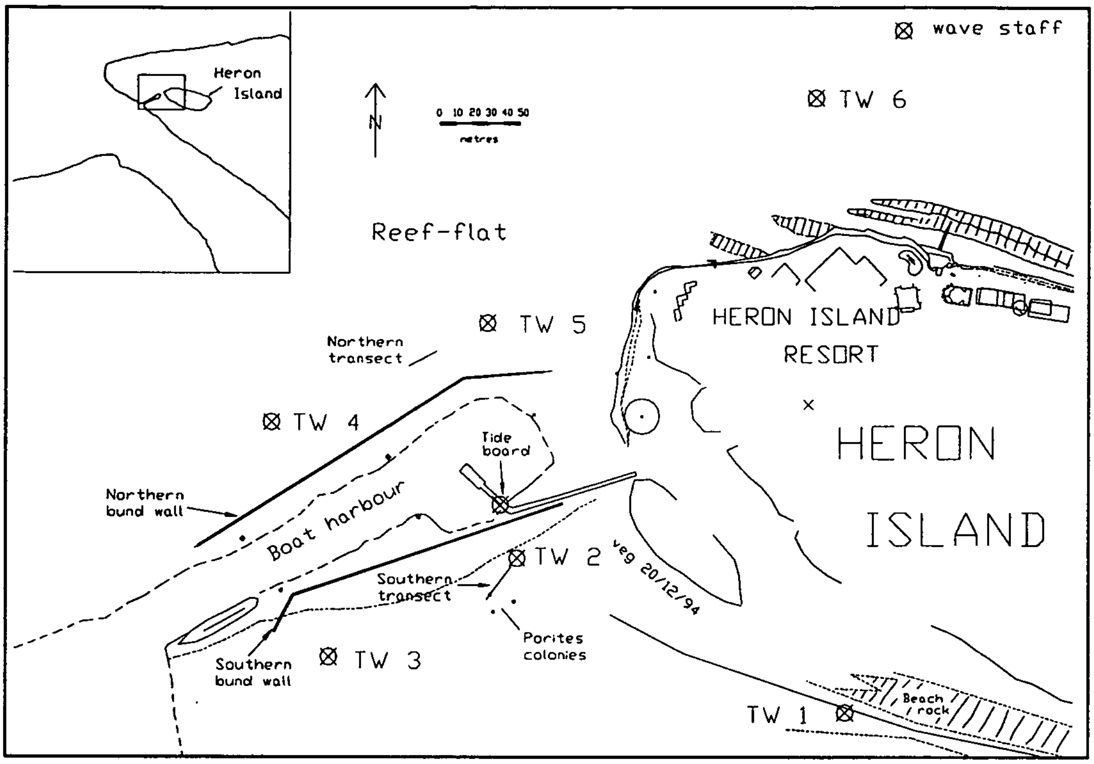

Figure 2. Heron Island – western end, showing location of boat harbour, bund walls, tide level measuring sites (TW 1–6) and reef transects

RESULTS

Following bund wall construction, lowest low tide on the reef-top is maintained at or close to the level of the bund walls (0.86 m LWD). Before construction (15 September 1993), low tide water level fell to 0.7 m LWD on the northern side of the boat harbour (figure 3) and 0.75 m LWD on the southern side. The water level on the reef-top drops slowly during the period that the harbour tide level is below the bund walls. The level on the reef-top is not affected by the actual level in the boat harbour, only by the length of time that the boat harbour level is lower than the walls. Consequently, in figure 3, the difference in harbour tide levels on 15 September 1993 and 30 June 1996 has had no affect the reef-top levels. During neap tides, the harbour tide level may not fall below the level of the bund walls (0.86 m LWD).

Construction of the bund walls raised the water-level on the reef-top on the northern side of the boat harbour by 0.14 m as measured at TW 4 (figure 3) and also TW 5 (locations in figure 2). The reef-top water levels on the southern side of the boat harbour were raised by a smaller amount ranging from 0.06 m at TW 2 to 0.09 m at TW 3. These values are valid for the relatively calm wind and wave conditions as experienced on both 15 September 1993 and 30 June 1996. Water levels on the reef-top are affected by ambient wind and wave conditions as well as tides and are raised during conditions of strong winds and large off-reef waves (Gourlay and Hacker 1996). On 24 April 1994, when there was a moderate to fresh southeasterly breeze, low tide water level on the southern side was raised by 0.12 m, relative to conditions prior to bund wall construction.

The corals have already responded well to the increase in low tide level on the reef-top. The results for coral growth presented here are only preliminary as the project is ongoing. The amount of vertical growth of *Acropora* since bund wall construction above the previous growth limit, the dead coral level, was greatest closest to the northern bund wall, ranging from 118 to 145 mm between TW 4 and TW 5, then decreasing with distance from the bund wall to 15 mm near TW 6, which is 240 m from the bund wall (figure 4). This is consistent with earlier findings that the influence of the boat harbour and channel on water level and hence on coral growth does not extend further than 400 m from the harbour (Neil 1991).

The tagged *Acropora* spp., located near TW 2, TW 4 and TW 5 (figure 2), have grown since bund wall construction (table 1). An individual measured branchlet from the colony near TW 5 has grown by a total amount of 186 mm (166 mm vertically) since it was tagged in July 1994, approximately six months after bund wall construction. Others have grown by

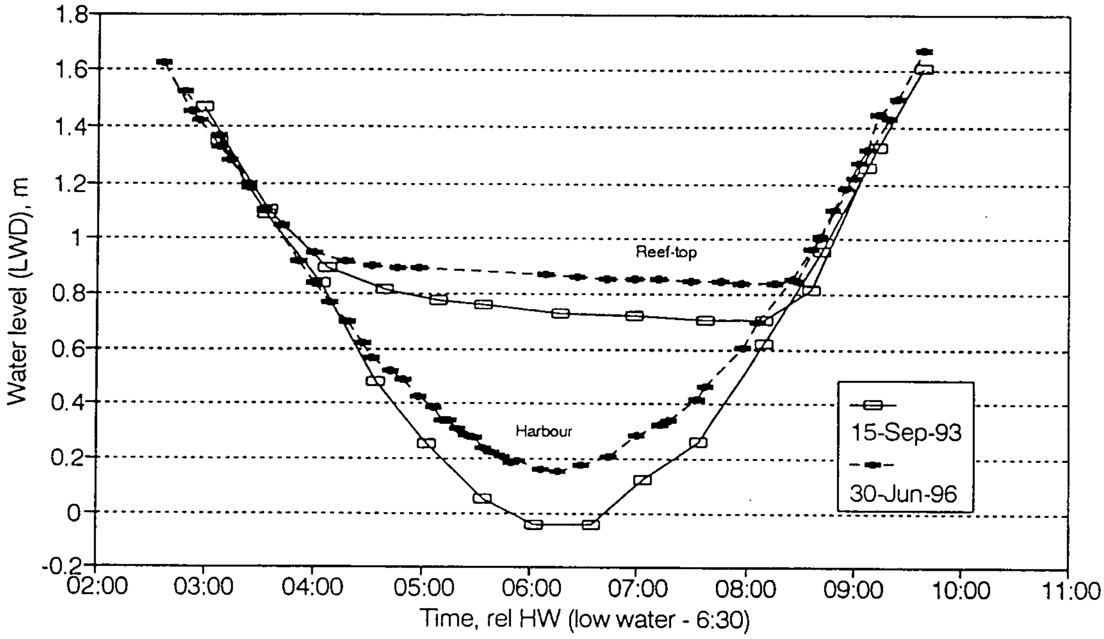

Figure 3. Tide levels on the reef-top at TW 4 and in the boat harbour before (15-Sep-93) and after (30-Jun-96) bund wall construction

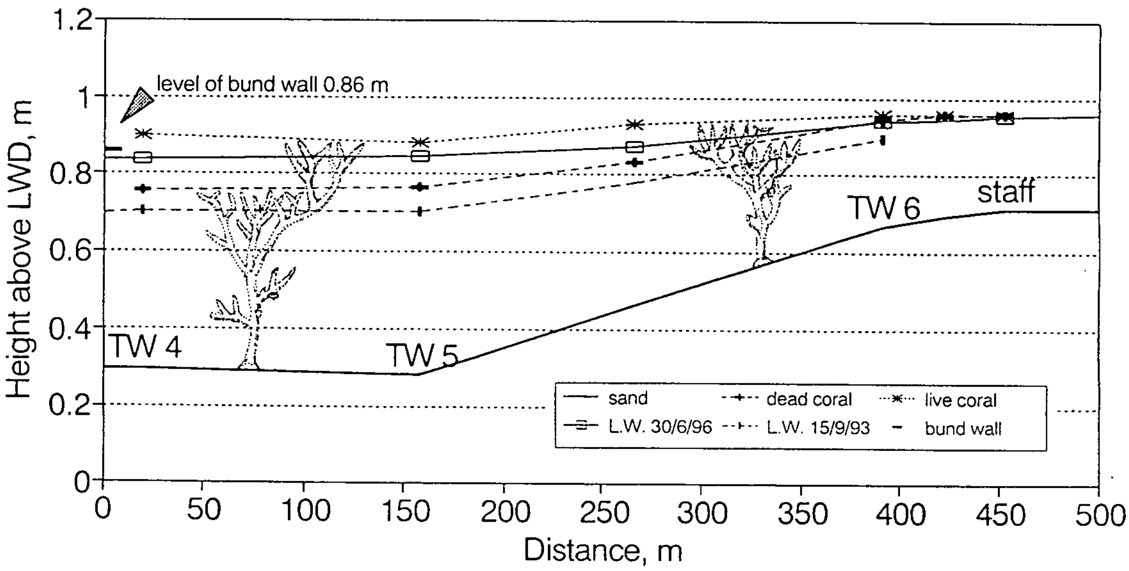

Figure 4. Variation in amount of growth of *Acropora* along 500 m transect between TW 4 and wave staff

smaller amounts. The amount by which the water level has been raised is less near TW 2 (0.06 m) than on the northern side. This is reflected in branchlets from the colony near TW 2 growing less than those on the northern side. Moreover growth in the colony near TW 2 is changing form and the branchlets are becoming stunted.

Table 1. Vertical growth of *Acropora* branchlets relative to LWD, July 1994 to July 1996

Acropora colony	level July 1994 m, LWD	level July 1996 m, LWD	vertical growth mm
TW 2 - 1	0.913	0.945	32
2 - 2	0.810	0.886	76
TW 4 - 1	0.711	0.877	166
4 - 2	0.761	0.854	93
4 - 3	0.779	0.886	107
TW 5 - 2	0.772	0.842	70
- 2s	0.782	0.842	60
5 - 3	0.808	0.883	75

The three *Porites* colonies, south of the boat harbour, are growing above a microatoll level of approximately 0.75 m (table 2). Neil (1991) describes how water level changes resulting from harbour reconstruction in 1987 affected coral growth levels north of the boat harbour. The microatoll level of 0.75 m is considered to be that determined by reef-top water levels prior to this reconstruction. Consequently, as *Porites* is a slow growing species, the colonies do not indicate a direct response to the bund wall construction, but they do show a growth response in both height and area to the raising in reef-top water-levels since 1987. It is expected that the *Porites* colonies will continue to grow in height until their growth in the vertical direction is limited by the low tide levels on the reef, now controlled by the bund walls which are at 0.86 m. Then, it is expected that they will begin to form new microatolls at a level above the existing one.

Table 2. Growth in height and areal extent of three *Porites* colonies south of boat harbour (heights are to LWD and are an average of 5 portions of the colony)

		Atoll level	13/7/94	27/7/95	28/6/96	Increase 94–96	Annual growth rate
Porites 1	height	0.744 m	0.831 m	0.843 m	0.854 m	0.023 m	12 mm/a
	area		0.171 m^2	0.217 m^2	0.259 m^2	51%	0.044 m^2/a
Porites 2	height	0.758 m	0.806 m	0.818 m	0.823 m	0.017 m	8 mm/a
	area		0.108 m^2	0.143 m^2	0.179 m^2	66%	0.036 m^2/a
Porites 3	height	0.744 m	0.829 m	0.846 m	0.849 m	0.020 m	10 mm/a
	area		0.186 m^2	0.253 m^2	0.262 m^2	41%	0.038 m^2/a

Visual comparisons of aerial photographs taken before and after bund wall construction show that coral cover over the reef-top in the vicinity of the walls has increased. Existing colonies are extending in area and new colonies are becoming established on areas which had negligible coral cover in 1993.

The records of the two belt transects also show an increase in coral cover of approximately 30% for each of the two years of measurement. In both transects, *Acropora* species generally grew more than the other species present. A noticeable decrease occurred in the number and size of *Montipora digitata* in the northern transect after the first year, but after the second year this was reversed. In the last year (1995–96), there has been substantial larval recruitment by *Goniastrea retiformis* in the northern transect which could be related to the changed hydrodynamic conditions in that location. However, it may be a chance event.

CONCLUSIONS

Coral species along both sides of the Heron Island boat harbour have shown vertical growth in response to the raising of the low-tide water levels resulting from construction of the bund walls in 1993–94. The faster growing species, such as *Acropora*, have almost completely accommodated the 0.14 m rise in low-tide water level during 2_ years, whereas other species, such as *Porites*, are taking longer to catch up. Increase in coral cover has also been observed in the aerial photographs, the belt transects and in the growth of specific colonies. This increase in coral cover and also changes in species composition may be associated with the increased water levels and changed hydrodynamic conditions on either side of the boat harbour.

ACKNOWLEDGMENTS

This research is being undertaken as part of a monitoring project (funded by Great Barrier Reef Marine Park Authority) for the Heron Island Boat Harbour. Significant assistance, including 'in kind' support and accommodation, has been provided by P&O Heron Island Resort; Heron Island Research Station and Queensland Department of Environment. The field observations were undertaken with the assistance of postgraduate Civil Engineering students and undergraduate Environmental Engineering students from The University of Queensland. Reg Stonard assisted with figure preparation. The authors acknowledge that this research could not have been undertaken without this assistance.

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Quantifying organic content of material from coral reefs

SW Purcell
Department of Marine Biology, James Cook University Qld 4811

ABSTRACT

Analysis of organic content is a common approach for evaluating suspended particulates, sediment deposits and benthic vegetation from coral reefs. These materials, however, often contain thermally unstable carbonate particles that can bias common analyses such as ash-free dry weight (AFDW) determinations. This potential error was assessed by analysing coral reef sediments for organic content using the ashing method and comparing these values to those obtained from a modified procedure for organic carbon analysis in a LECO auto-analyser. Trials in which bleach-washed sediments were combusted over a range of furnace temperatures revealed that ash-free dry weight content of sediments increased from 3% at 400°C to over 40% at 650°C, with differential charring of various biogenic grains. Rapid determinations of organic carbon in a LECO auto-analyser were carried out on acid treated and untreated samples of a marine alga, with and without calcium carbonate. Simple acid treatments in re-usable glass vessels eliminated at least 99.4% of carbonate interference. This treatment did not significantly affect the remaining organic carbon phase, and average precision was 2.3% for biological material ranging from 0.3 to 16.0% organic carbon. Comparison of the two methodologies revealed that ash-free dry weight determinations of materials that contain coral reef sediments can be erroneous due to decarbonation of carbonate mineral phases.

INTRODUCTION

Analysis of organic content is a common procedure for evaluating biological and geological material from marine environments. Determination of ash-free dry weight (AFDW; also termed 'loss on ignition') is among the simplest of these, in which the amount of organic material in a sample is determined by subtraction of the weight of 'ash' (material remaining after combustion) from the initial dry weight. Bias in this method can arise from variable thermal instability of carbonate mineral phases at ashing temperatures (450–600°C); some of the CO_2 may be lost from the mineral phase and not exclusively from the oxidative decomposition of organic matter (Morse and Mackenzie 1990). A number of geological studies (Dean 1974; Telek and Marshall 1974; Hirota and Szyper 1975) have reported negligible dissociation of carbonate (reagent grade) at 500°C. In accord with these findings, recent studies on coral reefs have applied ash-free dry weight determinations to suspended solids, benthic sediments, epilithic algae and stomach contents of herbivores; all of which contain biogenic carbonates.

Knowledge of the suitability of ash-free dry weight determinations on material from coral reefs is lacking. In most shallow marine environments, particularly coral reefs, carbonates are typically of a complex mineralogy (Chave 1962) and can contain considerable proportions of unstable mineral phases, such as high-magnesium calcite that may begin to decarbonate below standard ashing temperatures. This study aimed to evaluate this potential error by conducting ashing trials of coral reef sediments over a range of temperatures and comparing the results with those from a new procedure for organic carbon analysis using a LECO auto-analyser. This is a simpler procedure for induction furnace analysis than those recently described by Cutter and Radford-Knoery (1991) and Nieuwenhuize et al. (1994) as it deals with carbonate interference by using as single-step acid-treatment of samples in reusable vessels to alleviate carbonate interference prior to analysis, and is validated in this study.

MATERIALS AND METHODS

Carbonate sediment samples (n = 4) were collected from a reef flat at Lizard Island (14°42'S, 145°28'E), Great Barrier Reef. These were cleared of organic material by soaking in three series of 10% bleach ($NaHClO_4$) followed by five series of 1 µm filtered tapwater, with minimum soak periods of 12 h. The samples were then oven-dried at 60°C, and stored in a desiccator with silica gell. Duplicate aliquots (approx. 1 g) from each sediment sample were weighed into pre-fired (650°C) and desiccated crucibles to the nearest 0.1 mg. These were combusted in a calibrated Carbolite® muffle furnace for 16 h in separate trials at 400, 450, 500, 550, 600 and 650°C, then were cooled in a desiccator for several hours before being reweighed to determine the ash-free content. Duplicate empty crucibles were also fired during each temperature trial and showed negligible weight loss of the vessels. Change in appearance of sediments (superficially and within grains) that were combusted at the standard ashing temperature of 500°C was checked with light microscopy. The contribution by weight of siliceous sediments in each sample was determined after carbonate dissolution in hydrochloric acid (HCl).

A LECO SC444-DR elemental analyser was used to quantify organic carbon content of triplicate aliquots of the same sediment samples. To permit acidification of samples, vessels (2 ml capacity troughs) were constructed from heat resistant HSQ quartz glass tubing (Heraeus Quarzglas) and were fitted into standard furnace boats. Aliquots (50 mg) of each sample were weighed to the nearest 0.1 mg in pre-fired vessels. These were then wetted with a few drops of deionised water and treated with 2 N AR hydrochloric acid, a few drops at a time, until the glass vessels were near full; this is enough HCl to liberate all CO_2 from 200 mg of carbonate material. The samples were then oven dried for 12 h at 70°C, then analysed in the LECO analyser. This machine combusts samples in a furnace at 1200°C and detects the amount of evolved CO_2 by infra-red spectroscopy, which is then converted to proportion of carbon using the initial sample weight. The glass vessels were rinsed in HCl and deionised water to allow multiple use, and have an estimated half life of about 50 analyses.

An experiment was carried out to assess the suitability of this procedure for analysis of organic carbon of biological material; it tested whether: a) organic carbon is affected by the acid treatment, b) interference from inorganic carbon is eliminated, and c) the procedure adds any organic carbon. Laboratory cultured *Enteromorpha flexuosa* (Chlorophyta), a non-calcified filamentous marine alga, was used as the biological material to be tested. Fresh algae were rinsed thoroughly in distilled water, oven dried at 60°C, and ground to a homogenous powder using a mortar and pestle. Aliquots (n = 6) of algae with and without $CaCO_3$ (AR grade), $CaCO_3$ alone, and empty vessels were treated with acid and analysed as outlined above, as were aliquots of untreated algae and $CaCO_3$. Additionally, samples of epilithic algae (n = 120) and detritus (n = 60) were also collected from Lizard Island (Purcell, unpubl. data), ground to a fine powder and analysed in triplicate using the above method. These field samples varied in the type of organic material and in the proportion of carbonate material present, providing a suitable range of samples to assess the within-sample precision of organic carbon analyses using this procedure.

RESULTS

Ash-free dry weight determinations (figure 1) indicate that decarbonation of washed coral reef sediments begins at low ashing temperatures, and dramatically accelerates between 550 and 600°C. The average proportional weight loss of sediments was 3–4% for furnace temperatures up to 550°C, but increased to 10.1% (± 0.1% SE) at 600°C and 40.3% (± 1.9% SE) at 650°C.

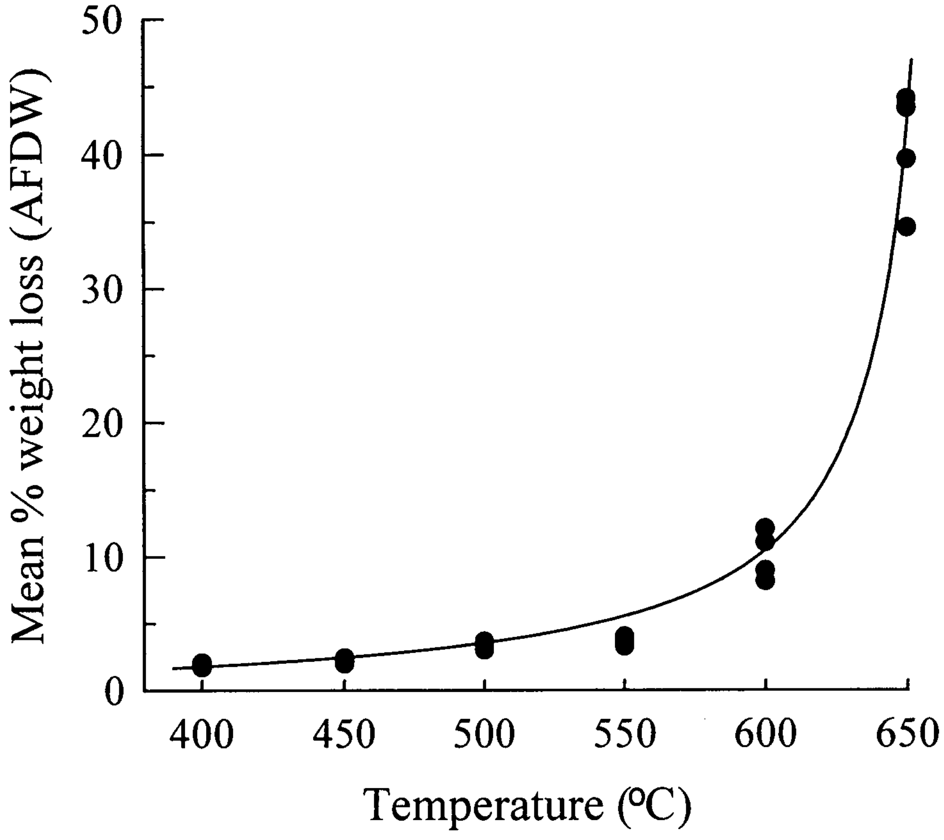

Figure 1. Plot of mean percentage weight loss (ash-free dry weight) of coral reef sediments at different furnace temperatures. Curve of best fit ($y = x/(-0.84x + 561)$; $r^2 = 0.981$) indicates early decomposition of carbonate material and increasing thermal instability at successively higher ashing temperatures.

Following ashing at 500°C most of the dominant sediment particles, such as those from coral, calcareous algae and foraminiferans, changed, both superficially and within grains, from off-white to dark grey in colour. This indicates that mineral decarbonation, rather than the combustion of a residual organic layer on sediments, was attributing to the weight loss upon ashing. This observation however, was not consistent amongst all particles, as some, such as those from bivalve shells and echinoid tests showed little signs of mineral decarbonation, indicating that thermal stability varies amongst the carbonates of different coral reef organisms. Siliceous minerals can bias the accuracy of ash-free dry weight determinations via the loss of lattice OH-water (Dean 1974), but were a negligible component by weight (mean = 0.48% ± 0.06% SE) of all sediment samples.

LECO analyses (figure 2) showed that detected values of organic carbon of acid treated algae samples were not significantly different from those of samples with added $CaCO_3$ or to control (untreated) samples (one-way ANOVA; $F = 0.24$, $p = 0.79$). This demonstrates that interference of carbonates is avoided with the acid treatment, with negligible loss (e.g. volatilisation) of organic carbon. Accuracy of the analyser was confirmed by the carbon analyses of untreated reagent $CaCO_3$, which varied less than 2% (relative) from the predicted value of 12%. Analyses of acid treated $CaCO_3$ showed that the acidification is capable of eliminating at least 99.4% of the interference from carbonates. Acid-only controls indicate that acid introduced carbon can be considered negligible, as this accounted for less than 0.2% of that detected in test algal samples. Average precision (SE/mean) of this procedure for organic carbon analyses was 2.3% for 180 carbonate-mixed biological samples from a coral reef, ranging from 0.34% to 16.01% organic carbon.

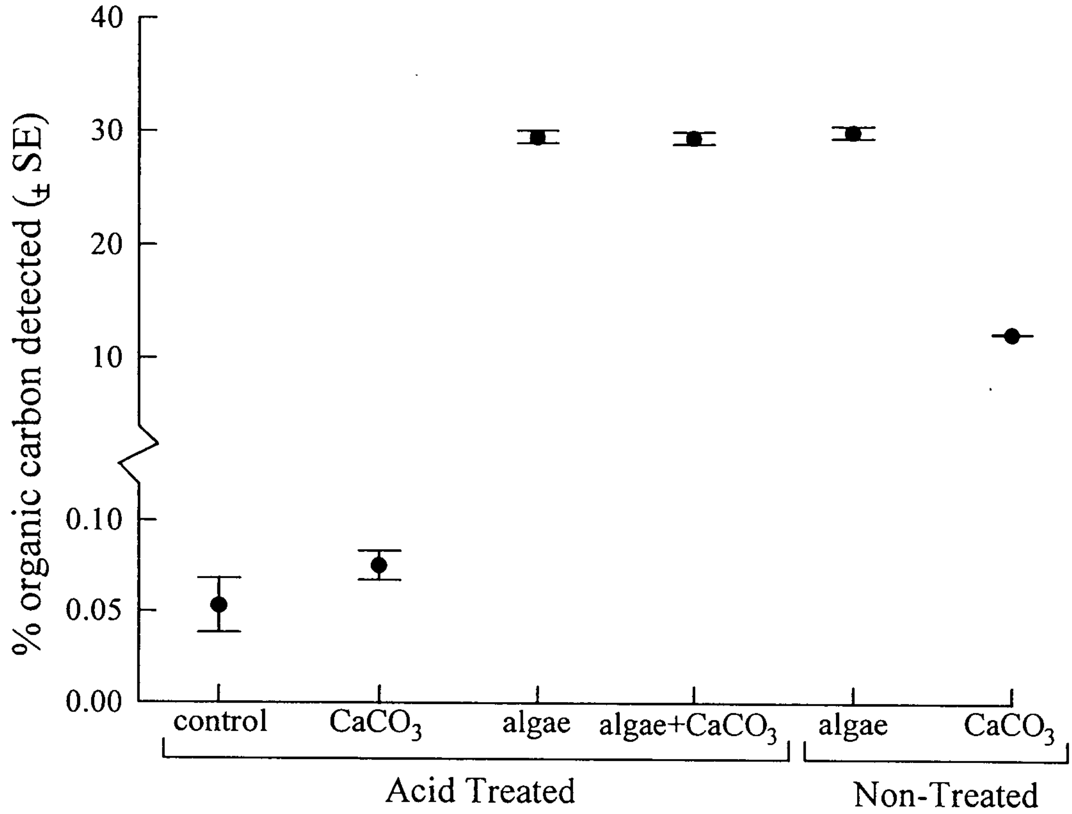

Figure 2. Mean organic carbon values of test materials using the LECO elemental analyser, with and without an acid treatment prior to analysis. Acid-only treatment is denoted as 'control'.

Comparison of values provided by the two methods using coral reef sediments reveals that ash-free dry weight determinations are markedly overestimating organic matter content. Although both methods indicate that some recalcitrant organic matter remained after bleach-washing, the ash-free dry weight values of sediments combusted at 500°C were more than an order of magnitude higher than LECO values (table 1). One must consider, however that ash-free dry weight measurements are for bulk combustible organic matter (C, H, N, S, O), whereas the LECO analyser provides values for elemental carbon. Organic carbon values were therefore divided by the mean proportion of organic carbon out of the weight of detritus within sediments from Lizard Island (0.36; unpublished data) to convert these to estimates of crude organic matter. Each of these 'corrected' values, which are now inflated to a comparable unit of measurement, are still at least six times lower than the ash-free dry weight determinations of aliquots of the same samples (table 1). This demonstrates that other components in the sediment samples, such as thermally unstable carbonate minerals, decomposed at the ashing temperature to produce an error of about 3% of the sample weight.

Table 1. Mean values (± SE) of percentage bulk combustible organic matter (%AFDW at 500°C), organic carbon (acid treatment and LECO analyses), and bulk organic matter (see text) for the same four coral reef (bleach-washed) sediment samples

Sample	% AFDW	% organic carbon (LECO)	% organic matter (corrected)
1	3.052 (± 0.006)	0.169 (± 0.005)	0.468 (± 0.009)
2	3.489 (± 0.138)	0.164 (± 0.014)	0.456 (± 0.024)
3	3.679 (± 0.005)	0.167 (± 0.005)	0.466 (± 0.010)
4	3.143 (± 0.086)	0.188 (± 0.024)	0.523 (± 0.043)

DISCUSSION

This study indicates that decarbonation of thermally unstable carbonate sediment particles can bias ash-free dry weight determinations in samples containing coral reef sediments. It appears that the bias is detectable at temperatures as low as 400°C, which is consistent with reports that the initial step in the decarbonation reaction for magnesium calcites can occur at 250°C (Morse and Mackenzie 1990). The marked escalation in weight loss of the sediments around 600°C is probably due to decarbonation of phases such as calcite, which has been shown to decarbonate at this temperature (Hirota and Szyper 1975).

Skeletal carbonates of calcifying organisms can be composed of a combination of minerals, such as calcite, aragonite and a spectrum of high-magnesium calcites (Chave 1962). It is not surprising that mollusc shells, which are composed of aragonite and calcite (Chave 1962; Milliman 1974), appeared unaffected after ashing at 500°C. Conversely, sediment grains such as those of calcareous algae and benthic foraminiferans are reported to have relatively large amounts of magnesium in the calcite making up the test (Chave 1962; Ross 1977), and were amongst those types which appeared most thermally affected.

The error in combusting biogenic sediments at the previously proposed ashing temperature of 500°C is particularly preclusive for quantifying organic matter from tropical coral reefs. Biogenic carbonates often comprise an overwhelming fraction, by dry weight, of biological samples from coral reefs compared to the actual organic material of concern. In these cases, the relative error in ash-free dry weight determinations is likely to be high, confounding our understanding of the role of organic material in these ecosystems. Applying correction factors for the decarbonation of carbonate (Telek and Marshall 1974) should be avoided for coral reef samples, as this depends on the composition of carbonate minerals which is likely to vary amongst spatially and temporally distinct samples. For determinations of organic carbon of sediments, benthic algae, or detritus from coral reefs, the method presented for acidification and analysis of samples (10–100 mg) using a LECO elemental analyser provides an accurate procedure in which the interference from carbonate minerals is alleviated.

ACKNOWLEDGMENTS

Thanks to S. Ness and A. Chappell (Advanced Analytical Centre, JCU) for advice on instrumentation, and to J.H. Choat and D.R. Bellwood for support. This work was funded by a Merit Research Grant from James Cook University of North Queensland.

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Coral skeletal destruction – boring sponges on the Great Barrier Reef

CHL Schönberg[1,2], *CR Wilkinson*[1] *and KN Hoppe*[3]
[1] *Australian Institute of Marine Science, PMB No. 3, Townsville MC Qld 4810*
[2] *Carl von Ossietzky Universität Oldenburg, Department of Zoology, PF 2503, 26111 Oldenburg, F.R. Germany*
[3] *Christian Albrechts Universität zu Kiel, Department of Zoology, Ohlshausenstr. 40, 24118 Kiel, F.R. Germany*

ABSTRACT

Little is currently known about the role of sponges in bioerosion on the Australian Great Barrier Reef. *Porites* colonies from three reefs on Great Barrier Reef (inner-shelf Pandora, mid-shelf Rib and outer-shelf Myrmidon Reef) were examined for evidence of bioerosion with emphasis on sponges. Patterns were found despite relatively low replication. Myrmidon Reef showed least evidence of bioerosion. On Pandora Reef, mollusc and especially *Lithophaga* bioerosion dominated. On Rib and Myrmidon Reefs, sponges were the main cause of bioerosion. We divided the sponges into two groups according to the appearance of borings. Chamberlike excavations were predominately found in Myrmidon Reef *Porites*, whereas porous boring was by far the main sponge boring encountered at the other sites. This suggests a change in the species composition along the gradient of changing environmental conditions from nearshore to offshore. Bioerosion by other organism groups was sparse and only of minor importance on Rib and Myrmidon Reefs. These results are basis for ongoing studies of implications for sponge bioerosion in context of environmental conditions and its management on the Great Barrier Reef.

INTRODUCTION

Sponges are important in the balance of coral reef construction and destruction (e.g. Goreau and Hartman 1963; Hartman 1977; Wilkinson 1983). They have been found to be the major agent of bioerosion in many warm-water habitats (Hein and Risk 1975; Bak 1976; MacGeachy and Stearn 1976; Hudson 1977; MacGeachy 1977; Scoffin et al. 1980; Highsmith 1981; Acker and Risk 1985; Risk et al. 1995). Some observations suggest that rates of bioerosion (Highsmith 1980; Hallock and Schlager 1986; Hallock 1988; Hallock et al. 1993; Risk et al. 1995) and the composition of boring sponge communities may change with changing environmental conditions, particularly with changes in nutrient concentrations or sediment loads (Rose and Risk 1985; Muricy 1991; Sammarco and Risk 1990; Klein et al. 1991; Cuet and Naim 1992; Carballo et al. 1994). Sponge communities are known to vary along a cross-shelf gradient on the Great Barrier Reef (Wilkinson and Cheshire 1989, 1990), but little is known about responses of boring sponge communities to environmental gradients or variation. Variation or changes due to human activities could be monitored or controlled if found to increase bioerosion processes. Our study on the Great Barrier Reef established a basis for future investigations of agents influencing sponge bioerosion.

MATERIAL AND METHODS

Massive *Porites* corals from three reefs on a cross shelf transect in the central section of the Great Barrier Reef near Townsville were examined for traces of bioerosion during a pilot study of the distribution of boring sponges. The material used was provided by D. Barnes and M. Devereux at the Australian Institute of Marine Science in Townsville. It consisted of 29 heads of *Porites* spp. sampled from similar reef environments of the outer-shelf Myrmidon Reef (120 km from the coast: 18.16°S, 147.23°E; n = 10), the mid-shelf Rib Reef (60 km from the coast: 18.29°S, 147.53°E; n = 10) and the inner-shelf Pandora Reef (16 km from the coast: 18.49°S, 146.26°E; n = 9) (Lough and Barnes 1990, 1992). Each coral was cut in half and one half each was cut into two quarters. The surface of each coral half, and one of the quarter surfaces perpendicular to the first cut, were studied. The origin of bioerosion traces was determined by the appearance of the excavations (MacGeachy and Stearn 1976; MacGeachy 1977; Sammarco and Risk 1990), proximity to clearly recognisable patterns and remaining tissue of the organisms. Bioerosion was traced onto transparent overlay film. Different colours were used to mark excavations by sponges, molluscs, 'worms' and 'others' (i.e. not belonging to the former groups or not possible to identify). The sponge category was further split according to the excavation architecture, indicating different sponge groups: smooth walled, relatively large cavities (in general between 1 and 5 cm in diameter); and fine-pored cheese-pattern borings only rarely wider than 1 cm per pore and with pitted walls. The circumference of each coral was traced distinguishing between live and dead surface. The drawings were traced and scanned for image analysis ('Digit' by Kim Navin and 'Image 1.47' by Wayne Rasband). Data were given as percentage of area removed per group related to dead area available on the corals, because 'available dead surface' differed significantly between the reefs (Kruskal Wallis, df = 2, H = 6.629, P = 0.0363) and is known to influence amount of bioerosion (e.g. Bak 1976; MacGeachy and Stearn 1976). Differences between the reefs were tested after lumping the group of 'worms' with the group of 'others' because of low values, and then comparing the sites with a nonparametric Kruskal Wallis test (df = 2).

RESULTS

All bioerosion cavities were under dead coral surfaces, and more than 90% were at the base of the colony. Proportions of 1.2 to 2.7% skeleton removed under dead surfaces were relatively low at all sites (figure 1). Amount of bioerosion showed large variation, most pronounced on Pandora Reef (figure 1). Nevertheless, there were significant differences between reefs.

The proportion of bioerosion per dead coral surface was slightly lower but not significantly so on Myrmidon, the outer-shelf reef, compared to the mid-shelf and the inner-shelf reefs, Rib and Pandora (Kruskal Wallis test, df = 2, H = 3.784, P = 0.1508). Sponges and molluscs were found to be the most important bioeroders, but they dominated on different reefs (figure 1).

There was only weak evidence that amount of sponge burrowing differed with distance from the mainland (H = 5.868, P = 0.0532), even though the activity was most pronounced mid-shelf, on Rib Reef. Sponges with large, smooth-walled chambers were only important on the outer-shelf Myrmidon Reef (H = 8.825, P = 0.0121). By contrast, sponges with porous excavations were far more common on the inshore and mid-shelf reefs (H = 8.937, P = 0.0115). The mollusc cavities dominated the Pandora Reef samples (H = 6.603, P = 0.0368), and were mostly made by *Lithophaga* spp.. The group of 'others' played a minor role, but caused significantly more erosion on Rib Reef than on Myrmidon and Pandora Reefs (H = 7.212, P = 0.0272).

Larger cavities were often associated with cracks through the coral skeleton. More than 90% of the sponge excavations did not penetrate deeper than 2 cm into the coral; along cracks they sometimes reached further. In a few cases, infection of deeper lying parts was caused by the incorporation of bioerosion into the coral when it grew over infected rubble.

DISCUSSION

Rates of sponge bioerosion in our Great Barrier Reef samples are 0.5 to 2% of the dead parts of coral (figure 1), which are lower values than on reefs of other parts of the world. For example, average sponge boring in *Porites astreoides* on Barbados is 3 to 6% (MacGeachy 1977); *Cliona caribbea* alone removes 20% on average on Grand Cayman Reef, West Indies (Acker and Risk 1985). In context of the hypothesis that bioerosion can indicate increased nutrient levels, one may ask whether this could be the main cause of our findings (Highsmith 1980; Hallock and Schlager 1986; Hallock 1988; Hallock et al. 1993; Risk et al. 1995). Former studies indicated strong evidence of differences in the productivity on the Great Barrier Reef and Caribbean Reefs, in which sponges in particular were suggested as useful bioindicators for nutrient concentrations (Wilkinson 1987; Wilkinson and Cheshire 1989, 1990).

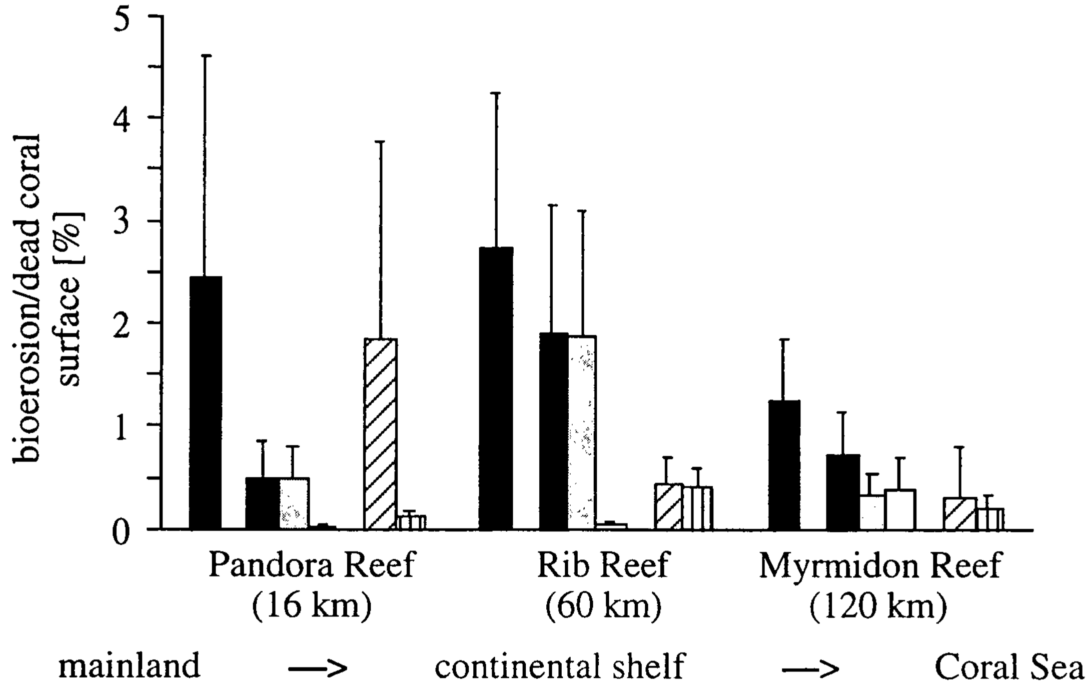

Figure 1. Bioerosion in *Porites* by different groups of organisms on a cross shelf transect across the Australian Great Barrier Reef. Bioeroders' groups were distinguished as:

- sum of bioerosion
- sum of sponge bioerosion
- 'porous' sponge bioerosion in cheese-patterns
- 'cavernous' sponge bioerosion with larger chambers
- mollusc bioerosion (mainly *Lithophaga* spp.)
- all other bioerosion ('wormlikes', others and not identifiable).

Number of coral heads used per reef: N = 9 for Pandora and 10 for Rib and Myrmidon Reefs. Error bars are 95% confidence intervals.

The present study is largely consistent with similar studies from the same area (Sammarco and Risk 1990), where sponges and *Lithophaga* spp. were also found to be the main bioeroders and to follow a similar distribution. However, our study revealed significant differences in the sponge community structure between the three reefs, not detected in the former study. This encourages more detailed investigations in future.

Large variation between samples complicated the estimation of the significance of bioerosion (figure 1). Also, the amount of bioerosion in a particular coral has been shown to be dependent on coral age or size, as most bioerosion originates from dead skeleton (e.g. MacGeachy and Stearn 1976). Thus, a range of criteria have to be considered when determining estimates of what is 'normal' and what is 'abnormal'.

Valuable information was obtained by concentrating on few groups of organisms. Sponges and *Lithophaga* spp. are clearly the most important bioeroders in *Porites* of the study area (figure 1). Most erosion was observed on Pandora and Rib Reefs, indicating increased abundance of bioeroders and/or of their burrowing activity. The larger size of *Lithophaga* burrows and the relative scarcity of sponges on Pandora Reef may reflect environmental conditions. As filter feeders, both groups benefit from particulate nutrient loads which are presumably higher on inshore and mid-shelf reefs, compared to the very oligotrophic Myrmidon Reef, on the edge of the shelf. Sponges may suffer from coastal sedimentation, which clogs their fine canal system and inhibits their photosynthetic symbionts. Offshore, predation may be a limiting factor. Grazing fish abundance increases seawards (Williams

1982; Williams and Hatcher 1983). The sponge population on Myrmidon Reef is dominated by a different group of sponges than on the mid-shelf and inshore reefs. This may be caused by different water quality requirements. Sponges creating numerous small pores may be better protected against environmental variation. It is, for example, difficult to kill them in infected aquaculture bivalve shells without killing their hosts as well (Thomas 1979; Lauckner 1983). Sponges causing larger erosion chambers which dominate on Myrmidon Reef have quite soft, delicate tissue which easily rots on slightest interference (Schönberg, pers. obs.).

Large bioerosion cavities may cause a greater loss in stability than small pores. The cavities are regularly associated with cracks extending further into the coral. Cracks seem to facilitate the spread of faster growing organisms, such as some of the sponges. In cases of ingrown infected rubble, the coral appears to be able to smother organisms in it by rapid growth or kill them by other means, because the bioerosion in the rubble rarely spreads into the surrounding *Porites* skeleton.

Many questions remain to be solved to determine whether rates of bioerosion are influenced by pollution or other changes. Do boring sponges react similarly to environmental changes as do other bioeroders? After disturbance, such as crown-of-thorns starfish attacks, more available surface could lead to dramatic increases in boring sponge recruitment. However, little is known about reproduction of Australian excavating sponges. Both the large and the small cavities cause considerable structural instabilities; corals which appear superficially unharmed, can be fractured in a moderate storm. Rates of bioerosion by sponges on the Great Barrier Reef will thus constitute important information for reef management.

ACKNOWLEDGMENTS

We thank M. Devereux, D. Barnes and J. Lough for access to their valuable samples and great assistance. They made this study possible. K. Navin wrote and helped us patiently with the digitising program 'Digit' and M. Dommisse helped us with 'Image'. C. Schönberg thanks the German Academic Exchange Service in Germany for supporting her work in Australia.

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The effect of depth and wave exposure on the density and porosity of *Pocillopora damicornis* in the Solitary Islands Marine Reserve, New South Wales

KA Spinaze, SDA Smith and RD Simpson
Department of Zoology, University of New England, Armidale NSW 2351

ABSTRACT

The aims of this study were to determine if the environmental factors of depth and wave exposure resulted in significant differences in the matrix density, bulk density and porosity of *Pocillopora damicornis*. Density and porosity measurements were determined by using a combination of methods based on the evaluation of buoyant weight. The results indicated that there was a significant difference in all measures between colonies nested within depth and exposure, but that there were no significant differences between depths, or between sheltered and exposed sites.

The significant differences between colonies collected from the same depth and same level of exposure may be related to high levels of natural variation in growth rates, or to genetic differences between colonies.

Studies on the natural variation of skeletal density and porosity are important as background information for any future studies on the effect of contaminants, such as phosphorus, which could affect skeletal density.

INTRODUCTION

Over the past nine years a major focus of research within the Solitary Islands Marine Reserve, New South Wales (29°30'S to 30°15'S) has been on the impacts of ocean disposal of sewage effluent on benthic communities (Smith and Simpson 1992, 1993). Recent concern over the likely impacts of a proposed new ocean outfall on corals within the Solitary Islands Marine Reserve led to a research plan to investigate the impacts of the existing Coffs Harbour outfall on corals at Korff's Islet, 750 to 800 m from the point of discharge and 200 m to the south of the Marine Reserve boundary. Investigations were to focus on changes to skeletal density of zooxanthellate species as preliminary results from the ENCORE project at One Tree Reef (Larkum and Steven 1994) had suggested that elevated nutrient levels resulted in reductions in skeletal density and increases in porosity of experimental coral colonies (D. Bucher, P. Harrison, pers. comm.).

Pocillopora damicornis (Linnaeus) is one of the most common corals in the Solitary Islands Marine Reserve and is found at all of the islands (Harriott et al. 1994), and also on nearshore reefs (Smith and Simpson 1991). Colonies are thick and stunted in comparison to the growth form of the species at lower latitudes (Veron et al. 1974; Harriott et al. 1994). *P. damicornis* is also the dominant zooxanthellate coral species at Korff's Islet (Smith, unpubl. data) and was therefore chosen for this study.

Prior to assessing the impact of elevated nutrients on coral skeletal density, it was first necessary to determine the background levels of variation under different environmental conditions. This preliminary study focused on quantifying variation in density and porosity between colonies growing under similar environmental conditions as well as under different regimes of depth and exposure to wave action.

MATERIALS AND METHODS

Specimens of *P. damicornis* were collected in March 1996 at Split Solitary Island, 8 km north-east of Coffs Harbour. Four isolated colonies of 20 to 30 cm diameter were randomly collected from depths of 8 m, 12 m and 16 m at an exposed (southern side of the island) and sheltered (north-western side of the island) site.

Colonies were bleached to remove coral tissue, and four terminal branches of 4 to 8 cm length were randomly chosen from each colony. Branches were placed in acetone for three weeks to remove gas bubbles and the remaining waxes, and kept in water for two weeks with the water changed weekly, following methods developed by Bucher (D. Bucher, pers. comm.).

The buoyant weight of each branch was determined by using an electronic balance (accuracy ± 0.01 g) which was placed on a perspex frame over a tub containing tap water. Branches were weighed on a perforated plastic tray suspended beneath the balance. Dry weights of the branches were obtained by drying the branches in an oven at 70°C until they achieved a constant weight.

Densities, volumes and porosity were determined from the following formulae (Spencer-Davies 1989; D. Bucher, pers. comm.).

Matrix Volume = Dry Weight in air - Saturated Buoyant Weight
Matrix Density = Dry Weight / Matrix Volume
Enclosed volume = Waxed Dry Weight - Waxed Buoyant weight
Bulk Density = Unwaxed Dry Weight/ Enclosed Volume.
Porosity = [Enclosed Volume - Matrix Volume] x 100/Enclosed Volume

The enclosed volume was found by covering the surface of the skeleton with paraffin wax heated to 105–110°C. This prevents the pore spaces becoming filled with the weighing medium while not adding significantly to the total enclosed volume (Oliver et al. 1983; Harriott, in press).

The experimental design to determine the effects of depth and water motion was a mixed model ANOVA with corals as a random term, and depth and exposure as fixed terms. The ANOVA had two crossed factors (exposure and depth), and one nested factor (coral colony nested in exposure and depth). The statistical procedure had two separate analyses, one testing differences between colonies nested in cells, and the second, a two-way crossed ANOVA, testing for differences between exposure and depths. This allowed for the correct partitioning of sums-of-squares. The mean-squares and the *F* statistic were calculated by hand. The group variances were homogenous to the extent that no transformations were necessary.

RESULTS

None of the three measures (matrix density, bulk density and porosity) differed significantly between exposure regimes or among depths (tables 1–3). The mean matrix density of *P. damicornis* was 2.703 $g.cm^{-3}$ (± 0.0942), the mean bulk density was 1.238 $g.cm^{-3}$ (± 0.2886), and the mean porosity was 54.28% (± 10.06).

The effect due to variation between colonies sampled from each depth and exposure combination (cell) was highly significantly different ($P < 0.001$) for each measure. This reflects large levels of heterogeneity in skeletal density of different colonies growing in the same environmental conditions.

Table 1. ANOVA table of the effects of exposure and depth on *P. damicornis* matrix density

Source of variation	df	SS	MS	*F*	*P*
Total	95	1.417			
Cells		0.024			
Exposure	1	0.003	0.003	0.048	>0.50
Depth	2	0.018	0.009	0.154	>0.50
Exposure x Depth	2	0.003	0.002	0.028	>0.50
Coral (within cells)	18	1.054	0.059	12.43	<0.001
Error	72	0.339	0.005		

Table 2. ANOVA table of the effects of exposure and depth on *P. damicornis* bulk density

Source of variation	df	SS	MS	*F*	*P*
Total	95	4.586			
Cells		0.362			
Exposure	1	0.064	0.064	0.503	>0.50
Depth	2	0.259	0.130	1.019	>0.50
Exposure x Depth	2	0.038	0.019	0.151	>0.50
Coral (within cells)	18	2.912	0.127	6.985	<0.001
Error	72	1.312	0.018		

Table 3. ANOVA table of the effects of exposure and depth on *P. damicornis* porosity

Source of variation	df	SS	MS	*F*	*P*
Total	95	5239.43			
Cells		416.87			
Exposure	1	103.71	103.710	0.574	>0.50
Depth	2	274.23	137.115	0.759	>0.50
Exposure x Depth	2	38.93	19.465	0.108	>0.50
Coral (within cells)	18	3251.98	180.666	8.282	<0.001
Error	72	1570.58	21.814		

DISCUSSION

Coral skeletal density has been found to vary with growth rate, slow growth producing high density skeletons (Barnes and Lough 1993; Van Veghel and Bosscher 1995). The generalised effects of water motion on coral growth and consequently density are presently unclear. There are two possible effects on skeletal density. Firstly, corals exposed to high wave motion may produce skeletons of low density as coral growth is limited by rate of exchange across the boundary layer (stagnant water which always surrounds an aquatic organism – Dennison and Barnes 1988). The thinner boundary layer which occurs in areas of high water motion allows for faster diffusion across the tissue/sea boundary, so increasing growth rates and consequently forming a skeleton of low density (Jokiel 1978). Secondly, higher wave motion may result in an increase of density by two processes. Denser skeletons may form to decrease the likelihood of fragmentation (Chamberlain 1978; Harriott, in press). Alternatively, water motion may reduce growth rates as it interferes with feeding by the polyps (Suresh and Mathew 1993) and reduces light due to increasing sedimentation (Suresh and Mathew 1993). The absence of differences in density in this study is similar to the results of Stambler et al. (1991) who, by experimental manipulation of water movement in tanks, found that water movement did not affect the growth of *P. damicornis*.

Decreased light availability has been demonstrated to result in reduced growth rates in corals (Rogers 1979). Consequently, a decline in growth rate with increasing depth is commonly found (Buddemeier et al. 1974; Spencer-Davies 1989; Dustan 1975; Heiss 1995; Highsmith 1979; Oliver et al. 1983). The outcome of the declining growth rate with increasing depth is often an increase in density with increasing depth (Baker and Weber 1975; Buddemeier et al. 1974; Heiss 1995; Hughes 1987). However, the lack of difference in density between depths that was documented for *P. damicornis* in this study has been found for other species. Hughes (1987) found *Porites astreoides, Leptoseris cucullata, Agaricia lamarcki, A. undata* and *A. fragilis* densities did not change over the depth range 5 to 30 m, while Dustan (1975) found no difference in bulk density for *Montastrea annularis* between 10 to 45 m.

The values of porosity, matrix density and bulk density for *P. damicornis* measured in the present study fell within the ranges documented by Bucher in preliminary studies of *P. damicornis* collected from North West Solitary Island (D. Bucher, pers. comm.). The lack of variation in density and porosity in response to depth or wave exposure may primarily result from significant ($P < 0.001$) variation among coral colonies. As each of the main effects (depth and exposure) were tested over the mean-square for corals nested within cells, the high value of this mean-square may have masked small, real differences between the different depth and exposure regimes. This large variation between colonies collected from the same depth and level of exposure may be related to high levels of natural variation in growth rates, or to genetic differences between colonies. Similar results have been found elsewhere; Suresh and Mathew (1993) found that growth was variable within a single colony of *Acropora formosa*, Buddemeier et al. (1974) found densities were quite variable in 15 coral species at the Marshall Islands, and Benzie et al. (1995) found high genetic variability within populations of *P. damicornis* at One Tree Island.

The results of this preliminary study are important for the design of subsequent studies to address the effects of sewage based nutrient enrichment on the skeletal density of *P. damicornis*. The high levels of variation between colonies growing under the same environmental conditions reduced the power of tests to determine differences between different environmental conditions. This indicates that replication at the colony level needs to be substantially increased so that analyses of differences between skeletal density and porosity of corals growing at polluted and control sites will have increased statistical power.

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SESSION 4

Large-scale phenomena and organism response

Cost-effective small-scale crown-of-thorns starfish eradication procedures using acid injections

David Fisk[1]*, Lyle Vail*[2] *and Anne Hoggett*[2]
[1] *Reef Research and Information Services, PO Box 5129, East Lismore NSW 2480*
[2] *Lizard Island Research Station, PMB 37, Cairns Qld 4870*

ABSTRACT

An investigation was undertaken to determine the most effective method of controlling the crown-of-thorns starfish (COTS) on small patch reefs. Two acid injection regimes were trialled over an eight month period and both significantly reduced the densities and size classes of COTS on isolated patch reefs. The frequent injection regime (approximately 2 person hours effort per week) was more effective at reducing COTS numbers than the infrequent regime (every four months, effort continued until COTS population was effectively zero). However, migration of individuals into the treated reefs was probably occurring. COTS density was the most important factor affecting the efficiency of control measures, and diver experience was also found to be very important. Efficient search methods should include a diver adopting an oblique observation position and a circular swimming motion around a feeding scar. It is recommended that an intensive eradication effort in the initial phases of a control program should be followed by frequent, less intensive effort.

INTRODUCTION

Control programs for the protection of small areas (1–2 ha) of reef from aggregations of crown-of-thorns starfish (COTS) have met with mixed success in the past. Birkeland and Lucas (1990) provide a good summary and assessment of these programs and concluded that the requirements of a successful control program should include (i) advanced warning of an impending threat to an area whereby a counter response can be mounted prior to the problem becoming apparent within the desired area of protection; (ii) a rapid response in cases where the primary motivation is to protect a specific coral community; (iii) sufficient available personnel who can be mobilised at short notice (though they noted that for very large aggregations unrealistic numbers of divers would be required to have an effect on COTS densities) and, (iv) the degree of aggregation of COTS which will determine the efficiency of the control program.

Control methods have focused on specific and non-specific chemical and physical means. The Great Barrier Reef Marine Park Authority concluded that injections of Dry Acid (sodium bisulphate) fulfilled the majority of requirements of an effective low cost control method (Lassig 1995). This study was aimed at experimentally assessing the effectiveness of small-scale COTS control measures using injection guns filled with a solution of Dry Acid. To date, no information is available on the most efficient way of carrying out small scale eradication programs using this technique. Factors considered in designing the control program included habitat type, density and size class structure of COTS, coral community composition, and the frequency and intensity of injection programs. An active COTS outbreak reported by researchers on Lizard Island in early 1995 provided a timely and accessible opportunity to test the application of the acid injection method.

MATERIALS AND METHODS

Three trips using Lizard Island as the field study base were scheduled four months apart between October 1995 and June 1996. Six reef sites all less than 10 m deep on the western side of Lizard Island (14°40'S, 145°27'E) were selected for study. Two sites were used as controls, two were used for a frequent/low intensity treatment, and two were used for an infrequent/high intensity treatment. Three sites are separate patch reefs with areas of approximately 2 hectares; the other three sites are approximately 2 hectare portions of larger patch reefs. The sites had similar initial COTS densities, similar coral community types, and were easily accessible.

Six reef sites were chosen for study. The 'frequent' treatment involved two divers visiting each site to inject COTS with sodium bisulphate as described by Lassig (1995) for one hour every week or two weeks. The 'infrequent' treatment involved two divers visiting each site to inject COTS every four months, maintaining the effort until COTS numbers leveled off to nearly zero (6 to 14 person hours per trip per site). Both treatments began in October 1995; subsequent 'infrequent' treatments were applied in February and June 1996.

At the time of each 'infrequent' treatment, COTS densities and size frequency distributions were estimated at each of the six sites before injecting COTS at the treatment sites. Densities were estimated again on the four treatment reefs immediately after the treatments had been applied to determine density changes due to the treatments. Densities were estimated by counting the number of COTS within four 50 x 5 m belt transects placed haphazardly within the preferred COTS habitat at each site. The density data thus provide an overestimate of COTS density on entire reefs. The diameter of each COTS within the transects was estimated and recorded within size classes to determine the size frequency distributions of the populations.

Efficiency of the injection treatments was measured in two ways: by diver efficiency in terms of number of COTS killed per unit time, and by the reduction in COTS density at the treatment sites.

Diver experience was measured by categorising the known history of those involved in the 'frequent' injection treatment program. Divers were classified into experienced or inexperienced categories according to whether they were active marine researchers or students and occasional recreational divers, respectively. Factors giving an advantage to an experienced diver included local knowledge of where the most COTS tended to be concentrated; the amount of diving experience; and experience of where to look for COTS within the general area of a feeding scar. The latter factor is probably the most important as efficient searching of the immediate area of a feeding scar can be time consuming.

Repeated measures ANOVA (ANOVAR) analysis of the COTS density data was used to determine differences due to treatment effects. Bartlett's test for homogeneous variances was applied in all univariate tests and multivariate polynomial contrasts. Tukey's post hoc tests were used with significant ANOVAR results to determine which main effects were significantly different to each other. The log(x+1) transformation was applied to frequency data to improve homogeneity of variances.

RESULTS

COTS densities

Densities of COTS varied significantly between treatments and over time (figure 1). the treatment by time interaction term was also significant; (ANOVAR, $P < 0.001$ in all cases). COTS densities were variable within each survey time, but the broad divergence in numbers in the second survey probably accounts for the significant interaction term. The trends in COTS densities with treatment groups follow the same rank order even though they have different trajectories (figure 1). The two control sites show higher densities than either of the injection treatment sites, while the 'frequent' treatments maintained the lowest COTS densities. Post hoc tests of survey times (Systat, Wilkinson 1990) revealed that there were significant differences in COTS densities between October and February ($P = 0.002$), October and June (P=< 0.001), and between February and June ($P = 0.003$). The multivariate single degree of freedom polynomial contrast for a linear model explained 92.5% of the change in densities over time (calculated from the proportion of the linear polynomial sum of squares over the within subject time sum of squares, Wilkinson 1990). Tukey's post hoc tests showed that in October there was no significant difference in COTS densities among the 3 treatments (control, 'frequent', and 'infrequent'). However, in February and June there were significant differences among most of the treatments (P values ranged from < 0.001 to 0.005). The exception was in June where there was no significant difference between the 'frequent' and 'infrequent' treatments ($P = 0.15$) though there were significant differences between the controls and the two injection regimes.

Relative COTS densities at the 'frequent' treatment sites (figure 2) are indicated by the number of COTS injected because a standard amount of sampling effort was used. At both sites, the initial density of COTS was reduced to about half after four consecutive weeks. During the following six weeks of regular weekly injections, COTS density varied from 28% to 78% of the initial density at site 1 and from 36% to 77% at site 2. After week 10, injection frequency was either weekly, once every two weeks or, on one occasion, once every three weeks. During this period, COTS density remained variable: at site 1 with the density ranging from 13% to 54% of the initial density, and from 32% to 105% at site 2.

COTS size classes

The size frequency distributions of COTS as measured by belt transect show that all six sites had a similar broad spread of size classes initially. The control sites show growth of the population during the study with no recruitment and some loss of large individuals. All four treatment sites show a reduction in the number of COTS and contraction towards a single dominant size class (21–30 cm diameter).

Size structure of the COTS populations at the 'frequent' treatment sites can also be determined from the injection records (figure 3; although the size classes differed slightly to those used in the belt transect method). The modal size class was 21–40 cm during most sampling periods, but the 11–20 cm class had the highest frequency occasionally, especially towards the end of the study period. On only one occasion (site 1, week 4, > 40 cm) was any other size class predominant.

Injection efficiency

Diver efficiency varied between treatments and with time (table 1, figure 2). The 'frequent' treatment recorded the highest diver efficiency initially (table 1), but this was substantially reduced at the two subsequent sampling periods because the initial COTS density was lower and fewer were found within the hour allowed for searching. Diver efficiency was lower but more consistent using the 'infrequent' treatment. The three points in table 1 represent a snapshot of diver efficiency over time. The gross number of COTS injected at the 'frequent' treatment sites (figure 2) gives a more continuous estimate, and great variability is evident with time.

The density reduction efficiency increased with time for both treatments. The relative efficiency (table 1) of the two injection regimes in reducing the densities of COTS over a short period of time differed markedly. In the beginning of the study, the higher number of hours spent at the 'infrequent' sites had a more immediate impact on COTS densities compared to the effort at the 'frequent' sites. The rate of reduction increased at the 'infrequent' sites in February indicating that this injection regime was having an effect on COTS densities. In contrast, the impact on COTS density of the regular 'frequent' injection visits improved over time. These data suggest that the most efficient strategy for reducing COTS densities at a particular site is to have an initial intensive effort followed by more regular and less intensive visits.

There was a large difference in the ability of experienced and inexperienced divers to find COTS in a specified one hour time period (ratio of 4:1, experienced : inexperienced; Chi-Square = 7.31, P = 0.03, df = 2).

DISCUSSION

Both injection regimes significantly reduced the densities of COTS. Sporadic migration of COTS into the treated reefs is thought to explain their continued presence, despite both highly intensive, infrequent eradication efforts and less intensive, frequent efforts.

On the infrequently visited sites where injections continued until no more COTS could be found, the cryptic behavior of COTS would ensure that not all individuals were injected on the initial visit. Post-injection transect surveys confirmed that large numbers of COTS

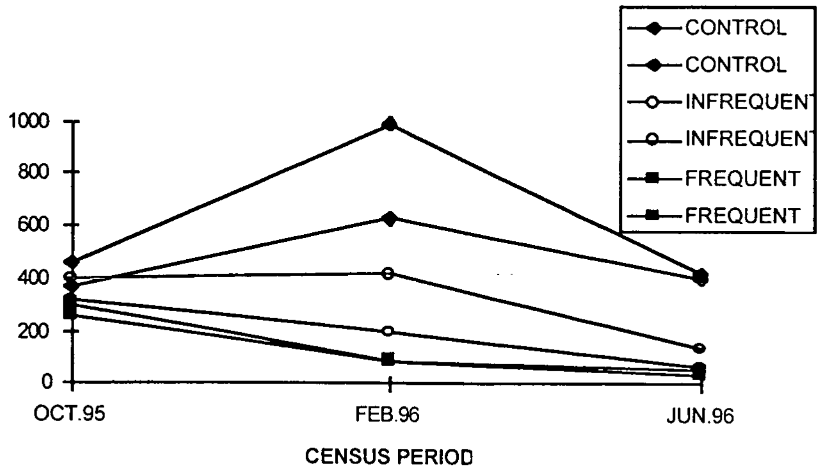


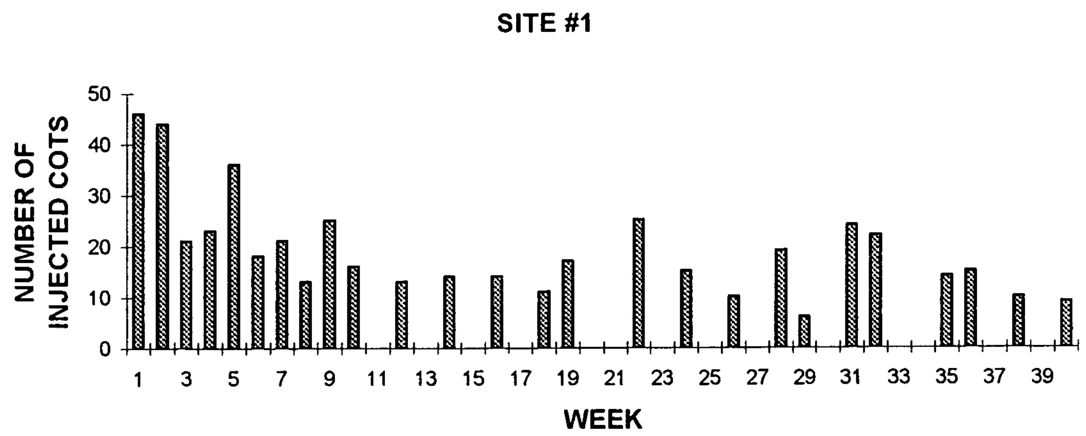
Figure 1. COTS densities from belt transect data are higher for non-treatment than for treatment sites. The injection regimes appear to be having some impact on reducing COTS densities, with the 'frequent' injection regime showing relatively lower densities to the 'infrequent' injection regime.

remained after the initial visit (table 1). The discipline imposed by a transect line clearly allows better detection of cryptic COTS than searches made by free-swimming divers.

However, it must be stressed that the densities obtained from transect counts are overestimates for the whole site because the transect tapes were laid in the areas of greatest COTS abundance. However, four months later, the average density of COTS at those sites had increased and this pattern was repeated at the final sampling period. There are three possible explanations for this pattern: (i) larval recruitment, (ii) inadequacy of the injection technique for killing COTS, and (iii) net immigration.

Larval recruitment at that time of year is unlikely given the known biology of the starfish (Moran 1986) and size frequency distribution of the populations (figure 3). Survival of injected starfish is also considered unlikely to have produced this pattern due to the successful trials of the technique conducted by the Great Barrier Reef Marine Park Authority (Lassig 1995). A few cryptic individuals may have survived injection as it was sometimes difficult to inject them in sufficient places, but this small number would not affect the results. This leaves net immigration to explain the difference between post-injection density at one sampling period and pre-injection density at the subsequent sampling period. Size frequency data support the possibility of immigration of 21–40 cm diameter individuals into the 'infrequent' treatment sites (figure 3).

At the frequently visited sites, the time constraint of one hour per visit for two divers would also ensure that COTS still remained at the sites after the first sampling period. However, in the absence of recruitment and assuming success of the injection technique, the density of COTS would be expected to approach zero and remain there within the period of the study if migration was not occurring. Transect counts (table 1) show that COTS density at these sites has approached zero but has never achieved it during the study period. The initial figure for COTS density on the two sites (300 and 260 per hectare, respectively) is an overestimate of the true value for the reasons outlined above. The 'best' COTS habitat occupies much less than half the area of each site, and COTS density within the poorer section was always very low. Using one-third of the initial density estimates to correct for habitat differences and an approximate area of each site as 2 hectares, 200 COTS are estimated to have been on Site 1 at the beginning of the study and 173 COTS at site 2. During the period of the study, 553 COTS were injected at Site 1 and 390 were injected at Site 2 (figure 2). The discrepancy between the estimated initial number of COTS and the number injected can only be explained by migration if recruitment and injection technique inadequacy are ruled out.



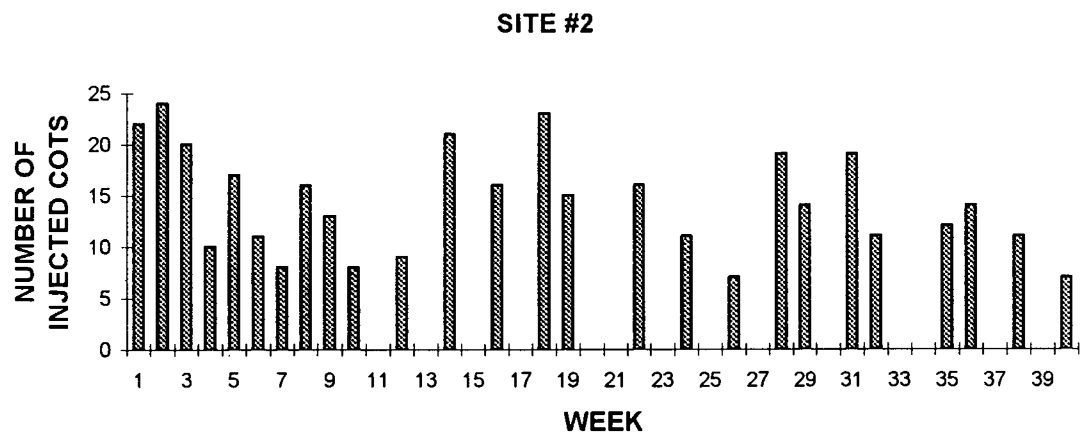
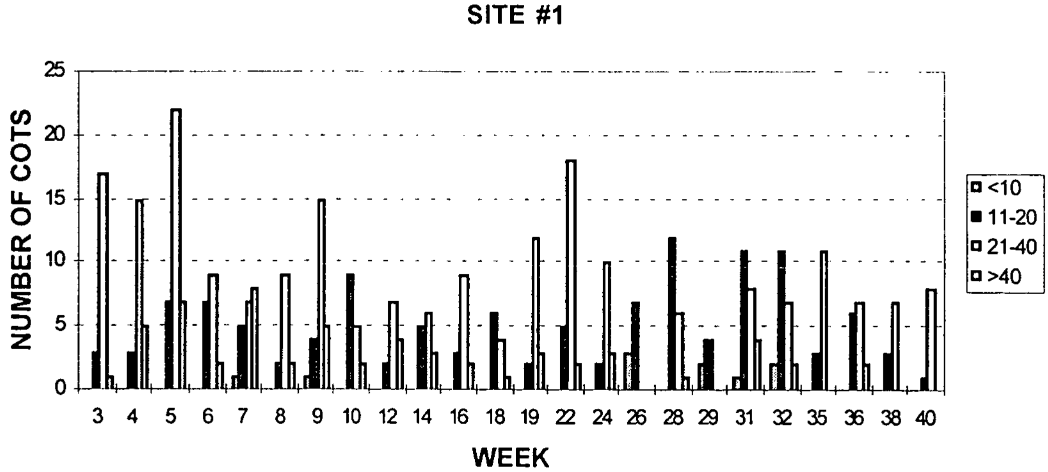


Figure 2. Number of COTS injected per visit for the two 'frequent' treatment sites between October 1995 and June 1996. There was an average visit interval of 7 days for the first approximately 135-day period but this interval extended to about 14 days during the latter part of the study.

Although no wind speed data are available, it was noticed that more COTS were injected at the 'frequent' treatment sites when the weather had been relatively calm for days prior to the visit. This may be due to more individuals adopting exposed positions during calm weather, or to increased migration between reefs during such periods, or both. It is unlikely that the difference was cause by increased diver effectiveness in calm weather because the same area was searched with the same degree of thoroughness under both calm and rough conditions.

This study indicates that the most effective strategy of controlling COTS numbers in areas of existing high COTS density is to apply an intensive eradication effort initially and to follow up with frequent, less intensive effort. However, the initial density of COTS, the rate of migration and the degree of effort required to significantly lower the densities may not be sufficient to have a beneficial result on coral cover (Fisk et al. 1996). Migration into the experimental patch reef sites means that COTS had to cross at least several tens of metres of sandy bottom. Migration rates may well be higher into small areas of larger reefs in which attempts are being made to control COTS numbers. This points to the importance of determining the most effective interval between visits for a 'frequent' injection regime for both continuous reefs and patch reefs. This frequency will change with time, depending upon the stage of the COTS outbreak (which will affect the size of nearby populations and the source of migration) and possibly upon the recent weather conditions. Input into the population from the annual recruitment cycle also needs to be addressed, perhaps with an additional intensive treatment each year at the stage when young COTS first become active on corals.



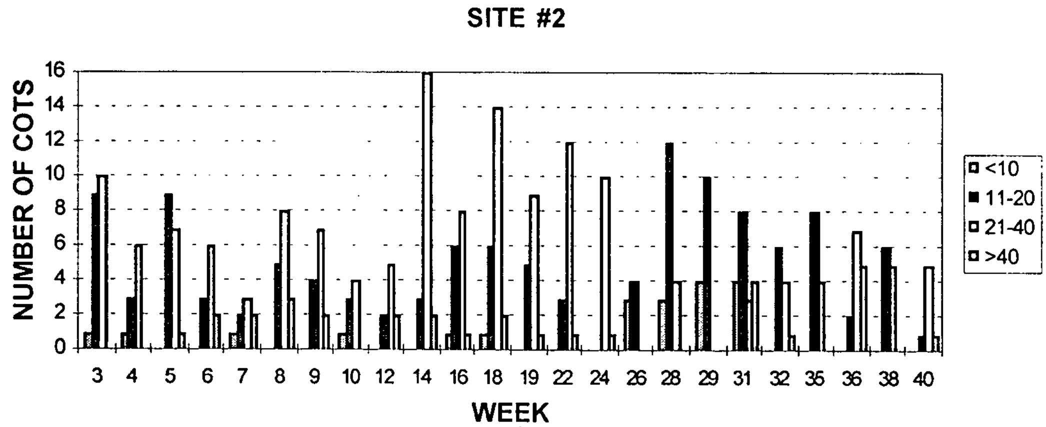


Figure 3. Size classes of injected COTS from the 'frequent' injection sites (#1, 2). Weeks refer to the number of weeks to June 1996 following the commencement of injection visits in October 1995. The legend shows the 10 cm interval size class categories.

Table 1. Injection efficiency at the 'frequent' sites (#1, 2) and at the 'infrequent' sites (#3, 6) from October, February, and June. The 'frequent' sites were regularly visited between these main survey trips. Initial COTS density refers to the belt transect estimates (belt transect area covered 1/10 of a hectare) of density prior to injection treatments. Post-injection densities are repeat surveys of the same areas at the end of each survey trip. The reduction efficiency in COTS densities are calculated from the initial and post-injection values.

Treatment	Effort (person hrs)	Diver efficiency (COTS/hour)	Initial density (COTS/ha)	Post-inj. density (COTS/ha)	Reduction Efficiency (%)
Frequent					
Oct 95	4	18	280	240	14%
Feb 96	4	10	85	-	-
Jun 96	4	5	45	5	89%
Infrequent					
Oct 95	14.2	12	360	165	54%
Feb 96	11	6	310	45	85%
Jun 96	14	8	105	-	-

This study has shown that diver experience is an important factor affecting the efficiency of control measures. A person experienced in both diving practice and in locating COTS is much more efficient in the injection procedure than an inexperienced person. This is due to that person developing a clear 'target image' and a learnt ability to rapidly find a COTS associated with a feeding scar. The target image refers to a diver's ability to instantly locate a small portion of a well-hidden COTS from a background mosaic of very different shapes and colours, usually by observing a small number of spines or part of an arm. Efficient search methods are the key to this learnt ability to find cryptic COTS and this can mean that a diver adopts an oblique observation position with a circular swimming motion at a distance of 1–2 m from the feeding scar so that the underside of corals and overhangs are surveyed.

ACKNOWLEDGMENTS

Thanks to all those who helped with the field work, in particular M. Portefaix and the staff at the Lizard Island Research Station. We appreciate Leon Zann's contribution with editorial comments on the draft.

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An alternative approach to the hydrodynamic design of infrastructure on the Great Barrier Reef: Norman Reef pontoon case study

SR Massel[1], IR Kapitzke[2] and PR Gleeson[2]
[1] *Australian Institute of Marine Science, PMB No. 3, Townsville Qld 4810*
[2] *Department of Civil & Systems Engineering, James Cook University Qld 4811*

ABSTRACT

The Great Barrier Reef Marine Park Authority stipulates a Category 4 tropical cyclone condition as the single criteria for the hydrodynamic design of tourist pontoon installations throughout the Great Barrier Reef region. Whereas tourism operators and designers criticise this approach to the selection of cyclone intensity as being too conservative for both structural safety and environmental protection, the rudimentary approach that designers conventionally use to determine design wave height may produce a non-conservative design that threatens pontoon safety. We use an alternative approach in a case study on the Norman Reef pontoon near Cairns and compare results with those used in the design of the installation. We propose that design cyclone intensity should be related to location within the Great Barrier Reef, acceptable risk of failure, and structure design life, and we show how the cyclone track and the wave prediction method significantly affect the design wave height incident on the pontoon. These findings are useful in the review and update of existing guidelines for pontoon installations on the Great Barrier Reef.

INTRODUCTION

Tourist pontoons, anchored on outer reef sites of the Great Barrier Reef, are important facilities for viewing the Reef and catering for increasing tourist demand. These installations must withstand severe tropical cyclone conditions, provide for the function and safety of the structure, and provide for the protection of the sensitive coral reef environment where they are located. Many tourism operators and designers are critical of the Category 4 cyclone criteria stipulated by the Great Barrier Reef Marine Park Authority for the hydrodynamic design of the pontoon structures and their moorings, claiming a substantial increase in the cost of the developments and unnecessary delays in project implementation. Hydrodynamic design for these structures involves choice of a cyclone intensity that provides an acceptable level of risk against failure and damage, and determination of the design wave height incident on the structure for this event. Whereas the Category 4 cyclone criteria may contribute to a *conservative* design with relatively low risk, the rudimentary analyses that are sometimes used for the wave design component may either overestimate the design wave height and further contribute to a *conservative* design, or alternatively underestimate the wave and thereby contribute to a *non-conservative* design. The present approach may therefore lead to an over-designed pontoon installation with excessive mooring hardware or to an under-designed structure with an unacceptable risk of breaking free from its moorings, damaging the adjoining coral reef, and threatening the safety of pontoon passengers and shipping in and adjacent to the Great Barrier Reef lagoon.

In this paper we address the shortcomings of the conventional method and use an alternative hydrodynamic design approach in a case study on the Norman Reef pontoon near Cairns. To determine cyclone intensity, we propose a risk assessment approach that takes account of structure location, structure design life, and the levels of acceptable risk for safety and for reef damage. For design wave height, we adopt a more rigorous approach that accounts for the cyclone track and the effects of the neighbouring reef matrix on waves incident on the pontoon.

Design criteria and background

The first tourist pontoons installed on the Great Barrier Reef in the early 1980s were barge-like structures less than 20 metres in length with improvised mooring systems, comprising chains and miscellaneous concrete and steel anchors. As larger and more complex installations were developed, and following a series of failures of pontoon components and damage to the reef at Lady Musgrave Island, Wistari, Agincourt No. 4, Kelso and Moore reefs in the late 1980s, Great Barrier Reef Marine Park Authority implemented the *Draft Pontoon Guidelines* (GBRMPA 1991) with the intention of providing a consistent approach to the design and assessment of these structures (Cook 1992). The *Draft Guidelines* adopt a precautionary approach, stipulating conservative Category 4 design criteria to account for shipping safety from mooring failure, and for environmental protection from mooring damage to the reef. Great Barrier Reef Marine Park Authority is potentially liable for human life and property losses resulting from mooring failure and is also obliged to protect the environmental integrity and the natural and cultural resources of the Great Barrier Reef World Heritage Property (Cook 1992). The conservative design criteria are further justified by Great Barrier Reef Marine Park Authority on the basis of the difficulties in the accurate determination of wind wave characteristics in the coral reef environment, a poor understanding of wave induced processes, absence of data on cyclone waves in the Great Barrier Reef, and shortage of data on the historical occurrence of cyclones, particularly in offshore areas and at specific reef sites.

On the contrary, many marine park tourism industry pontoon operators and designers consider the criteria are excessive, both in terms of safety and environmental protection. A Category 4 cyclone event has an average recurrence interval (ARI) of 500 years or more for most areas along the Queensland coast and these operators and designers claim that the design criteria for pontoon mooring safety is therefore not compatible with criteria for terrestrial installations. With regard to environmental protection of the reef, some claim that it is futile to provide such conservative criteria for pontoon-related damage when the reef is itself damaged by the cyclonic conditions. Nevertheless, environmental protection is vital for the future viability of pontoon operations as very few sites are available that meet the strict criteria for suitability (Massel et al. 1995).

Whereas the Category 4 cyclone criteria embodied in the *Draft Guidelines* has greatly reduced safety and environmental risks for pontoon installations, inequities and inconsistencies remain. A single criteria for cyclone intensity across the Great Barrier Reef region does not account for the spatial variability in the occurrence of cyclones of particular intensities; a Category 4 cyclone is more likely to occur in the Cairns and Central Sections of the Marine Park than in southern parts. The risk level is also inequitable because the design life of the structure is presently ignored; a temporary structure is less likely to experience an extreme event during its lifetime than a semi-permanent pontoon which may be moored in place for 10 or more years. A single design criteria ignores the differing conditions that may apply to safety and environmental protection of the pontoon; the level of acceptable risk for mooring failure threatening safety probably differs from that associated with pontoon or mooring movement which damages the reef.

Norman Reef pontoon

Norman Reef is a small platform reef, approximately 4 km^2 in area, located on the outer Great Barrier Reef approximately 60 km north of Cairns (figure 1). The Norman Reef pontoon is a modern installation operated at the site by Great Adventures. Serviced by a high speed catamaran that brings up to 500 visitors daily from Cairns, the pontoon provides a wide range of activities including reef viewing, snorkelling, scuba diving, underwater viewing and fish feeding. The pontoon structure is approximately 50 metres long x 16 metres wide, moored with a four point system that incorporates chains, concrete dumper and anchor blocks, and grouted screw anchors.

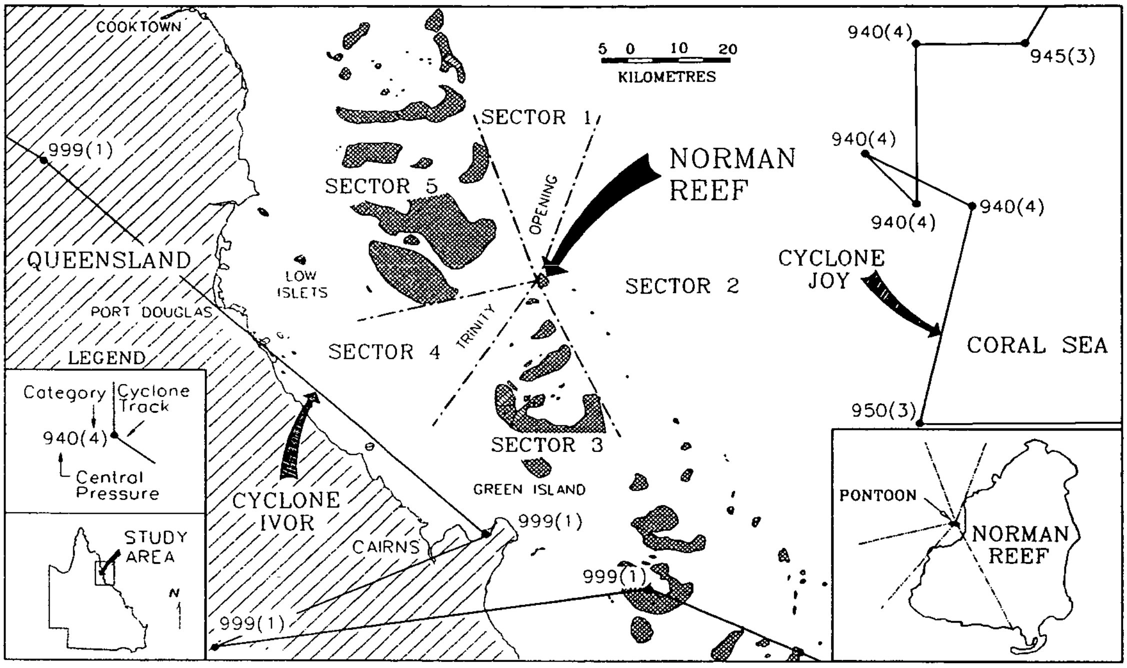

Figure 1. Norman Reef locality

Two distinct wave environments affect the Norman Reef pontoon and other outer reef sites on the Great Barrier Reef. Firstly, waves generated in the deep water ocean environment to the east of the reef are propagated into the reef system and may impact the pontoon. Secondly, waves generated within the reef environment to the west of Norman Reef are affected by the matrix of reefs within the Great Barrier Reef lagoon and are modified by dissipation, reflection and diffraction as they propagate through the reef system. Waves generated within the reef lagoon are generally smaller than the deepwater ocean waves because of the limited fetch distances between the pontoon site and the mainland coastline. Like other outer reef installations, the Norman Reef pontoon is located on the coastal (western) side of the reef and is therefore protected from open water conditions to the east (figure 1). The site is, however, exposed to open water wave conditions to the north, and large deepwater waves may therefore reach the pontoon from this direction, propagating through openings in the reef matrix. Waves incident on the reef from the east are attenuated as they propagate across the shallower water depths on the reef top (transmission), or are diffracted around the end of the reef to the pontoon site (diffraction).

To determine waves incident on the pontoon from various directions, the seascape surrounding Norman Reef has been divided into five sectors (figure 1). Sector 1 represents a 40° opening in the reef matrix from 20° west to 20° east of north. Sector 2 (150°) encompasses the open ocean region to the east which is sheltered from the pontoon site by Norman Reef. For Sectors 3 (south) and 5 (north-west), significant portions of the coastal side of Norman Reef are sheltered by the neighbouring reef matrix. Sector 4 is a 40° opening to the south west (Trinity Opening) through which waves generated in the reef lagoon may propagate onto the pontoon site. The critical wave conditions incident on the site may therefore be: (i) Sector 1 deepwater ocean waves; (ii) Sector 2 deepwater waves attenuated by Norman Reef; and (iii) Sector 4 fetch-limited waves generated within the reef lagoon.

Risk assessment and cyclone intensity

Whereas pontoon location and acceptable risk level for failure of the structure or damage to the reef do not feature in the Great Barrier Reef Marine Park Authority's Category 4 cyclone criteria, these factors can be incorporated in an alternative risk assessment approach that takes account of the encounter probability of cyclones of various intensities at a particular site. In this approach, once the acceptable level of risk or probability of occurrence (P) is adopted for a particular site and type of installation, the average recurrence interval (ARI) for the design cyclone occurring within the life of the structure (L) can be determined from the following relationship:

$$ARI = \frac{1}{1-(1-P)^{1/L}}$$

For the hydrodynamic design of the Norman Reef pontoon, the designers have adopted a 100 year ARI synthetic cyclone condition, in lieu of the Category 4 criteria, to match mooring integrity and structure safety criteria for other marine structures. Furthermore, they advocate a 20 year ARI cyclone for the environmental protection condition. The design uses the relationship between ARI and central pressure for cyclones occurring within 185 km of the coast near Cairns, established by the Beach Protection Authority (BPA 1984). The BPA cyclone intensity and ARI data for the Cairns region are presented in table 1, together with the estimated maximum wind speed, cyclone category, and probability (P) of the cyclone occurring within a 20 year period. The table shows that the likelihood of cyclone occurrence within a structure life of 20 years varies from P = 4% for a Category 4 cyclone (500 year ARI, central pressure = 946 hPa); to P = 18% for a 100 year ARI cyclone (958 hPa); and to P = 64% for a 20 year ARI cyclone (970 hPa).

Table 1. Cyclone characteristics for coastal zone within 185 km of Cairns

Average Recurrence Interval – ARI (yr)	Mean Central Pressure (hPa)	Estimated Maximum Wind Speed (m/s)	Cyclone Category	Probability of Occurrence – P (%) for L = 20 yr
2	987	26	2	99.99
10	975	34	2	88
20	970	37	2	64
50	963	41	3	33
100	958	44	3	18
500	946	50	3 / 4	4

In an alternative hydrodynamic design approach for the Norman Reef site, we use two actual and one synthetic cyclone designs for storms passing within close proximity of the pontoon (figure 1). These are (A) – cyclone Joy (Category 4, actual, December 1990) which passed 60 km east of the site; (B) – cyclone Ivor (Category 1, actual, March 1990) which passed 40 km west of the site; and (C) – cyclone 'Ivor' (Category 4, synthetic) which follows the same track as Case B. Using the data from table 1, and by examining historical data on cyclone tracks from 1910–1982 (after BPA 1984), we have estimated the probability of occurrence of these events for comparison with results from the original project designs.

Design wave height

Conventional pontoon hydrodynamic design approaches commonly use Young's second generation model (Young 1989) for deep water wave prediction, and methods based on the Shore Protection Manual (SPM 1984) for attenuation. The SPM approach does not adequately allow for the sheltering effects of the reef matrix and coastline, but these factors are incorporated in an alternative approach initially developed by Krylov (1966) and outlined by Massel (1996). This method analyses energy in spectral components propagating within a specified angle range between adjacent reefs, and is not limited to broad open water conditions as are most deepwater wave prediction models.

Designers for the Norman Reef pontoon have considered the Sector 2 deepwater waves attenuated by Norman Reef and the Sector 4 fetch-limited waves generated within the reef lagoon. They ignore the Sector 1 deepwater waves or have incorporated these within Sector 2. Using Young's deepwater wave model and a rudimentary approach for attenuation and sheltering effects, they estimate wave heights for a 950 hPa cyclone (100 yr ARI – safety criteria) and a 970 hPa cyclone (20 yr ARI – environmental criteria) passing within 50 km of Norman Reef. Table 2 presents the results for the 100 yr ARI event for Sectors 2 and 4, including the deepwater wave height and period, the most severe wave incident at the pontoon site, the cyclone characteristics, and the encounter probability for a 20 year pontoon life.
In the alternative approach, we consider the Sector 2 waves attenuated by Norman Reef and the Sector 1 deepwater ocean waves that propagate through the reef matrix directly onto the

pontoon site (after Gleeson 1996). We have ignored the Sector 4 fetch-limited waves as these are less severe than the Sector 1 condition. The analysis shows the most severe conditions are Case A – cyclone Joy (940 hPa) for Sector 2 waves, and Case C – cyclone 'Ivor' (940 hPa) for Sector 1 waves. We have used Young's model for the Sector 2 deepwater waves and Krylov's method for deepwater waves propagated through the 400 opening in Sector 1. Transmission and diffraction effects for Sector 2 are based on Massel (1996). Results are presented in table 2.

Table 2. Cyclone and wave parameters for Norman Reef

Design Case	Cyclone Average Recurrence Interval - ARI (yr)	Cyclone Mean Central Pressure (hPa)	Cyclone Category	Probability of Occurrence – P (%) for L = 20 yr	Critical Sector for Waves	Deep-water Wave Height (m) / Period (s)	Wave Height at Pontoon Site (m)
Original Design - safety	100	950	3	18	2 4	7 / 8 – 12 5 / ?	4 3
A – cyclone Joy	500	940	4	4	2	11.8 / 14.1	2.5
B – cyclone Ivor	< 2	995	1	~100	1	1.5 / 5.7	1.5
C – cyclone 'Ivor'	>> 500	940	4	<< 4	1	10.3 / 12.5	10.2

Comparison of design approaches

Some comparisons can be made between alternative design approaches on the basis of the wave heights and cyclone intensities presented in table 2 for the various design cases. In Sector 2, the original design predicts larger waves than for Case A at the pontoon site (4 m cf. 2.5 m) although the cyclone intensity is less, the probability of occurrence is greater, and the predicted deepwater wave height is less. This shows that the rudimentary approach used by the project designers to determine the wave attenuation from Norman Reef yields slightly *over-conservative* results, whereas the alternative approach (Case A) using transmission and diffraction studies provides more realistic results. No direct comparisons can be made within Sector 1 as the original design did not separately consider the deepwater waves incident from this direction. Nevertheless, and in spite of its very low probability of occurrence (<< 4 %), the predicted 10.2 m wave from Case C provides a far more severe condition than the worst case original design for the site (4 m – Sector 2). This indicates that the present structure design may be *non-conservative* and demonstrates the shortcomings of conventional approaches that do not adequately account for the propagation of waves through the reef matrix. The alternative approach using Krylov's method examines a more severe condition, but provides a more realistic wave height determination for Sector 1. This method is also suited to Sector 4, where the rudimentary wave height analysis undertaken in the original design has most likely produced *over-conservative* results.

CONCLUSIONS

The present approach to hydrodynamic design is limited both in the selection of the cyclone intensity and in the determination of design wave height. Notwithstanding the importance of a precautionary approach for safety and environmental protection for the pontoons, the present approach which stipulates a single Category 4 criteria across the region is too simplistic. Other factors such as location, structure design life and level of risk should be incorporated into the selection of cyclone intensity. Furthermore, the commonly used rudimentary approach to wave height prediction is not able to satisfactorily take account of the cyclone track and the attenuation effects on waves propagating through the reef matrix. The risk assessment approach to the selection of cyclone intensity, and the more sophisticated wave height prediction methods such as those developed by Krylov, are more suited to the complex environmental conditions of the Great Barrier Reef. This alternative approach not only provides flexibility for the Great Barrier Reef Marine Park Authority to meet the various requirements for safety and environmental protection, but also addresses marine park tourism operators' concerns about impractical over-conservative designs.

The hydrodynamic design approach recommended for pontoon installations on the Great Barrier Reef is (i) adopt a level of risk appropriate to the structure and the coral reef at the site; (ii) choose the design cyclone intensity corresponding to that risk; and (iii) determine the most severe wave height incident on the structure for that event. This approach should be further developed by undertaking other case studies that consider appropriate risk levels and cyclone intensities and examine cyclone track and directional distributions, and the effects of the reef matrix on design wave heights. The results are useful in the review and update of the existing *Guidelines* for pontoon installations in the Great Barrier Reef and in the refinement of hydrodynamic designs for exposed sites such as the Norman Reef pontoon.

ACKNOWLEDGMENTS

This research is supported by the Australian Cooperative Research Centres Program through the CRC Reef Research Centre. We acknowledge permission from Great Adventures and the designers of the pontoon installation at Norman Reef to use the project data in this study.

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Investigating future threats from tropical cyclones, storm surges and sea level rise

A Barrie Pittock, Kathy McInnes and Kevin Walsh
CSIRO Division of Atmospheric Research, PMB1, Aspendale Vic 3195

ABSTRACT

In this study, we investigate the possible impact of climate change on tropical cyclones, and how such changes may affect extreme sea level events. A brief review is presented of the current state of the science in relation to tropical cyclones under greenhouse conditions and of the approach being taken at the Division of Atmospheric Research using a regional climate model. A storm surge model is used to perform a simulation of flooding on Dunk Island caused by a severe tropical cyclone.

INTRODUCTION

Tropical cyclones and their associated storm surges are among the most destructive natural phenomena known. As population and tourism expands in the region, the effects of tropical cyclones and sea level rise due to global warming in Queensland will become increasingly important.

Knowledge of present day tropical cyclone climatologies combined with high-resolution storm surge modelling can provide the necessary information on extreme sea level heights and their probable recurrence interval for a range of coastal planning applications. However, this methodology could yield misleading results if climate change due to the enhanced greenhouse effect brings about a significant change to the cyclone climatology for a given region. Furthermore, where knowledge of extreme sea level recurrence intervals due to tropical cyclones is required, changes in the mean sea level due to climate change must also be considered.

The effect of climate change on tropical cyclones is presently uncertain. Nevertheless, there are several areas of active research. At the Division of Atmospheric Research, an early version of a regional climate model (DARLAM) has demonstrated a reasonable ability to simulate the current observed distribution of tropical cyclone numbers and tracks in the Australian region. Some results from this version of the model are shown. We plan to further improve the model's simulation of tropical cyclones so that it can be used to construct scenarios of the effect of climate change.

In this study, we investigate the extreme sea levels and flooding produced by tropical cyclones under present climate conditions. New techniques for determining the impact of climate change on tropical cyclone climatologies will be evaluated in order to deduce possible changes in tropical cyclone intensity, frequency and location of occurrence. Any estimated changes to cyclone climatology, together with estimates of global sea level rise, will then be used to investigate possible modifications to the extreme sea levels and inundation which may occur with changing climate.

Simulations of tropical cyclones using climate models

While there is some confidence in predictions of climate change for the mean climate of some atmospheric variables, predictions of the influence of climate change on tropical cyclones are uncertain (IPCC 1995; Walsh and Pittock 1996). Tropical cyclones are not yet well simulated at the horizontal resolutions typical of climate models. Additionally, in several regions of the globe, the numbers and geographical distribution of tropical cyclones are strongly influenced by ENSO (Evans and Allan 1992; Basher and Zheng 1995). Despite some recent advances in the ability of GCMs to simulate the present-day observed variations of ENSO (e.g. Roeckner et al. 1995), the state of ENSO in a changed climate remains unknown.

Nevertheless, climate models have great potential to answer some of the questions associated with the influence of the enhanced greenhouse effect on tropical cyclones. The recent work of Bengtsson et al. (1995) and Tsutsui and Kasahara (1996) showed that a climate model could be used to simulate a realistic climatology of tropical cyclone tracks and numbers in many regions of the globe. Here we discuss a related approach being used at CSIRO, in which a regional climate model (DARLAM) is nested within a lower-resolution global climate model and the tropical cyclone climatology of the Australian region is simulated.

Regional climate models have been used with some success to improve the simulation of climate compared to that produced by coarser-resolution global models (e.g. Giorgi et al. 1994; McGregor and Walsh 1994; Walsh and McGregor 1995; McGregor 1996). The ability of DARLAM to simulate the January climatology of tropical cyclones in the Australian region has recently been evaluated by Walsh and Watterson (1996). In this study, DARLAM was run at a horizontal resolution of 125 km and ten separate Januarys were simulated. Note that these model-simulated months do not correspond to any particular calendar months, as the tropical cyclone-like vortices were entirely generated within DARLAM and do not depend on day-to-day observations. It was found that DARLAM has a reasonable ability to simulate tracks and numbers of tropical cyclones, but only in regions where the mean climate of the model was good. Figure 1 shows tracks of the simulated tropical cyclone-like vortices. Here, tracks of storms weaker than observed tropical cyclone strength have been included to give a better indication of typical tracks. The tracks and regions of formation are similar to reality, although numbers of storms of tropical cyclone strength tend to be slightly underestimated compared to observations.

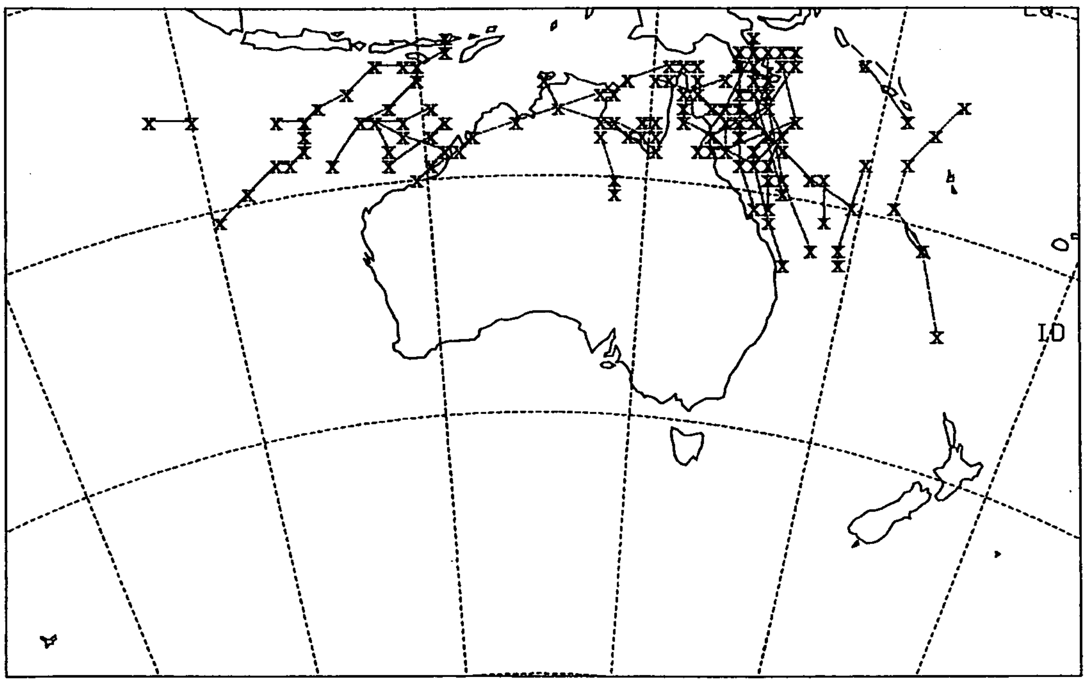

Figure 1. Cyclone tracks generated by DARLAM, for January conditions at 125 km resolution

Intensities of tropical cyclones are generally not well simulated by DARLAM at this resolution, however. This is not a surprising result, as the typical size of the region where the strongest winds occur in observed tropical cyclones, the eye wall region, is typically much smaller than the horizontal resolution of DARLAM used to generate figure 1. Higher horizontal resolution is necessary to obtain stronger storms and therefore a better representation of reality. We have therefore also simulated an individual tropical cyclone-like vortice at a horizontal resolution of 30 km to determine the impact of higher resolution. This is a 'multiply-nested' simulation in that the region simulated at 30 km is nested within the 125 km simulation, which is in turn nested within the global model. Figure 2 shows the results for two consecutive days of simulation. The contours are mean sea level pressure in hPa, while the shading is rainfall. At 30 km resolution, the storm is clearly more intense than at 125 km, with a lower central pressure and a much tighter gradient of isobars. This suggests that the use of higher horizontal resolution, perhaps using a multiply-nested approach to save computer time, could give an improved simulation of observed tropical cyclone intensities. However, there remains considerable work to be performed before numerical models can be used unambiguously to answer the questions surrounding the effects of climate change on tropical cyclones.

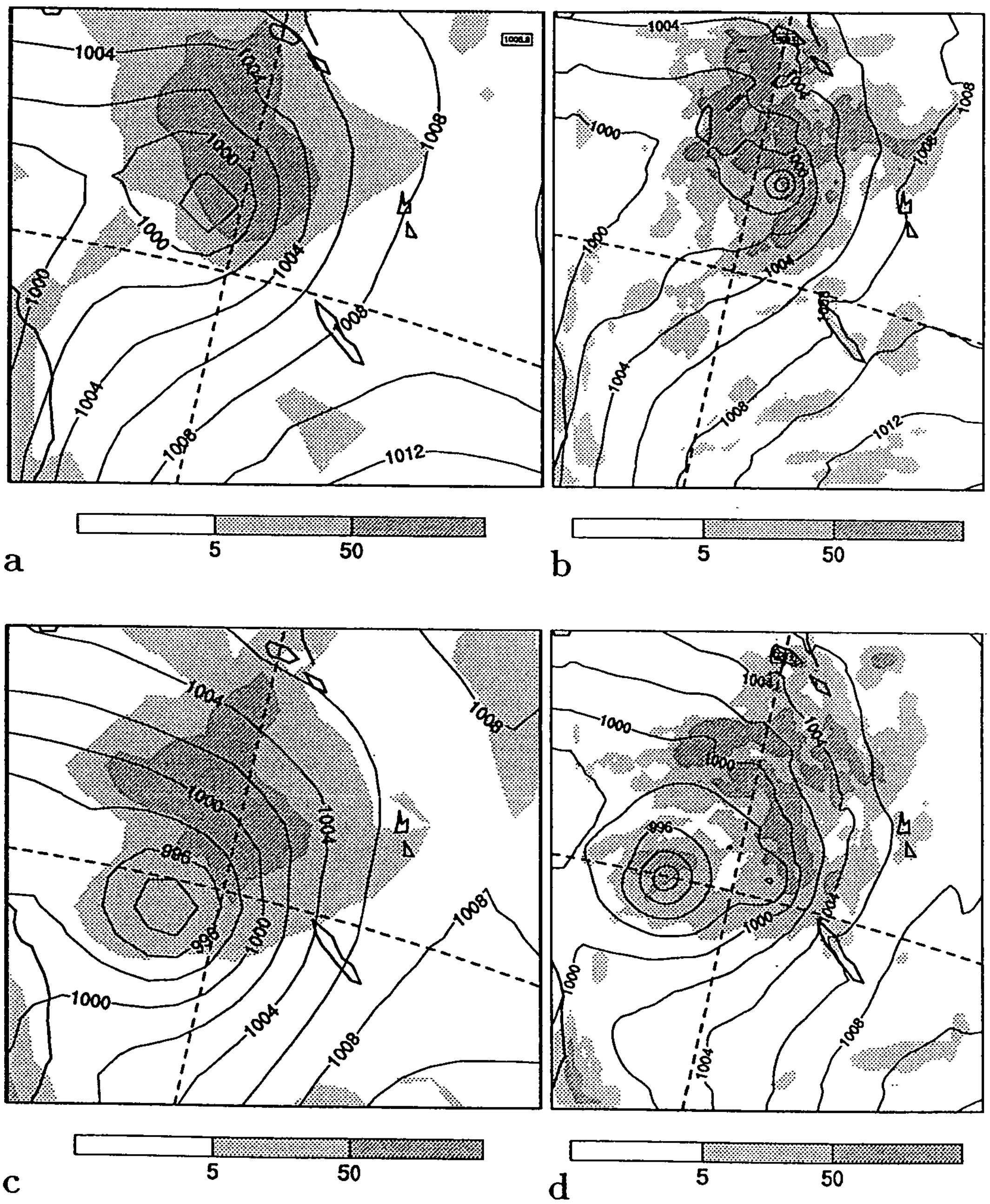

Figure 2. Simulated tropical cyclone near New Caledonia for two consecutive days: for (a) and (c), 125 km horizontal resolution; and for (b) and (d), 30 km resolution. Lines are mean sea level pressure in hPa, while shading is precipitation in mm per day.

Storm surge inundation modelling

The model used in this part of the study is the GEMS (Global Environmental Modelling Services) Storm Surge Inundation model. This model has been used in other storm surge inundation studies (e.g. Hubbert 1995; McInnes and Hubbert 1996). An important feature of the inundation algorithm developed for this model is the incorporation of a flow rate dependency on the rate of grid cell wetting and drying which is based on the modelled currents adjacent to the coastal interface. This approach gives more realistic flooding rates in wide relatively flat coastal margins compared with other more commonly used inundation techniques, where inland grid squares adjacent to the coastline become instantaneously flooded the moment the storm height exceeds the topographic height of the adjacent land cell (e.g. Falconer and Owens 1987).

An example of a tropical cyclone impacting on Dunk Island will be presented to illustrate the modelling technique. A set of cyclone parameters is chosen and the analytical cyclone model of Holland (1980) is used to generate surface wind and pressure fields. Figure 3 shows winds from a 922 hPa cyclone moving across the model domain with the cyclone path and coastal crossing point configured to maximize the impact on Dunk Island.

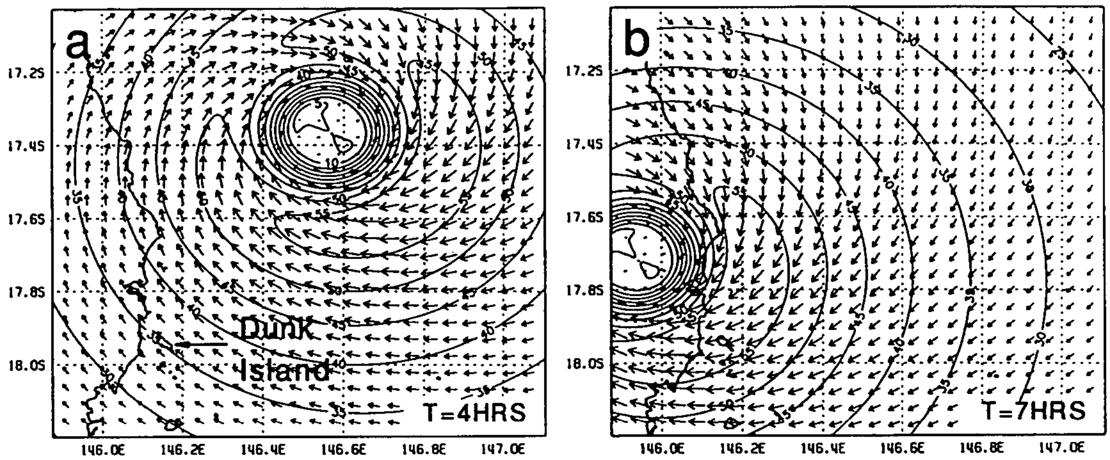

Figure 3. The winds field for a tropical cyclone configured with a central pressure of 922 hPa, tracking to the south-west to make landfall to the north of Dunk Island. Units are in m s^{-1}

A storm surge simulation is then performed at 1 km horizontal grid resolution over a large coastal region. This simulation provides the storm surge elevations for the open boundaries of the high resolution storm surge inundation simulations. For practical reasons, tidal effects are not applied on the outer boundaries of the low resolution domain and a fixed coastline version of the model is used. Figure 4 shows the storm surge elevations produced by the model at hourly intervals as the cyclone crosses the coast.

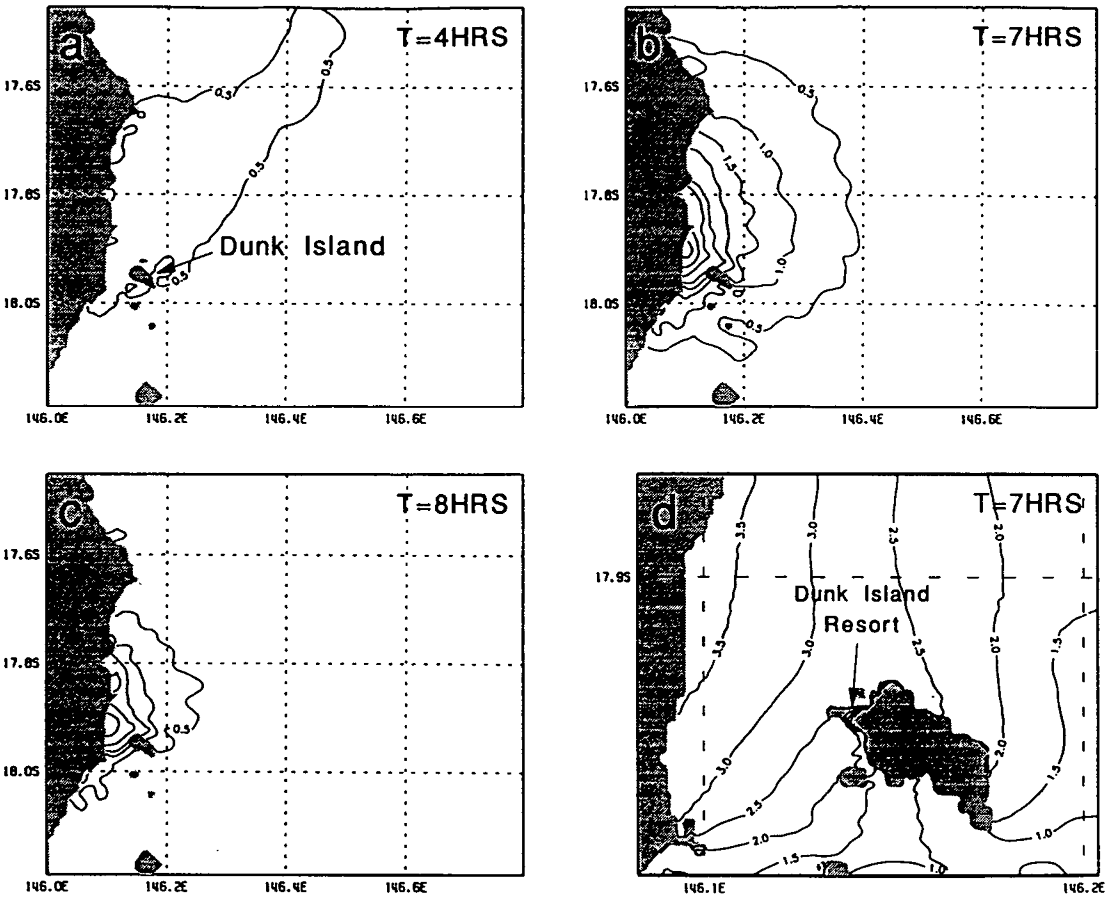

Figure 4. Simulated storm surge elevations on the outer domain for the times shown (a)–(c), and on the high resolution grid, at the time corresponding to the maximum surge produced (d)

A more detailed simulation at a horizontal resolution of 100 m is conducted on a smaller region centred on Dunk Island. Tidal phase and amplitudes can be applied to the boundaries of this inner domain, although in the present example, they have been neglected. The storm surge contours on the high resolution grid are shown in figure 5, while figure 6 illustrates the simulated ocean currents and the inland grid cells which have become inundated.

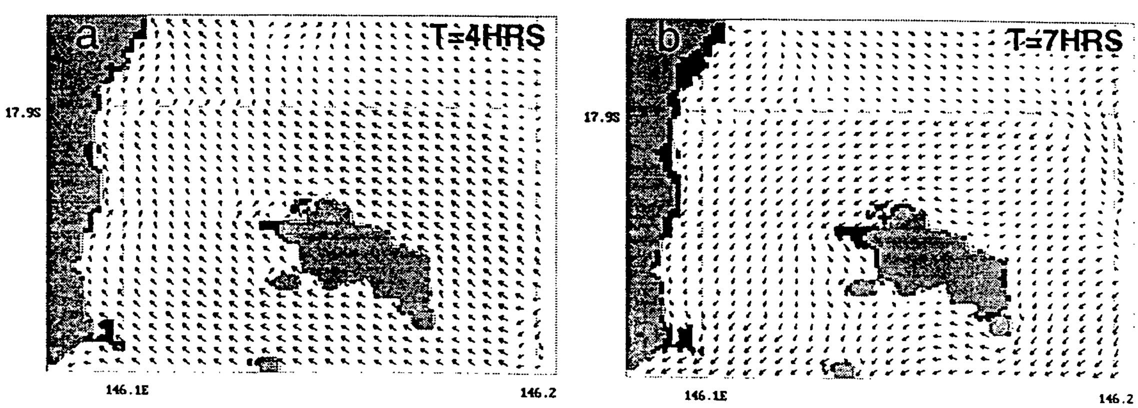

Figure 5. Modelled currents and inundated areas (shaded in black), for the times shown, on the high resolution grid

Although the peak surge occurs on the mainland coast, the lowest lying regions located on the westernmost part of Dunk Island are also flooded. It is in this region that the island's tourist resort is located, and it would probably be completely inundated.

CONCLUSIONS

In this paper, an ongoing study has been described which investigates the impact of climate change on tropical cyclone climatologies and their effect on extreme sea level return periods. A regional climate model is being used to better resolve the features of model generated tropical storms so that greater realism can be achieved for cyclone climatologies generated under present climate conditions. In this way, greater confidence can be placed in model simulations of changes which occur under enhanced greenhouse conditions. A model simulation of the storm surge resulting from a severe cyclone crossing the coast to the north of Dunk Island is presented and indicates that would become completely inundated.

In subsequent work, a Monte Carlo technique will be applied to run the storm surge model over a chosen region using present day tropical cyclone climatologies combined with tidal effects to estimate the likely recurrence intervals of extreme sea levels. The impact on these return periods of possible changes to the cyclone climatologies and mean sea level brought about the enhanced greenhouse effect will also be investigated.

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Tropical cyclone impacts on the coral reefs of the Great Barrier Reef region

Marjetta L Puotinen
Department of Tropical Environment Studies and Geography, James Cook University of North Queensland Qld 4811

ABSTRACT

Tropical cyclones can have significant long term impacts on coral reef ecosystems, such as the Great Barrier Reef, where reef damage has been documented from such storms as cyclones Ivor (1990), Joy (1990) and Celeste (1996). However, despite the importance of the Great Barrier Reef from both an environmental and economic standpoint, no study has assessed the long-term risk of cyclone damage to individual reefs throughout the entire region. Understanding cyclone impact risk to Great Barrier Reef reefs requires examination of the entire region over time because 1) cyclone forces impact reef structures within days or hours, 2) a single storm can impact a large area of the region at once, and 3) over time storms repeat over the entire region. My goal is to model the distribution of cyclone impact risk across the reefs of the Great Barrier Reef from 1969 to 1996 by integrating meteorological, ecological and spatial models within Geographic Information Systems (GIS). As the first reconstruction of cyclone impact across the entire Great Barrier Reef, this study will have two main outputs: 1) identification of reef areas most likely damaged by cyclones over the past 27 years, and 2) estimates of the 'return times' for cyclones capable of causing ecologically significant damage at each reef site.

INTRODUCTION

Tropical cyclones can have significant long term impacts on coral reef ecosystems. In the Great Barrier Reef region, damage to coral reefs has been documented from such storms as cyclones Ivor (1990), Joy (1990) and Celeste (1996) Although many studies worldwide have investigated the impact of cyclones on reefs, most have concentrated on very local spatial and temporal scales, such as for a reef or a single group of reefs (Woodley et al. 1981), or for a single species (Massel and Done 1993), and often for a single storm (Done 1992b). In the Great Barrier Reef region, studies have covered only a fraction of the area's almost 3,000 reefs and only a few of the 77 storms recorded by the Bureau of Meteorology (1996) since 1969. Thus, despite the importance of the Great Barrier Reef from both an environmental and economic standpoint, no study has assessed the risk of cyclone damage to reefs across the *entire* region.

Yet understanding the risks to Great Barrier Reef reefs from cyclones requires a broad scale approach encompassing the entire Region over a long time series for several reasons. First, cyclone forces impact entire reef structures, not just individual corals, affecting the function of the whole ecosystem, not just the integrity of its parts. Second, a single cyclone can impact a large proportion of the Great Barrier Reef at once, and over time storms repeat over the entire Region. Further, as is typically the case with coral reefs, patterns of impact cannot be resolved at very local scales (see Green et al. 1987), due to high natural variability in the reef characteristics that influence its vulnerability to damage. Finally, resolving the impacts of disturbances that operate over areas larger than that under study ('scaling up') is questionable (Green et al. 1987; Hatcher et al. 1987; Turner et al. 1993).

METHODOLOGY

A three-step 'recipe' for modelling cyclone impact risk

To improve our understanding of the long term impacts of cyclones on the reefs of the Great Barrier Reef, I have developed a simple, three-step 'recipe' for examining cyclone impacts from 1969–1996 using Geographic Information Systems (GIS). Storms earlier than 1969 are not considered due to the poor quality of the data (Holland 1981).

The potential for impact of a natural hazard on a resource depends on both the intensity of the hazard and the vulnerability of the resource to damage. Therefore, my approach involves modelling 1) the distribution and concentration of cyclone energy for each storm (the hazard) and 2) the exposure and structural resistance of reefs to that energy (vulnerability), to 3) predict the likely level of physical damage (low, medium, or high) to each reef (divided into four sites: NE, NW, SE, SW) for each storm that has passed through the region since 1969 (figure 1). The results will be field tested with

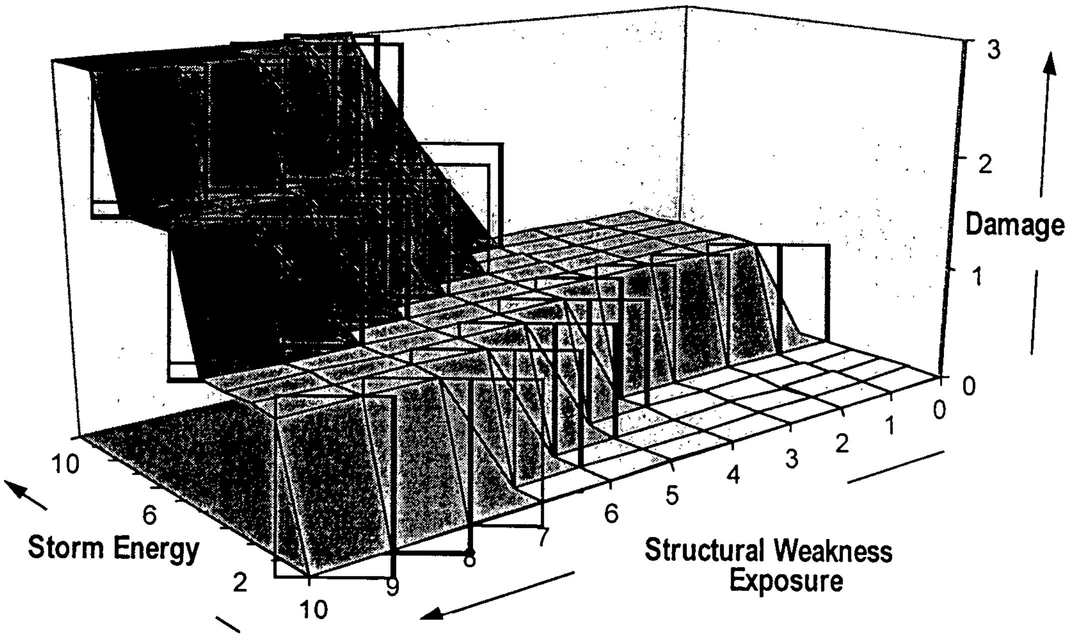

Figure 1. Factors determining cyclone impact risk across the Great Barrier Reef region

historical data from cyclones Ivor (1990), Joy (1990) and Celeste (1996) and possibly damage surveys of storms that pass through the Great Barrier Reef region during the upcoming 1996–97 cyclone season.

Planned project outputs

As the first reconstruction of cyclone impact on coral reefs across the entire Great Barrier Reef, this study will have two main outputs: 1) identification of coral reef areas most likely damaged by cyclones over the past 27 years, and 2) estimates of the 'return times' for cyclones capable of causing ecologically significant damage at each coral reef site. In addition, a technical report entitled, 'An Atlas of Tropical Cyclones in the Great Barrier Reef Region: 1969–1996' is currently in press. The purpose of this extensive set of 100 maps and 50 charts is to provide a compilation of the paths of tropical cyclones through the Great Barrier Reef region and their basic characteristics from 1969–1996 (Puotinen et al. in press). In the atlas, the cyclone data is illustrated by three types of maps and charts: 1) *overview:* maps of the number of cyclones, path crossings, and length of path crossings by 1° latitude and 1° longitude boxes and charts by 1° latitude blocks, 2) *yearly:* maps of all the cyclone paths in the vicinity of the region separately for each year, and 3) *closeup:* maps of every cyclone path in the Great Barrier Reef divided into 2° longitude and 1° latitude blocks (figure 2, last page).

ACKNOWLEDGMENTS

This work is partially supported by the CRC Reef Research Centre, through Dr Terry Done of the Australian Institute of Marine Science. Some baseline GIS data in the maps in figure 2 were provided by the Great Barrier Reef Marine Park Authority through a cooperative agreement.

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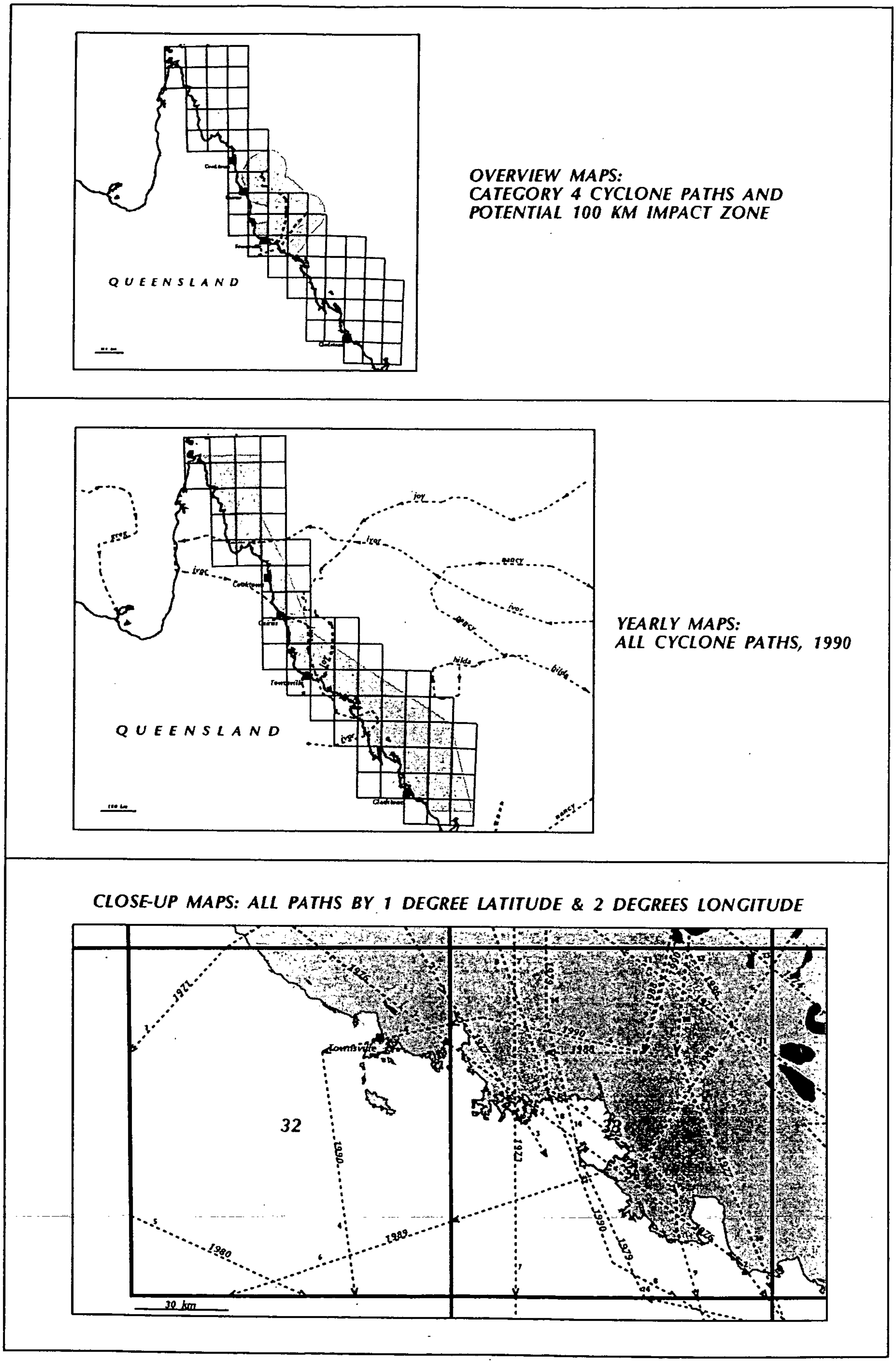


Figure 2: *Sample maps of those provided in, "An atlas of tropical cyclones in the Great Barrier Reef Region: 1969-1996."*

ADDITIONAL SESSION

Management-science links

Pontoon dynamics in a coral reef lagoon: numerical modelling and field studies

MF Britton[1] and AJ Johnston[2]
[1] Postgraduate student, CRC Reef Research Centre, James Cook University Qld 4811
[2] Head, Department of Civil & Systems Engineering, James Cook University Qld 4811

ABSTRACT

The increase in the number of visitors to the Great Barrier Reef has resulted in the need for larger tourist pontoons, located on the outer reef. The understanding of the structural dynamics of pontoons in the unique hydrodynamic loading environments of the Great Barrier Reef is uncertain, and there is a need to quantify the effects of current, wind and wave forces on pontoons and mooring systems, not only to resist cyclonic loads but also to minimise coral damage and provide added comfort for pontoon visitors. This paper gives the results from the experimental validation of a mathematical model written to determine tension / displacement characteristics of a typical Great Barrier Reef multicomponent catenary mooring system. This model will provide a tool for applying 'quasi-static' or 'dynamic' techniques to mooring system design. An inertial measurement unit (IMU), that utilises accelerometers and angle sensors to provide motions in six-degrees-of-freedom, has been purchased and installed at Norman Reef pontoon. Preparations for its installation, including laboratory performance testing and development of a data acquisition program, are discussed, and preliminary field results obtained since installation in September 1996 are presented. Objectives of the study are: to improve the understanding of the dynamics of pontoons located in the Great Barrier Reef; to utilise dynamic analysis results from a finite element hydrodynamic model (AQWA) to evaluate conventional'static'design approaches; and to undertake field measurements to verify the results from the numerical model.

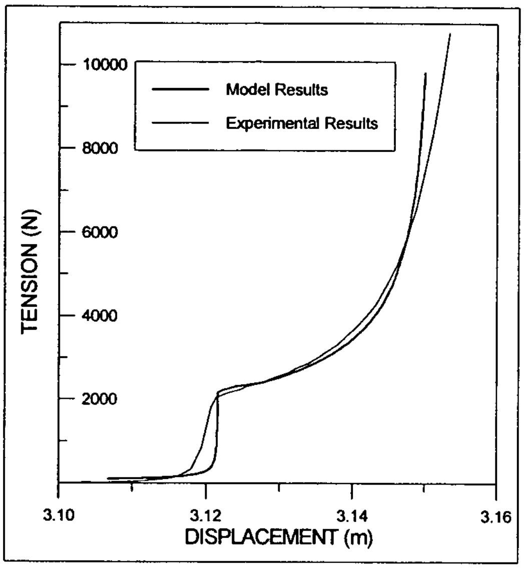
INTRODUCTION

The majority of pontoons in the Great Barrier Reef are moored by an array of multicomponent mooring lines consisting of heavy chain, a permanent anchor and a dumper block. This type of arrangement provides additional mooring stiffness when the length of chain is restricted because of shallow water and the lack of space associated with mooring pontoons close to reefs. As a result, the tension/displacement characteristics of these moorings are very non-linear.

The dynamics of mooring systems has only recently been considered an important aspect of mooring design. The problem is complex and difficult to model and, therefore, dynamic analysis is almost exclusively restricted to large offshore drilling operations due to prohibitive cost. Conventional design techniques for the small scale tourist pontoons within the Great Barrier Reef are purely static and do not include any dynamic effects that normally increase predicted tensions in mooring lines (Van den Boom 1985). Designs for Great Barrier Reef moorings to resist cyclonic loadings are usually conservative, not only due to the approach used to determine cyclone intensity and design wave height (Massel et al. 1996), but also as a result of the factors of the safety that are applied in the mooring design. This investigation attempts to provide designers with techniques for applying aspects of dynamic analysis to conventional design methods, so that mooring designs are improved.

Static tension/displacement model

A tension/displacement model for catenaries has been written and validated through a small scale experimental study (Tesolin 1995). The study also successfully validated numerical studies (Ansari 1980) for multicomponent mooring lines. Figure 1 illustrates the non-linear horizontal tension/displacement characteristics exhibited by a typical Great Barrier Reef mooring arrangement, and provides a comparison between model and experimental results.



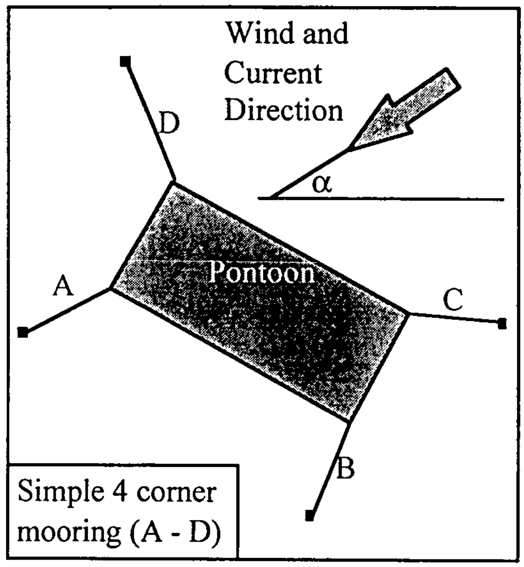


Figure 1. Model v. experimental results

Figure 2. 2-dimensional static model

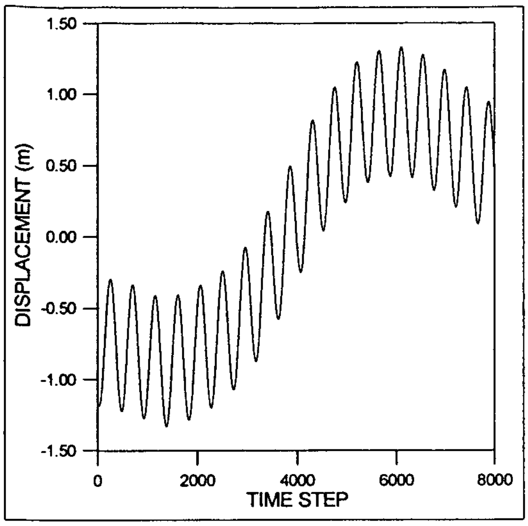
For static and equilibrium analysis of a mooring system, the relationship described in figure 1 can be evaluated for each individual mooring line and combined to give a simple 2-dimensional static model (refer figure 2) of a mooring system under mean wind and current loading (similar to Ansari 1991). Incident angle α can be defined for each loading source, the magnitude of which is dependent on pontoon draft for current forces, and windage for wind forces. The solution to the problem involves force and moment equilibrium in the horizontal plane and provides the basis for the application of dynamic wave frequency motions to static design procedures. Little is known, however, of the nature and magnitude of pontoon motions, particularly under severe cyclonic conditions.

Inertial Measurement Unit (IMU)

The IMU (Watson Industries, USA) is a state-of-the-art solid state gyro system incorporating a magnetometer for heading measurement, rate gyros for the angular measurements and three orthogonally mounted linear accelerometers to measure acceleration. Output format is 14 bit binary, allowing a potential resolution of 0.2 mg for acceleration and 0.02° for angle measurements, and the sampling rate is dictated by the number of channels accessed, with a maximum of 58 Hz for the 6 primary channels.

Extensive laboratory performance testing of the IMU was undertaken (Wright 1996) prior to field installation. Tests to evaluate accelerometer performance involved a Wave Rider Buoy Testing Apparatus, modified to apply 2-D fixed amplitude sinusoidal motions to the IMU. The amplitude of the circular motions was set at 0.94 m and period of rotation was approximately 8 seconds.

Accelerations were manipulated in EXCEL using a simple trapezoidal method to derive displacement, however, approximations of boundary conditions and integration constants resulted in considerable integration drift in the displacement series (refer figure 3). This drift was successfully eliminated using a numerical procedure which evaluated relative positions of individual peaks and troughs (refer figure 4).



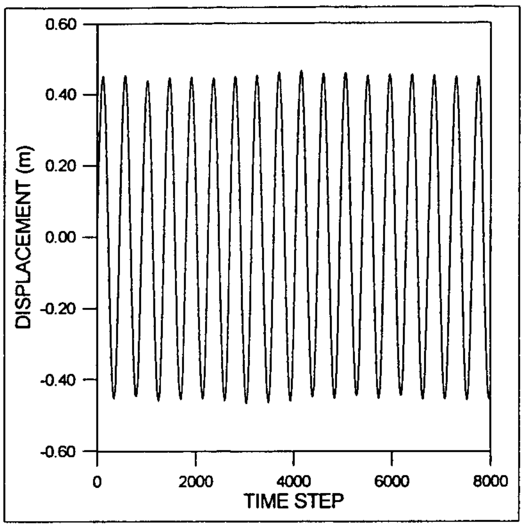


Figure 3. Vertical displacement (with drift)

Figure 4. Adjusted vertical displacement

The data recording software supplied with the IMU is capable of recording only 5 minutes of data in a low resolution decimal format, and proved insufficient for field conditions. A data acquisition program was therefore written in Visual Basic to address specific laboratory and field recording requirements, and to provide a visual interface for pontoon visitors.

The IMU was installed at Norman Reef pontoon, located on the coastal (western) side of the reef at latitude 16°25'32.7" south and longitude 145°59'27.0" east, approximately 60 km from Cairns in the Great Barrier Reef lagoon. The Norman Reef pontoon is operated by Great Adventures Outer Reef Tours and is protected from the east and south-east by the adjacent reef except for waves that travel across the reef at times of high tide, however, the pontoon and inner edge of the reef has minimal protection from waves approaching between the north-east and west. As a result, the site has potential for significant direct exposure to wave energy during severe cyclonic conditions, predominantly from deep water waves rounding the northern tip of the reef through Trinity Opening (refer figure 5).

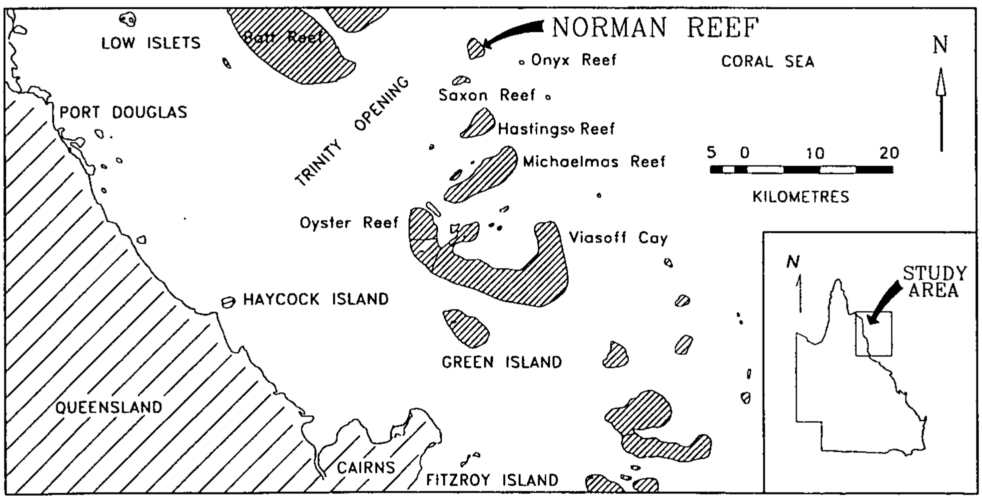


Figure 5. Site map of Norman Reef

This exposure of Norman Reef pontoon to severe cyclonic conditions was a major consideration in the choice of site for this research project. Other important factors considered were locality, access to mooring and pontoon design information, and structural simplicity of the pontoon, and attached mooring system for the purposes of numerical modelling.

The primary concern when recording field data was to acquire data simultaneously with wave recordings from the companion CRC Reef Cyclone Waves and Water Levels study, which also has field instruments at the site. Data was recorded for the same period as the wave pole (25 minutes on the hour), with considerable effort made to reduce data volume by evaluating 2 minutes of data prior to the hour, and controlling IMU recording activities under perceived 'normal' or 'storm' conditions.

The data acquisition system, powered by a battery/charger arrangement capable of 5 days autonomy, was trialed over the period 5–22 September 1996, during which 8 data files of pontoon motions under perceived 'storm' conditions were recorded and stored (refer to table 1 for details). Wave data were not recorded for this period, so corresponding environmental conditions were estimated using wind and tide recordings at Norman Reef (Cairns Meteorology Bureau).

Table 1. Details of 'storm' data recorded including approximate winds and tides

File	Type	Nearest Tide		Nearest Wind Recording		
Date (ddmm) Time (24 hour)		Time (24 hour)	Height (m)	Time (24 hour)	Magnitude (knots)	Direction (degrees)
16091100	Storm	1052	High 2.18	0700	16	150
20091600	Storm	1628	High 2.26	1600	23	350
20091700	Storm	1628	High 2.26	1600	23	350
20091800	**Storm**	**1628**	**High 2.26**	**1600**	**23**	**350**
20091900	Storm	1628	High 2.26	1600	23	350
20092000	Storm	2300	Low 1.26	1600	23	350
20092100	Storm	2300	Low 1.26	1600	23	350
20092200	Storm	2300	Low 1.26	1600	23	350

Data for FILE 20091800 was analysed and is presented as a sample of wave frequency motions under moderate northerly wind conditions. Figure 6 illustrates displacements in the surge, sway and heave directions (x, y and z). Corresponding angular displacement data (roll, pitch and yaw) are presented in figure 7.

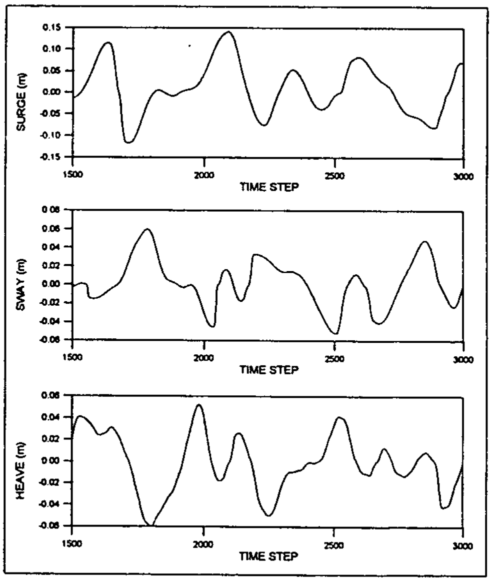


Figure 6. Surge, sway and heave motions

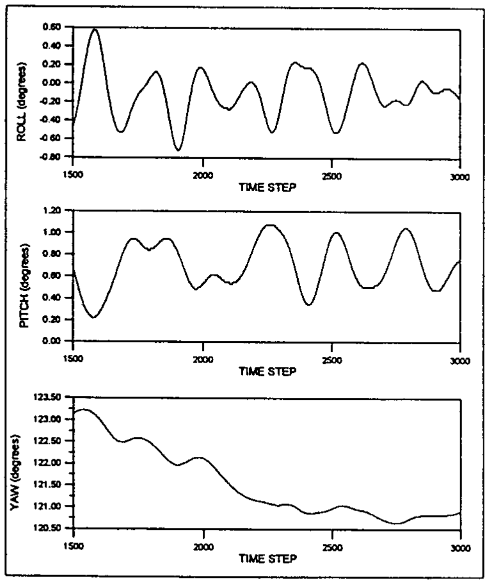


Figure 7. Roll, pitch and yaw displacements

Although these recorded displacements are of minimal amplitude, they suggest that the Norman Reef pontoon will undergo large amplitude motions in severe conditions. With the aid of simultaneous wave recordings (both time series and spectra), such motions can be used for comparison purposes with predicted motions from the hydrodynamic model.

AQWA hydrodynamic model

AQWA (WS Atkins, UK) is a commercial suite of programs built around the Morison's equation and diffraction theory and is commonly used for the analysis of motions and loads on large drilling platforms in deep water (Perry and Clark 1987). Some of AQWA's capabilities include 3-D diffraction/radiation analysis of regular wave action around a single floating body (not moored) to determine added mass and damping coefficients; calculation of forces from irregular waves, wind and current, to determine the equilibrium values of body position and mooring loads; computation of motions and loads at any point in the assembly to deduce significant and extreme linear response for any given wave spectrum; and modelling fully non-linear mooring (catenaries) with time histories of 'slow drift' and 'wave frequency' motions.

DISCUSSION

The tension/displacement numerical model provided excellent comparisons with experimental observations, despite the omission of cable stretch and anchor holding factors, particularly in the strongly non-linear region where the dumper block lifts off the ground (approximately 3.12 m, figure 1), and minor differences in curve form were a result of friction in the experimental apparatus. The 2-D static model (refer figure 2) has been applied to evaluate changes in pontoon equilibrium position resulting from tidal movements, static wind and current loading, and mooring line pretensioning. Dynamic motions about these equilibrium positions can provide accurate predictions of mooring line tensions.

Extensive performance testing of the IMU under laboratory conditions produced results which validated the manufacturer's specifications. For all constant amplitude/frequency tests performed, amplitudes of displacement resulting from the simple integration and drift elimination procedures were within 4.4% of the predicted value of 0.94 m. Vibration associated with the testing apparatus was found to partly cause this error, suggesting that for field conditions, higher levels of accuracy can be obtained.

Changing amplitude and frequency conditions were also recorded so as to evaluate the performance of analysis procedures under field conditions. Changing conditions introduced significant integration drift (occasionally with amplitude up to 20 times that of the sinusoidal oscillations) where individual peaks and troughs were poorly defined. It was found that reducing the length of the time series reduced integration drift amplitude sufficiently to provide accurate results.

The preliminary field data recorded during the trial period suggests that the IMU has a resolution capable of accurately recording the slightest of motions. Table 1 indicates that the motions of the pontoon are largest with northerly winds. South-easterly winds coinciding with high tides, allowing waves to propagate across the reef, also provide conditions of significant pontoon motion. The maximum amplitude of linear displacement observed was approximately 20 cm for the surge direction, which was most closely aligned to the incident direction of wind and waves.

The integration drift elimination procedure was successfully applied to these series, which exhibited a partially random nature. However, care must be taken when applying this procedure to low amplitude field motion as in some cases, high amplitude residual drift motion remained in the adjusted series resulting in false amplitude and frequency spectra.

The raw data series for yaw clearly exhibits large amplitude, low frequency deviations (approximately 2.5°). This highlights another issue relating to the drift removal procedure; for adjusted linear displacements, the process does not permit analysis of low frequency drift motions since these are removed (if they existed) by the integration drift correction procedure.

The programs of the AQWA suite are all based on a finite element mesh of the object and its attached mooring lines. A mesh is presently being formulated for both a generic pontoon and the case study pontoon at Norman Reef, and AQWA's relevance to small scale Great Barrier Reef pontoon modelling in shallow water is presently being investigated.

ACKNOWLEDGMENTS

The authors wish to acknowledge the assistance of the staff at Great Adventures during field activities at Norman Reef. The support of the CRC Reef Research Centre and James Cook University of North Queensland is also gratefully acknowledged.

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Philosophy of marine park management

Denise Russell
Department of General Philosophy, University of Sydney NSW 2006

ABSTRACT

This paper looks at the current policy of the Great Barrier Reef Marine Park Authority of conservation with the minumum of regulation and discusses the advantages and disadvantages of this approach over alternative positions. The former policy allows for wide use of the Park by a variety of user groups along with ranges of protection including the preservation of representative examples of ecosystems. One alternative view urges a more cautious approach to marine park management entailing more restrictions on human actions to further guarantee the health of the Reef. Interconnections between different elements in the ecosystem are highlighted in a way which would lead to a different type of zoning than is currently in place. The philosophical underpinning to such an alternative approach is then explored.

INTRODUCTION

The Great Barrier Reef is the largest marine coral ecosystem in the world. It is an area of enormous diversity, of great beauty and scientific interest, yet highly vulnerable to human interference. The setting up of the Great Barrier Reef Marine Park in 1975 and the Authority (GBRMPA) to manage the Park were significant advances in the preservation of the Reef but the key philosophical principles which have in the past formed the basis of the Authority's management decisions do have some flaws.

The management philosophy is one which seeks to achieve conservation with the minimum of regulation. It aims to ensure a high level of usage which is consistent with maintenance of the ecological system and which will be accepted as reasonable by society. Two key figures in forming management policy, Graeme Kelleher and Richard Kenchington, state that 'an understanding of the Reef and the processes which maintain it is necessary before sensible decisions can be made about competing uses, and *before limitations can be placed on potentially destructive uses*' (author's emphasis) (Kelleher and Kenchington 1982). Kelleher was for many years responsible for planning and policy development for the Great Barrier Reef Marine Park Authority and Kenchington is the author of a recent comprehensive book on marine park management.

Zoning plans have been developed in line with these management principles but it is important to note that a Marine Park is not the same as a Marine National Park. Most of the Great Barrier Reef Marine Park is zoned for general use which restricts mining and spearfishing only. Less than 10% in the Cairns Section for instance is zoned Marine National Park and even this area has various sub-zones. The largest has only fairly light restrictions on some fishing and collecting. These 'A' zones are adjoined to buffer zones where trolling for pelagic fish is allowed but no other fishing. Buffer zones then adjoin reefs where fishing is prohibited. Very small areas are zoned for Scientific Research and Preservation. The Authority has claimed that 'the provisions of the Marine National Park Zones are similar in concept to those of national parks on land' (GBRMPA 1988).

The aim to support a high level of use and a diversity of human activities in a fragile environment, while meeting certain human interests, may easily run counter to the aim of conservation. The marlin fishing sport is a good example of weaknesses in the management philosophy. The sport is still widely promoted internationally and Lizard Island has been host to a Marlin Classic where marlin weighing hundreds of kilograms were hauled onto the beach.This is a barbarous sport, no different from big-game hunting. An alarming report published by a previous director of the Lizard Island Research Station stated that the big game fishing boats frequently call into the Cod Hole (which is in a National Park Zone because it houses sixteen or so large potato cod). To entertain their clients when the marlin aren't biting, the crew dangle a tail roped tuna from the back of the boat and the cod fight for the bait. In the process the fish inflict wounds on each other. The cod who gets the bait incurs mouth and body damage in the resulting tug of war. This activity is not illegal as it doesn't count as fishing. The line has no hook (Quinn 1990). That this is permissible in an area of the tight zoning, should lead us to reflect on the philosophy behind the zoning.

Another weakness in the philosophy is contained in the phrase 'before limitations can be placed on potentially destructive uses. It is the idea that if you can't prove that an activity is hazardous allow it to go ahead. Not so long ago one member of the Great Barrier Reef Marine Park Authority even followed this philosophy through to oil drilling on the Reef when he said that 'if no research is done or if no unacceptable risk can be demonstrated, exploratory drilling may well be permitted leading to exploitation if oil is discovered' (Baker 1977). This was written after several oil spills had devastated marine environments in other parts of the world and very close to the time when other dangers in oil exploration and drilling had been brought to the attention of the public. Overseas witnesses to the Royal Commission on Petroleum Drilling in Great Barrier Reef Waters in 1974 testified that an offshore oil industry once established could do more lasting damage to marine life through small but continuous spills, detergent treatments, discharge of water and mud used in drilling and other kinds of pollution than even single large spectacular oil accidents would do (Connell 1971). Hopefully Baker's position would no longer be endorsed, but nevertheless it was a view which presumably he took to be consistent with Marine Park Management after the Great Barrier Reef Marine Park Authority had been established and so it should lead us to reflect on whether the philosophical base is providing enough safeguards.

My central thesis in this paper will be that when we are dealing with an area of such profound importance and fragility it is far preferable to take the stand that we should prohibit or restrict or encourage against activities unless we have good reasons for thinking they are harmless. This should apply to all activities in the Park, not just oil exploration or drilling. Two others that desperately need further restrictions are fishing and tourism. The harm that tourists and tourist development are doing to the Reef is abundantly clear to the casual observer (Vandome 1990–91; Craik 1981; Hundloe 1990). Yet tourism in the Cairns area is increasing at a rate of roughly 30% per annum (Vandome 1990–91). Unless there is a turn-around in policy the development of mass tourism will soon be upon us with widespread use of large highspeed boats to hitherto remote areas and the explosion of tourist facilities on the mainland with consequent destruction of mangrove forests which help to enrich the reef environment.

The harm done by depletion of fish stocks may not be realised until it is too late. There is very little research into the long-term viability of Reef fishing and attempts at monitoring reef fish have not been successful. There is not even consensus on the appropriate method for monitoring (Lassig et al. 1988). Yet very little restriction is placed on what fish are taken. Again the philosophy that is operating is: wait and see if these practices are dangerous. The sad truth is that we might not have very long to wait. Also as Richard Grigg has pointed out, over-fishing and related ecological imbalances are one of the key factors in the significant declines in the condition of many of the world's reefs, as over-fishing impacts on the competition for space between algae, bio-eroders and corals (Grigg 1994).

The violation of the cultural values of aboriginal people is also a distinct possibility with a management policy that favours minimal regulation, even within a conservation framework. Again it may be the case that this violation by fishing or tourism in certain areas may not be recognised until it is too late, a case in point may be the ancient burial area adjacent to Hardy's Reef.

Further flaws in the philosophical base of the management practices stem from acceptance of a land-based model, assuming the area can be divided into reasonably distinct regions albeit with buffer zones. This model is questionable on land but it is nonsense in the sea because of the dispersal in the plankton for sometimes hundreds of kilometres of the larvae of marine plants and animals. In an extensive study done in the mid-80s by Gordon Bull, larval drift was recorded up to 728 kilometres though some perhaps most larvae settle in three days, 3–8 nautical miles away from the spawning area. The conclusions from this study relate to about one third of the corals on the Reef and they establish the interconnectedness of different Reef regions (Bull 1984). Similar extremes in the dispersal of fish larvae have also been found (Firth 1986; Leis 1986). Quite a few make their way to Sydney waters only to die off when the water cools in winter. These sorts of findings have gained further support by recent work at AIMS. For example, Peter Doherty has found that baby reef fish can swim up to 100 kilometres, in seven days.

Other examples throw a shadow over zoning: the cod in the Cod Hole do not always stay in their small national park zone. They may stray into the nearby zone where trolling is legal. The scientist working in the Scientific Zone on Lizard Island may be frustrated to find her subjects killed in legal fishing a few hundred metres from the shore.

Kenchington in *Managing Marine Environments* (1990) designates 'conservationists' as an interest group, and an interest group that should be given a hearing along with the fishing and tourist interests. This position sits rather oddly with his statement of the management philosophy mentioned above as being concerned with conservation. It might be thought that this would make the managers conservationists too and not just people responsive to conservationist interest groups. I believe however that the rhetoric of conservation in the management philosophy is undercut by the rider 'with the minimum of regulation'. Kenchington goes on to make the rather odd claim that the 'perfect' solution to addressing the three concerns of conservation, fishing and tourism can be represented by the mid-point of a triangle.This might lead one to assume that the three interests are to be weighted equally, but that this is clearly not so is revealed in his recommendations for zoning: the goal of 'preserving coral reef undisturbed by humans' is thought to be met by preserving 5% of reefs free from human access other than for purposes of approved research or management projects and this 5% should as far as practicable achieve minimum disruption to fishing and tourism. Five per cent is then to be set aside for tourism and 90% for local and export fisheries (Kenchington 1990). The idea is that small 'representative examples of ecosystems' are preserved. But this is to make nonsense out of the idea of an ecosystem – the parts can't have autonomous existence as illustrated in the study of larval drift mentioned above.

There are threats to the Reef from activities in areas adjacent to the Park, in particular from land run off and proposed oil exploration/drilling. A philosophy which accepts the zoning model within the Park makes it easy to look upon the Great Barrier Reef as a unit separate from the adjacent land and sea. It makes it difficult for the Authority to act as a political force countering the threats from adjacent areas. If the notion of interconnectedness of regions within the Park is accepted then it would be easier to see the interconnection between the Reef and non-Reef areas. Just seeing that is not going to be sufficient to overcome huge problems however, for example, problems generated by the Commonwealth jurisdiction over the Marine Park and the State jurisdiction over the land, and problems generated by the Commonwealth's need to comply with international agreements on shipping (Connolly 1974). Ships in the Reef channel have had an average of one oil spill a year from 1970. Often these spills are deliberate and large fines do not work. The safeguards in place to handle oil spills are hopelessly inadequate. It is difficult for the Great Barrier Reef Marine Park Authority to do anything about this and even the hands of the Federal Government are tied to some extent because of international shipping laws relating to the free passage of shipping. Yet urgent action is desperately needed.

Sketch for an alternative philosophy of reef management

The philosophical stand that limitations should be placed on potentially destructive uses of the Reef when the research is in that shows the destructiveness should be overturned. Given the present trend toward degradation of many coral reef ecosystems, pointed out in the editorial in the journal *Coral Reefs* in 1994, the policy of 'wait and see' if an activity is harmful in an area of such profound biological diversity is very dangerous indeed. Instead a more cautious approach should be adopted based on the principle that if we know that an activity is harmful to the Reef or if we are unsure of its effects then prohibit, restrict, or encourage against. That should be the basic philosophical standpoint. Yet given the very uneven effectiveness of the exercise of power from above, the principle should ideally lead to self-policing. This is a mammoth problem with commercial shipping and fishing which are areas requiring tighter government intervention, e.g. extension of the pilot scheme for ships passing through the Reef, banning of shipping during coral spawning, putting more resources into the oil contingency plan: Reefplan. It is heartening to see that in 1995 funding was obtained for a research program to investigate the potential use of bioremediation to clean up oil spills in tropical areas but it may be still doubted that Reefplan resources are enough to handle large spills.

Self-policing works well with smaller scale activities. The tour boat operators in Hervey Bay exemplify this. There is a good sense of community and recognition that the regulations regarding whale watching are worth keeping to protect the industry.

An alternative philosophy of Reef management should also take more account of the interconnections not only between different parts of the Park but also between the Park and its land and sea edges. The imposition of zones masks this reality. Obviously some local regulation is required e.g. spearfishing of the cod in the Cod Hole has to be illegal but local regulation could take place within an overall perspective of interconnectedness. The danger with zoning is that it gives a licence to harmful activities within certain areas and orients people's thinking away from the whole. It is only by keeping the whole in mind that we will have a chance of protecting the Reef. I will now look at these two philosophical directions in more depth.

The no-harm principle

I have suggested that the basic philosophical standpoint in relation to Reef management should be that if we know that an activity is harmful to the Reef or if we are unsure of its effects then prohibit, restrict or encourage against. But what is behind this? Why not harm the Reef?

A large part of inter-human morality is that one should not cause harm to other humans. This is captured in the Christian ethic but extends more broadly underpinning the legal systems of the Western world. There is also a similar principle operating legally to protect animals from cruel treatment by humans. Some philosophers have argued for an extension of this human-animal morality to include not only a prohibition on cruelty but a questioning of any human acts which cause animals to suffer, even if this is in the name of science (Regan 1983).

When thinking about philosophical support for a principle that urges against harm to the Reef, something even further must be envisaged. This support cannot find its base simply in inter-human relations, nor in human-animal relations. Some broader concept is needed. It is likely that this broader concept is going to emerge from the new field of ecological ethics.

Ecology is 'the broadly based branch of biology that deals with relations between living organisms and their environments'. The perspective of interconnectness that I mentioned above is obviously informed by ecology. Not all ecologists take up the issue of how best to maintain an ecosystem but some who do have suggested an ethical stance called by Arne Naess 'deep ecology'. 'The essence of deep ecology is to ask deeper questions' to go beyond science into realms of ethics and politics' (Naess 1985). In 1973 Naess laid down the basic tenets of deep ecology. To focus only on two that relate to an ecological ethic: there is first the rejection of the human-in-environment image in favour of a view of all 'organisms as knots in the biospherical net or field of intrinsic relations. An intrinsic relation between two things A and B is such that the relation belongs to the definitions or basic constitutions of A and B, so that without the relation A and B are no longer the same things' (Naess 1973).

Secondly, a principle of biospherical egalitarianism is propounded: 'the equal right to live and blossom is an intuitively clear and obvious value axiom'. Naess claims that 'its restriction to humans is an anthropocentrism with detrimental effects upon the life quality of humans themselves. This quality depends in part on the deep pleasure and satisfaction we receive from close partnership with other forms of life.

I concur with the first point about humans as relations but the biological egalitarianism is problematic. It draws on a philosophy of rights but it is unlikely that there will be any clear way of deciding between competing rights and thus to ascribe them is an empty gesture. Naess grants that some killing and exploitation of other species may be necessary but then where does one set limits? A doctrine of equal rights is useless here.

Also Naess is caught in a logical conflict. He claims that a) restricting rights to humans is anthropocentric with an implied criticism of anthropocentrism, and b) the reason why we shouldn't restrict rights to humans is because humans suffer from this restriction. But this reason is anthropocentric. He is saying we should behave ethically towards the biosphere as this will benefit humans so his own views is anthropocentric and flawed on his own terms. Devall and Sessions (1985) have developed Naess' ideas for an ecological ethic but run foul of the same problems, in fact they get into a more explicit logical problem. They attribute inherent or intrinsic value to the well being and flourishing of all human and nonhumnan Life and state that this is understood as value 'independent of any awareness, interest or appreciation of it by a conscious being'. Yet the reason given for believing in biospecies equality is that 'if we harm Nature then we are harming ourselves'. So attributing value to the biosphere is not independent of human interest.

Val Plumwood (1991) attempts to provide an ecological ethic that sidesteps these difficulties: the basis for placing value on an ecosystem is for her, that ecosystems possess broadly teleological properties e.g. the maintenance of ecosystem stability. Teleological properties constitute a goal, an end or direction to which the ecosystem tends or for which it strives, and which is its own.These properties are not anthropocentric. Ecosystem stability helps the ecosystem to survive and flourish and that is what makes it a value and it would continue to be a value even if no human purpose was thereby served. The value of stability is inherent in the ecosystem and an ecological ethic would be one that respects this property. It would need to be recognised that there is something our actions may aid, or turn aside and frustrate, that it is not the case that all states of affairs have equal value with respect to the ecosystem. We would have to think a lot harder before we can say 'it doesn't matter' but Plumwood believes that this is an acceptable consequence of moving out of an anthropocentric perspective and into an ecological one.

Holmes Rolston (Rolston 1974–5) extends this view further defending the idea that once we come to an understanding of ecosystems it is clear that an ecological ethic emerges. He says that there is 'a moral "ought" inherent in recognition of the holistic character of the ecosystem, issuing an ethic that is primarily ecological'. In the description of the ecosystem notions of stability, integrity and beauty enter. Description is imbued with evaluation so an 'ought' is not so much derived from an 'is' as discovered simultaneously with it: 'the values seem to be there as soon as the facts are fully in, and both alike are properties of the system'. What is right is that which preserves the system's beauty, stability and integrity (Rolston 1979). Ethics is no longer confined to relations between humans, or relations between humans and other animals. It is extended to the transactions between humans and the environment. So humans ought to act to preserve these qualities.

This would lead to a morality of Reef use that escapes economic expediency. It would also lead to a morality of Reef use which does not prioritise open use of the Reef by humans for reasons other than economic expediency e.g. the kudos of catching a marlin, the freedom to anchor anywhere to explore the Reef etc.

Some might still persist in wanting a further basis for this morality, asking why are stability, integrity and beauty to count as values? Holmes Ralston would argue that they count as values because they constitute the excellences of the ecosystem. And to ask why ought humans to maximise the good of an ecosytem is on a par with the question why ought humans to maximise human good. Humans and ecosystems both have value and as such are deserving of respect. He is urging 'a shift of paradigms, the values hitherto reserved for man are reallocated to man in the environment'. Nature ceases to be merely 'property' or there for human use. He rejects the crude belief that man is the only value to be considered in managing the world and that the rest of nature can be thoughtlessly sacrificed to his welfare and whims. Nevertheless it is granted that in upholding the good of an ecosystem, humans may themselves by enhanced. It is simply that this human benefit is not the basis of the morality.

Following this direction of thought which emphasises caring for biosystemic welfare does allow for alteration, management and use. It may be that humans can have a role in governing what has hitherto been the partial success of the evolutionary process. Interference with and rearrangment of nature's spontaneous course is still permitted but this should complement the beauty, integrity and stability of the biosystem, not do violence to it. The morally right acts are not necessarily those which maintain the ecosystem status quo but those which preserve its beauty, stability and integrity. It is for scientific research to tell us what counts as stability of an ecosystem which will then facilitate the estimate of its beauty and integrity. In ecosystems with presently acknowledged great beauty, extreme caution should be exercised in interfering and rearranging so that rather than prioritising human use, we should support the 'no harm principle' that if we know that an activity is harmful to the Reef or if we are unsure of its effects then we should prohibit, restrict, or encourage against this activity.

ACKNOWLEDGMENT

I would like to thank Lizard Island Research Station for the use of their library.

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Investigation of load capacities of mooring anchor systems

***K van Donderen*[1], *B Greensill*[2], *B Way*[3] *and AJ Johnston*[4]**

[1] *Engineer, Connel Wagner P/L, Brisbane Qld*
[2] *Project Manager, Evans Deakin Engineering P/L, Brisbane Qld*
[3] *Research, Development and Export Manager, Pacific Marine Group, Townsville Qld 4810*
[4] *Engineering Program Leader, CRC Reef Research Centre and James Cook University Qld 4811*

ABSTRACT

The design of foundations for structures that are placed in the Great Barrier Reef is uncertain since the structural strength of calcareous soils is poorly understood. Furthermore, there is an urgent need to develop environmentally friendly mooring systems to cater for the increasing numbers of boats using Great Barrier Reef sites. Screw anchors that are permanently drilled into sand have attracted recent international attention.

Objectives of this study were to determine uplift, lateral and oblique load resistances for anchors; to determine the effect of cyclic loading on anchor load resistance; to design land based and laboratory tests that will assist in the understanding of full-scale anchors in reef coral sediments.

This paper will describe screw anchoring and discuss test results associated with the accurate recording of load applications and resulting displacements in siliceous sands when monotonic and cyclic loadings were applied. A land-based test bed was designed and constructed to test a grouted screw anchor. Eight test anchors were subjected to uplift, lateral and cyclic loads. Load test equipment was designed and fabricated to allow monotonic uplift and lateral load tests and cyclic load tests to be undertaken.

INTRODUCTION

Mooring systems are provided at various locations in the Great Barrier Reef to provide safe anchorages for marine vessels and pontoons. As tourist numbers increase and public use of marine vessels increase the need for more public mooring systems has been recognised. The final acceptance of proposed anchor systems for new projects that are considered by the Great Barrier Reef Marine Park Authority requires an assessment of uplift and lateral load capacities. Under normal conditions a boat, or a pontoon, attached to a mooring system will induce an inclined (vertical) load to the anchor and this load will fluctuate in response to wave action.

The detrimental impact on reefs by conventional anchors is caused by dragging anchors and chains across coral areas. Where permanent pontoons are moored along the outer reef, anchor systems are also provided to protect the structure against various environmental loads, for example wind and current. In an effort to control further anchor damage of the Reef, alternate anchor systems are being considered for public moorings and pontoons in the future.

A common anchor system used on the Great Barrier Reef is the direct embedment anchor. It differs from conventional anchors in that it does not need to move to develop restraint since it is driven into the sea floor. Pacific Marine Group Pty Ltd developed the design and installation of a grouted screw anchor system and they have in the last five years installed approximately one hundred moorings off the Queensland coast.

LITERATURE REVIEW

Calcareous soils are generally deposited in a much looser state than comparable silicate soils and are generally more compressible thus contributing to poor foundation performance, (Airey and Randolph 1988). There is widespread agreement in the literature that the skin friction of calcareous soils is lower than that of siliceous soils, the principal reason being their high compressibility. The cyclical nature of loadings induced through wave action to offshore structures is important when determining the performance of sediment under cycles of loading (Jewell 1993).

A screw anchor is usually made from a steel shaft with a single flight screw helix welded at the toe, or multiple helices welded at equal spacings along the shaft. The screw anchor is installed by applying a vertical downward load to seat the start of the helix and then rotating its shaft to force the anchor to penetrate into the soil (Ghaly et al. 1991).

Most research work related to calculating uplift resistance of piles in sands has been associated with the design of foundations for offshore structures and transmission towers. The uplift capacity of a pile is dependent on the skin friction that is mobilised on the pile shaft and the effective weight of the pile. Skin friction is a function of soil density and effective lateral pressure (Sowa 1970). The lateral pressure is assumed to be related to the effective overburden pressure. The lateral earth pressure coefficient is difficult to assess as it depends on many factors including the friction angle of the soil, soil density, diameter of pile, surface roughness of pile, length to diameter ratio of pile and the method of installation (Rao and Venkatesh 1985; Poulos 1990).

Piles are frequently subjected to lateral forces and moments. The method of determination of lateral resistance of a vertical pile is more complex than that for determining uplift resistance. Research involving full scale and model testing has been undertaken to determine the resistance to lateral loading of piles in various soil conditions. The effects of repeated loading on the holding capacity of anchor systems are not documented extensively, although the literature does indicate that cyclic loading has a detrimental effect on the strength of anchors (Clemence and Smithling 1984).

The limited literature available on the effect of cyclic axial loading on piles in sand indicates that there is a remarkable reduction in the load capacity of the pile (Poulos 1990). This loss appears to be derived primarily from the degradation of skin friction as cyclic loading proceeds. The influence of the number of cycles increases as the amplitude of cyclic load increases and this promotes significant strength reduction. The effect of lateral cyclic loading due to the occurrence of wind and wave loading on piles, or anchors, in sand may significantly affect the load resistance of the pile, however limited literature is available on this topic.

EXPERIMENTAL SETUP

Although numerical or laboratory approaches have previously been employed in the technical literature, it was decided that in this study that a number of full scale tests would be undertaken. Full scale modelling provides results from anchors subjected to actual loads that reflect typical in situ conditions and these results can be used directly to design cost effective mooring systems. Ultimate load capacities and related displacements obtained from full scale testing can be readily checked against existing theory, both for uplift and lateral modes of loading on the reef.

The experimental setup was designed to allow uplift and lateral load testing of grouted screw anchors to be undertaken under both submerged and saturated conditions. For these tests, the loads were applied monotonically and cyclically. Monotonic testing was done to provide a comparison of results with both other researchers and the present cyclic test results. Cyclic testing was carried out to simulate normal environmental loading conditions.

A land-based test bed was constructed at PMG premises in South Townsville and it was designed to accommodate eight grouted screw anchors placed under submerged conditions. For all load applications, the direction of likely movement of an anchor and the area which might be disturbed by the anchor were considered. Sufficient spacing between anchors was selected to ensure that anchor-soil effects from one test did not interfere with other test anchors. Based on the possible mode of failure for uplift, a minimum spacing of 2400 mm between anchors was chosen. For the rotation condition resulting from lateral loading a minimum spacing between anchors of 2000 mm was selected. Ground surface level monitoring during testing confirmed the maximum extent of soil movement. The grouted screw anchors were installed using an Installation Machine (underwater drilling rig) developed by PMG. The screw anchor shaft consisted of 100 x 100 x 6 square hollow section galvanised steel shaft with a single, 400 mm diameter helix near this tip. A 25 mm diameter grout tube was provided through the centre of the shaft and protruded 250 mm outwards from the tube. Two stirrer plates were welded to the shaft at intermediate points and a flange plate was provided at the top of the anchor.

The method of installation for each anchor was similar, but the time required to install the anchors varied. The average installation time was approximately half an hour. The anchors were screwed into the ground and the grout pressure during anchor penetration monitored and recorded. The anchors were also rotated in and out of the substrate three times in an effort to provide an even distribution of the concrete mix along the entire length of the grouted screw anchor. Once all anchors were installed they were left for over two weeks to allow the grout to cure.

The monitoring equipment included a portable computer connected to a data logger that was connected to a transducer interface. The load cell and up to three Direct Current Displacement Transducers were attached to channels of the transducer interface.

The uplift load test was designed to simulate uplift loading in alignment with the vertical axis of a grouted screw anchor. Uplift load and uplift displacements were monitored for each test. The lateral load test was designed to simulate that of a horizontally applied force on a vertical grouted screw anchor.

DISCUSSION OF RESULTS AND CONCLUSIONS

A disturbed sample of material obtained from the test bed was subject to a range of laboratory tests in order to determine the soil properties. The parameters obtained from testing were compared with the results of other researchers. Field testing was also undertaken to compare and confirm the laboratory test results. Both laboratory and field test results were applied in the analysis of results.

Based on field testing of the grouted screw anchor a number of findings were obtained.

Test load results for monotonic uplift (tables 1 and 2) and lateral test (table 3) were significantly different from those predicted by theoretical methods. The ultimate uplift load resistance was 1.75 times greater than that derived from pile theory, however the resistance corresponding to 10% of diameter displacement was 1.1 times greater than that using pile theory. The ultimate lateral load derived from Broms' equation for short unrestrained piles was 2.0 times greater than the actual ultimate lateral load resistance derived from the load-displacement curve using the slope-tangent method. In addition, the resistance corresponding to a displacement of 10% of the anchor diameter was 60% of the theoretical value. Although there were significant differences between test results and those predicted by theory, the characteristics of load displacement graphs were consistent with those of other researchers.

Table 1. Monotonic uplift load resistance – test results

Test Parameter Description	Test Number	
	1	2
Ultimate uplift load	36.3 kN	35.3 kN
Displacement at ultimate load	26.7 mm	17.5 mm
Uplift residual load	26.6 kN	20.5 kN
Final recorded displacement	93.7 mm	107.4 mm
Derived allowable load based on factor of safety	24.2 kN	17.7 kN
Displacement at allowable load	3 mm	2.5 mm

Table 2. Comparison of theoretical and actual parameters

Parameter Description	Theoretical	Actual
Diameter of anchor	600 mm	608 mm
Saturated unit weight of soil	19 kNm^{-3}	19.7 kNm^{-3}
Effective unit weight of anchor	6.76 kN	6.52 kN
Length of anchor	2.3 m	2.1 m
Ultimate uplift load	20.4 kN	35.8 kN
Skin friction factor (F = Ktanø)	0.3	0.6
Skin friction	3.2	6.8

Table 3. Monotonic lateral load resistance – test results and design values

Test Parameter Description	Test Number	
	5	6
Ultimate lateral load	18.6 kN	19.5 kN
Displacement at ultimate load	26.0 mm	18.0 mm
Final recorded displacement	89 mm	118 mm
Derived allowable load based on factor of safety	12.4 kN	13.0 kN
Displacement at allowable load	7 mm	7 mm
Final ultimate capacity	50.2 kN	22.2 kN

For the cyclic uplift load tests (table 4) there was a significant difference between the two test results. Only one cyclic uplift load test was undertaken to a maximum load level of 48% of the maximum monotonic uplift load resistance (test number 3) and only one at 91% (test number 4). Although a single result at each level of loading is inconclusive, there are indications that cycling of load causes a reduction in strength of the anchor.

Table 4. Cyclic uplift test results

Test Parameter Description	Test Number	
	3	4
Number of cycles	53	19
Maximum cyclic uplift load	17.0 kN	32.5 kN
Percentage of ultimate	48%	91%
Minimum uplift load	0 kN	0 kN
Average cycle time	13 seconds	38 seconds
Final ultimate capacity	50.2 kN	22.2 kN

Both the uplift cyclic load tests showed an initial high level of displacement in the first cycle, followed by a reasonably uniform rate of displacement with each successive cycle. Toward the end of the 50 cycles of loading the rate of displacement increased indicating the onset of failure.

Only one cyclic lateral load test (table 5) was undertaken to a maximum load level of 62% (test number 7) and one test to 99% (test number 8), of the monotonic lateral load resistance, respectively. Even with this difference in maximum cyclic loading there was no significant difference in ultimate resistance for the same number of applied cycles. In addition there was a negligible reduction in the ultimate lateral capacity as illustrated when comparing the two cyclic test results with the monotonic lateral load result.

Table 5. Cyclic lateral test results

Test Parameter Description	Test Number	
	7	8
Number of cycles	49	50
Maximum cyclic lateral load	11.9 kN	18.9 kN
Percentage of ultimate	62%	99%
Minimum lateral load	0 kN	0 kN
Average cycle time	24 seconds	40 seconds
Derived ultimate capacity	17.9 kN	18.3 kN

The lateral cyclic load tests (table 5) initially illustrate a high level of displacement believed to be due to a settling-in effect as soil particles fill void spaces. This trend was followed by a general decline in successive displacement as soil becomes more densely packed.

A plot of results on a cyclic stability diagram proposed by Poulos (1988) confirm observations made during the test that high cyclic load levels may lead to reduced ultimate load capacities and these may promote unstable conditions.

The test results were overall, inconclusive as only two types of each test were undertaken due to cost and time limitations. There is a need to undertake more fullscale testing to achieve a higher level of confidence in test results.

ACKNOWLEDGMENTS

The authors wish to acknowledge the considerable support given to the project by Pacific Marine Group, Townsville and the CRC Reef Research Centre.

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Integrating research and development into decision making for natural resource management in coastal northern Australia

Daniel H Walker[1], Andrew KL Johnson[1] and Jennifer A Bellamy[2]
[1] *CSIRO Division of Tropical Crops and Pastures, Davies Laboratory, Townsville Qld 4814*
[2] *CSIRO Division of Tropical Crops and Pastures, Cunningham Laboratory, St Lucia Qld 4067*

ABSTRACT

A brief analysis of the requirements in fostering mechanisms for the integration of recent and current research into decision making is undertaken in this paper. This analysis is illustrated by some of the activities of the CSIRO Coastal Zone Program in north Queensland, particularly the development of a decision-support environment for addressing the off-site impacts of land use change and development of the Herbert Resource Information Centre. This collaborative and community-based resource is aimed at improving the basis of decision making in natural resource and related management in the Herbert River Catchment.

INTRODUCTION

The 1992 Inter-governmental Agreement on the Environment commits all levels of government in Australia to achieving a balance between economic development and environmental integrity through the concept of Environmentally Sustainable Development. The impacts or potential impacts of increasingly intense natural resource exploitation in the coastal zone on the marine environment, the Great Barrier Reef being of particular note in north eastern Australia, are well recognised (Resource Assessment Commission 1993). As a result, strategies are demanded that balance economic development in the coastal zone with downstream impacts, such as that on the marine environment (Brown 1995).

Scientists traditionally respond to such challenges by advocating that further research is needed to fill gaps in our understanding. This reflects the pre-eminence of a belief system that asserts that there can be rational and objective management of natural resources (Lang 1990; Funtowicz and Ravetz 1990 for a more general discussion). Indeed Boehmer-Christiansen (1994) asserts that 'The very success of physical and natural sciences ...lies in the self-seeking belief which scientists (but few others) tend to share that there is a very direct link between more knowledge and appropriate action.'

Continued research may be needed to enable more informed and appropriate management of natural resources at the terrestrial–marine interface in northern Australia. The rational scientific approach is increasingly being challenged by our greater understanding of the complexity and indeterminism of natural systems and by the apparent irrelevance of much research to decision making (in as far as it often has minimal impact on practical resource management). Together these have eroded the belief that knowledge is all that is required. In order to more effectively integrate scientific understanding into the decision making process, researchers are now seeking to understand the process itself.

In this paper, we propose that the adage that 'further research is needed' provides scientists with little opportunity to have a positive impact on sustainable natural resource management. Only by being prepared to invest in understanding the context of decision making and by finding novel ways of facilitating the uptake of past and future research by decision makers can scientists hope to have a significant and consistent impact on practice. We explore this new role for research and development (R&D) providers by reference to some current activities in integrated natural resource management at a catchment scale in the Herbert River Catchment of north Queensland.

Limitations to the contribution of science to natural resource management

Research addressing natural resource management issues is based on an unwarranted confidence that it will lead to 'objective and rational management of natural resources'.

This implies that there are demonstrably correct solutions to natural resource management problems; that is that we can achieve decisions based on unanswerable and irrefutable logic. This is naive, in that it does not recognise that natural resource management is *inherently* a political process in which different needs and interests are balanced. Where policy is presented as being based solely on scientific evidence, this is almost inevitably a politically expedient 'fig leaf' for more complex motivations and compromises (Boehmer-Christiansen 1994). Effective natural resource management can occur without formal research but not without an effective political process.

Quite apart from the political nature of natural resource management, 'objective and rational management' may often be unattainable. Science is itself a political process (though highly institutionalised), being based on attaining consensus amongst peers with the consensus achieved in ecology generally more speculative than in physical sciences. Predicting processes at an ecosystem scale may simply be an intractable task since issues may be so complex and indeterminate that predictive understanding may be practically, or even theoretically, unattainable. Certainly, a strong case can be made that process-based understanding of ecosystem behaviour in response to stresses can often only be weakly predictive (Peters 1991). Catchment scale resource management deals with complex ecological, social and economic interactions in a dynamic situation with long time-frames and often considerable separation between cause and effect and the potential for irreversible outcomes (e.g. Norton et al. 1996). As a result, uncertainty and ignorance need to be managed and communicated so that they become recognised inputs to the decision making process (Funtowicz and Ravetz 1990; Costanza et al. 1992; Dovers 1995).

In short, the traditional assumption that science can provide unambiguous answers becomes hard to defend when applied to natural resource management. Given the uncertain and complex nature of ecosystems, we have to accept that more scientific knowledge does not necessarily lead to better answers at a scale and within a timeframe appropriate for action.

Maximising the contribution of science to decision making

While research rarely solves natural resource management problems, it clearly can contribute to their solution. We argue that, in order to optimise this contribution, researchers need to:

- understand the context of decision making;
- understand and seek to facilitate the processes of analysis and synthesis for natural resource management; and
- seek to facilitate the integration of research outputs into these processes.

Understanding the decision making context

The context of decision making encompasses legislative, economic, historical and social considerations. Knowledge and data are the fuel for the decision making process in natural resource management, but the same fuel can be placed in different engines to quite different effect. A failure to appreciate context of application, the nature of the engine, is a recipe for irrelevant research.

Northern Australia has a history of limited planning and control. Government planning and management remains anathema to many rural residents, particularly in the north. So, while effective natural resource management is agreed as being necessary, the process is politically unacceptable. At the same time, centralised government resources are being constantly reduced. In response to both these pressures, the State and Federal governments' preferred direction for natural resource management in northern Australia is towards negotiated and consensual management by multiple stakeholders and decision makers (Brown 1995). Initiatives such as Property Management Planning, Landcare and the Integrated Catchment Management (ICM) program in Queensland are prominent examples of this ethos.

The participants in these initiatives have become major clients for research in rural north Queensland. However, in order to meet their needs, the processes themselves must be understood. What is required in, for example, understanding ICM as a decision making context?

In October 1991, an Integrated Catchment Management Strategy for Queensland was released by the State Government. The Strategy is intended to provide a framework for fostering cooperation and coordination between landholders and other resource users, community groups and government agencies involved in the use and management of natural resources. It is dependent on landholders, the community in general and government having a sound understanding of the interactions between natural resources and the need for a coordinated catchment-wide approach for addressing issues affecting these resources.

To understand the implications of this initiative, we need to evaluate the process of implementation of ICM: to identify social, economic and institutional factors that facilitate or hinder this process, to evaluate the impacts in terms of attitude and behaviour and the tractability and severity of resource use conflicts and, thereby assess the specific technical and related information needs for effective ICM in a wet tropical environment. This demands consideration of the resource use and social history of a catchment, the legislative and institutional context of resource use, community and stakeholder attitudes and, of course, the nature, availability, distribution and use of current knowledge about relevant biophysical processes. A current multi-disciplinary project over five years is undertaking precisely this type of evaluation in the Herbert catchment of north Queensland.

Understanding and facilitating analysis and synthesis in natural resource management

If research providers can be criticised for failing to understand the context of application, they can also be criticised for failing to facilitate the uptake of existing knowledge. While there is much research relevant to catchment scale natural resource management in northern Australia that needs to be done, there is a lot that has been done already. This includes both formal research results and the vastly greater pool of experience of landholders, natural resource management professionals and the broader community. Much of this knowledge is, for one reason or another, inaccessible to those involved in the natural resource management decision making process. Research providers should be able to re-package it to make it accessible, or provide the necessary tools to access and use it in its present form.
In 1995 a series of interviews were held with advisers from three state government agencies and industry working in the Herbert catchment of north Queensland. These interviews sought to characterise natural resource management tasks undertaken by these individuals at that time (see Walker and Johnson 1996) and to obtain a broader perspective of the needs they had and constraints under which they operated in providing advice on natural resource management issues to decision makers such as local government. Some of the constraints and opportunities that they identified are described below under five headings that characterise steps in the process.

Step 1 – Problem formulation
The activities of the advisers interviewed involved comparatively little routine work, but advisers were often faced with questions on quite new issues. As a result, one of the first problems faced by many advisers in addressing a new situation was – what is important here? What should I be considering? Addressing these questions demands a systems level view of biophysical issues, which is rarely effectively provided by research agencies. The challenge for research providers is how best to provide the information that advisers need to decide the issues that merit consideration in any particular context.

Step 2 – Task analysis
Having decided on a range of issues that merit consideration, the adviser must decide how to address them. This requires an understanding of the level of accuracy and precision required, but also an understanding of the data resources and analytical tools available for use in analysis, and the limitations associated with these resources. Where does this information come from and who should provide it?

Step 3 – Data analysis
Data analysis may take a number of forms. In many instances experience may be enough. In other instances accessing and interpreting data about a site may suffice. However, there will be instances where informed advice demands a more sophisticated analysis. Researchers can make a large contribution to the accessibility of data resources, both by expanding the natural resource data that is available and by developing means of allowing potential users to find and interpret those data effectively. When advisers need to perform structured

analyses, they are generally applying generic analytical tools that are research outputs to their particular instance. Researchers are accomplished at providing generic tools but less so when it comes to providing guidance in the application of those tools to site specific contexts. For example, any analytical tool will be based on a set of assumptions. These may be implicit or explicit but either way are often not effectively communicated to potential users.

Step 4 – Synthesis
A response to a request for advice on a complex natural resource management issue will often require the synthesis of a range of analyses and arguments. A typical issue here was how best to integrate local knowledge and experience with more formal analyses of data, how to interpret the former in terms of the latter or *vice versa*. Research advances in systems perspectives on resource use are not easily accessible to practitioners.

Step 5 – Presentation
The politics of natural resource management, particularly where contentious, put pressure on advisers for unambiguous answers. However, these will often not be available. Appropriate presentation of what is available and what it means is, therefore, very important (Funtowicz and Ravetz 1990). Advice must be accessible and defendable. It must be presented at an appropriate levels of abstraction, for example predicting trends and presenting scenarios, rather than providing precise but quite possibly incorrect predictions. Uncertainties and assumptions must be clearly stated without undermining the advice. The data/knowledge must be plausible – particularly where using predictions as evidence.

Given the above requirements, the task of the professional natural resource manager is challenging. There are, however, many opportunities for research contributions. For example, the above analysis has underpinned the development of an advanced decision support environment for natural resource management called NRM Tools (Walker and Johnson in press). The toolkit is designed to provide the flexibility of application demanded by users (Walker and Johnson 1996) in combining and recombining analytical functionality to meet the demands of particular tasks. As such, NRM Tools is a powerful environment in which to package and deliver research outputs. NRM Tools provides a mechanism whereby decision makers can make use of quantitative models. It also provides means of delivering qualitative or semi-quantitative knowledge and guidelines produced by research by developing knowledge-based systems (most familiar in the form of expert systems) that can be integrated into decision-support tools. NRM Tools not only provides a means of making this analytical functionality more readily available to users, it also provides means of facilitating their use. In particular, modules are currently under development that *support* problem formulation ('I've been asked to comment on this change in resource management – what possible implications should I be considering?') and task analysis and tool construction ('I want to assess the implications of this land use change on water quality and flooding risks – what data and analytical tools do I have to help me do this?').

Facilitating the uptake of research outputs

Research initiatives such as the development of NRM Tools add value to biophysical research in making it available to managers. However, this is only true where the technologies upon which such outputs are based are themselves accessible. They may often not be. Here again, there are opportunities for researchers.

The Herbert Resource Information Centre (the HRIC) was established because many such decision makers in the Herbert River catchment did not have adequate access to basic information about the catchment. The HRIC is a community-based and collaborative joint-venture which integrates a large range of high quality data about the Herbert catchment into a GIS (Geographic Information System). The partners to the HRIC are the Hinchinbrook Shire Council, CSR (the sugar milling company in the catchment), the Herbert Productivity Board, the Queensland Department of Natural Resources and CSIRO. Two Centre staff manage the data sets and undertake advanced analyses as required. Much routine analysis is undertaken directly by staff in the participating organisations.

As well as introducing GIS to the catchment, and thereby providing much more effective access to the range of data available about the catchment than was previously available, the HRIC provides both the technical requirements and ethos required for the use of NRM

Tools by managers within the catchment. CSIRO's involvement in this project has, therefore, both been of benefit in establishing a resource that is useful in its own right and has fostered a context for uptake of research outputs, in this case NRM Tools.
The HRIC provides a context in which data, scientific knowledge and method can be better integrated into local political processes by local people. The collaborative nature of the centre can be expected to have an impact on the flow of information and the course of debate in the catchment.

CONCLUSIONS

The creation of new knowledge usually involves institutions that are different from those concerned with its application and dissemination. However, what is clearly increasingly required is that the former better understand the latter if they intend to justify their existence in terms of impact on natural resource management rather than advancement of knowledge *per se*. Boehmer-Christiansen (1994) identified seven ways that experts can further their own interests in policy development. The first three of these are: emphasise uncertainty and incompleteness of knowledge; emphasise complexity and difficulty; emphasise threats that can be tackled with more science and technology. We would suggest that the reality of natural resource management in the 1990s means that these strategies are a fast-track to irrelevance. We suggest it is far better to invest effort in exploring techniques by which scientific expertise can be transformed into information relevant to natural resource management.

Science is often more comfortable in providing advice on what ought to be done and why, rather than practical advice on how it might be achieved (Boehmer-Christiansen 1994). Initiatives such as the NRM Tools and HRIC are designed to provide practitioners with access to scientific resources which they can then apply to the 'how' problem. Our vision is one in which data, knowledge and scientific judgements of that data/knowledge can all be made available for integration into a negotiation process that attempts to deal with inherent uncertainty. Therefore, there is a considerable focus on communication of the principles, values and assumptions underlying analyses. Ideally initiatives such as NRM Tools and HRIC should ultimately lead to co-design of research in which researchers and local stakeholders interact to explore the extent to which applied science can make a contribution to effective and sustainable natural resource management.

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Towards a scientifically based implementation plan for ecologically sustainable use and biodiversity conservation in the Great Barrier Reef World Heritage Area

***Leon Zann*[1] *and Jon Brodie*[2]**
[1] *Southern Cross University, PO Box 157, Lismore NSW 2480*
[2] *Great Barrier Reef Marine Park Authority, PO Box 1379, Townsville Qld 4810*

ABSTRACT

The Great Barrier Reef Marine Park and World Heritage Area functions as a multiple-use Marine Protected Area. Many human activities occur within and adjacent to the Great Barrier Reef World Heritage Area which may pose threats to the long-term ecological integrity of the system. These include fishing, shipping, tourism, recreation and run-off from urban and agricultural landuses. The social values of the area, e.g. wilderness values and traditional cultural values may also be threatened by increasing human activity of the above types. Although ecological threats to the Great Barrier Reef World Heritage Area have been identified and prioritised through comprehensive research activity, a coherent management strategy based on these priorities has not emerged.

Management of potentially damaging activities in the Great Barrier Reef is spread among a variety of agencies although the Great Barrier Reef Marine Park Authority maintains a limited level of overall coordination. Likewise, although general goals, objectives and strategies for ecological sustainable use (ESU) and conservation of biodiversity are found in the Great Barrier Reef Marine Park Act, Great Barrier Reef World Heritage Area Strategic Plan and other legislation and policies, these are very general and lack detail required for their practical implementation. Important scientific findings over the past 20 years have not been adequately used in zoning and management plans and a systematic biodiversity description of the Great Barrier Reef able to be used in representative area selection is still lacking. A scientifically-based management plan to implement ESU and biodiversity conservation is therefore of a high priority. This plan should be developed from the broad principles of ESU and biodiversity conservation, and from identified threatening human uses and impacts.

The framework for this plan is outlined in this paper and criteria are discussed for (1) identifying species requiring special management; (2) identifying potentially vulnerable species; (3) systematising an approach for conservation of ecologically important and representative habitats; and (4) prioritising management effort of human use against the severity of risk imposed.

INTRODUCTION

At the time of the establishment of the Great Barrier Reef Marine Park 21 years ago, the concept of large, multiple-use managed areas was very new, the Great Barrier Reef region and ecology of coral reefs were not well known scientifically, and the urgency for establishment of zoning plans precluded detailed baseline and theoretical scientific studies on management strategies. Nevertheless, the 'Great Barrier Reef model' which subsequently developed is widely regarded as successful and has been applied to other reef areas around the world (Kelleher et al. 1995).

The Great Barrier Reef Marine Park and World Heritage Area functions as a multiple-use Marine Protected Area (GBRMPA 1994). Many human activities occur within and adjacent to the World Heritage Area which may pose threats to the long-term ecological integrity of the system. These include commercial and recreational fishing, shipping and related port activities, tourism, recreation and coastal urban and agricultural landuses (Zann 1996). The social values of the area, for example wilderness values and traditional cultural values, may also be threatened by increasing human activity of the above types. No formal comprehensive risk assessment for the Great Barrier Reef has been carried out but over the last decade considerable research has been carried out to identify the existing and potential threats to the system.

Over the past two decades much has been learnt about the Great Barrier Reef, of the structure and function of coral reefs and marine ecosystems, and of planning and management of marine protected areas. Environmental degradation has continued, and the goals of ecologically sustainable development (ESD) and conservation of biodiversity have also been developed as national and international priorities (CoA 1992). Zoning plans have been developed for 360,000 sq km of the Great Barrier Reef Marine Park. The Great Barrier Reef Marine Park Authority has grown from a handful of staff to a professional agency with 150 staff (GBRMPA 1996). Scientific support has increased from a handful of coral reef scientists around Australia to internationally known coral reef research centres at the Australian Institute of Marine Science, James Cook University of North Queensland and the CRC Reef Research Centre.

It is therefore timely to examine the Great Barrier Reef Marine Park Authority's planning strategies for the maintenance of the Great Barrier Reef's biodiversity in light of scientific discoveries over the past two decades, our knowledge of the main threatening activities and goals of ESD and biodiversity conservation. The following paper (1) reviews Great Barrier Reef Marine Park Authority and Commonwealth strategies for ESD and biodiversity conservation; and because a coherent biodiversity management plan is lacking, (2) recommends a framework for the development of a detailed implementation plan for ESD and biodiversity conservation in the Great Barrier Reef Marine Park.

REVIEW OF GREAT BARRIER REEF MARINE PARK AUTHORITY POLICY FOR ECOLOGICALLY SUSTAINABLE DEVELOPMENT AND BIODIVERSITY CONSERVATION

Ecologically sustainable development is defined as: 'using, conserving and enhancing the community's resources so that ecological processes, on which life depends, are maintained, and that the total quality of life, now and in the future, can be increased' (CoA 1992). The concept has been widely embraced by all levels of government in Australia and by economists, industrialists and conservationists in the private sector. However, ESD is an ambiguous term and widespread scepticism remains amongst ecologists on its feasibility (e.g. Ludwig et al. 1993).

Ecologically sustainable use (ESU) is the primary goal (or 'critical issue') of Great Barrier Reef Marine Park management (GBRMPA 1994). The term is analogous, but preferable to ecologically sustainable development (ESD) and is an acknowledgment that, in logic, there must be limits to continued development if renewable resources are to be sustained.

'Biodiversity' is defined here as the variety of life forms: different plants, animals and microorganisms, the genes they contain and ecosystems they form (DEST 1993). The concept particularly emphasises the interrelated nature of the living world and its processes. However, like ESU, it is a broad goal and has been difficult to develop prescriptive management objectives for the tens of thousands of Great Barrier Reef species.

Strategies for ESU and biodiversity conservation are contained in a range of legislation, regulations and policies, and in formal decisions of the Great Barrier Reef Marine Park Authority, zoning plans and other sources. The *Great Barrier Reef Marine Park Act 1975*, amendments and regulations protect corals and certain other species, prohibit certain endangering processes (e.g. mining, oil drilling), provide for development of zoning and other management plans and powers to stop threatening processes. The formal decisions of the Marine Park Authority contain general and specific strategies for managing particular issues, and reflect the evolving, issue-driven approach to management which characterises the Great Barrier Reef Marine Park model.

Other Commonwealth and State Acts protect certain Great Barrier Reef Marine Park species and prohibit certain threatening processes. Commonwealth government policies (e.g. the Ecologically Sustainable Development strategy), and bilateral and international agreements and conventions also contain goals and objectives for biodiversity management (e.g. World Heritage Convention).

With the exception of the protected species/taxa identified, the above legislation and policies are very general, and refer to broad goals and concepts. For example, the Great Barrier Reef World Heritage Area Strategic Plan's goals are 'protection', 'maintenance of ecology' and 'ecologically sustainable use' (GBRMPA 1994). Details on the mechanisms by which these goals may be achieved are invariably lacking.

The Great Barrier Reef Marine Park Strategic Plan does attempt to provide hierarchical steps and processes to achieve ESU and biodiversity management. For example, it identifies the key issues or objectives in the management of the Great Barrier Reef Marine Park as (1) the maintenance of the ecology; (2) management to achieve ecologically sustainable use; and (3) maintenance of traditional, cultural, heritage and historic values. The main 25 year objective is 'to ensure the persistence of the Great Barrier Reef World Heritage Area as a diverse, resilient, and productive ecological system ...'. Several 'broad strategies' are given to achieve this objective (e.g. 'manage use of the Area in accordance with ecological sustainability and the precautionary principle.'). Five year objectives and strategies are given, from which the Great Barrier Reef Marine Park Authority Corporate Plan objectives may be developed (e.g. table 1).

Table 1. Some objectives and strategies in the Great Barrier Reef World Heritage Area Strategic Plan relevant to biodiversity conservation (GBRMPA 1994)

5 year objectives	Strategies
1.1. To have in place integrated management strategies for the conservation of the Great Barrier Reef WHA) and strategies to achieve them	1.1.1. Develop, in consultation with stakeholders, integrated planning for *conservation* of the Area ... 1.1.2. Document existing biological communities as appropriate ...
1.2. To have in place clear policies for the conservation of major biological communities ...	1.2.1. Develop ... policies for the conservation of the following biological communities: coral reefs, mangroves, island vegetation, seagrass, Halimeda beds, inter-reefal areas and the Great Barrier Reef lagoon.
1.4. To protect representative biological communities ... to act as source areas, reference areas, and reservoirs of biodiversity and species abundance	1.4.1. Identify and protect representative biological communities ...
1.5. To pay special attention to conserving rare and endangered species	1.5.1 Identify species which are endangered in the Area and threats to their survival
1.6. To aim to prevent ecologically unsustainable loss and degradation of marine and terrestrial biological communities ...	1.6.1. Develop mechanisms to address the cumulative impacts of localised projects through regional planning and management plans.

The Strategic Plan however fails to provide unambiguous, scientifically-based targets and mechanisms for ecologically sustainable use (ESU) and biodiversity conservation. It does not attempt to define the processes by which ESU may be attained (e.g. the objective of 'prevention of unsustainable loss' is circuitously achieved by a strategy 'to develop mechanisms to address cumulative impacts'). It makes no attempt to identify threatened species, define limits of acceptable change to habitats, proportions of habitat which should be totally protected, or the number, size and spatial arrangements of protected areas or specify how representative biological communities can be identified.

The Strategic Plan recognises that management of potentially damaging activities in the Great Barrier Reef, which may adversely affect conservation values, is spread among a variety of agencies. Great Barrier Reef Marine Park Authority maintains a limited level of overall coordination. Catchment landuse activities are managed by Queensland Department of Natural Resources through the Integrated Catchment Management process; management of fisheries and fishing is by Queensland Department of Primary Industries and Queensland Fish Management Authority; shipping activities and oil spill management is by the Australian Maritime Safety Authority and Queensland Department of Transport; and urban and industrial landuse activities management is by the Queensland Department of Environment (GBRMPA 1994).

ASSESSMENT OF THREATS TO Great Barrier Reef ECOSYSTEMS

While management of use has apparently been relatively successful, in view of the current favourable assessment of the state of the Great Barrier Reef (Wachenfeld et al. 1996), pressure on the system has been generally low compared to the other major reef systems which lie in developing nations (e.g. Veron 1995). Thus management success may be partially illusory and management systems inadequate in the face of pressures from greatly increased use of the system. No consistent system for prioritising management resource allocation against risk has yet been implemented. The current crisis state of dugong populations in the southern half of the Great Barrier Reef Marine Park (Marsh et al. 1996) may mark the first evidence of significant management failure, perhaps reflecting lack of focus on managing the environmental effects of fishing.

The only identifiable catastrophic risk to a significantly sized area of the Great Barrier Reef is that posed by a major oil spill. A major oil spill, either to the east of the Great Barrier Reef or in the inner shipping channel, will cause extensive damage to nearby habitats – mangroves, intertidal seagrass and shallow reefs. There is very limited capacity to deal with such a spill (Raaymakers 1996). Measures to minimise the risk of a spill are slowly being introduced but the position of the Great Barrier Reef as an international shipping route prevents many management solutions being easily implemented. Research into clean-up technology suitable for use in the Great Barrier Reef environment is minimal.

An uncertain risk for the Great Barrier Reef is the cycles of crown-of-thorns starfish outbreaks. These have caused major apparent damage to reefs in the central part of the Great Barrier Reef but it is still unclear as to whether they are a totally natural occurrence, mainly human induced or perhaps natural but with their frequency increased by human activity (e.g. Moran and Lassig 1996).

The most important chronic threats to the Great Barrier Reef are believed to be those arising from increased terrestrial run-off of pollutants associated with agricultural and urban activity; the effects of trawling; and localised physical damage from anchoring of tourist, recreational and fishing vessels (Zann 1996). The biological level of risk and severity of damage from these impacts has been hard to quantify against the large inherent natural variability in the system. In general most habitats in the Great Barrier Reef appear to be in 'good' condition reflecting limited effects from these impacts at present.

A SUGGESTED FRAMEWORK FOR A GREAT BARRIER REEF BIODIVERSITY CONSERVATION PLAN

The development of a scientifically-based plan for ESD and biodiversity conservation is a monumental, but not impossible, task. The following briefly discusses the issues in ESD and biodiversity conservation, and suggests a framework for the development of a strategy and implementation plan. It builds on existing objectives and strategies and suggests (by way of example) some scientifically-based mechanisms for their implementation, or research which is needed to identify such mechanisms.

Ecologically sustainable use: a 'top down' approach

ESU is a modern term and is implicit in Great Barrier Reef Marine Park Authority's goal of 'wise use in perpetuity', and in the multiple use managed area model. ESU may be a simplistic concept or philosophical ideal which not easily grounded in ecological science, but it is clearly a preferable to present, unsustainable, market-driven development. ESU and the application of the 'precautionary principle', which places the onus of proof onto the developer or exploiter, reflects a new and cautious approach to resource use and environmental management (Driml and Zann 1996).

It is important that the concept or ideal of ESU is translated into practical, scientifically-based management actions by the Great Barrier Reef Marine Park Authority and the CRC Reef Research Centre. From goals can be developed principles, objectives and actions for implementation. Some practical implications of ESD/U to management of the Great Barrier Reef biodiversity are suggested in table 2.

Species conservation: a 'bottom up' approach

The 'top down' large ecosystem management and ESU approach (above) must be complemented by a 'bottom up' species management approach to ensure that biodiversity is retained. Many coral reef species are rare, and many are regarded as 'ecologically redundant' (not necessary for the function of the ecosystem). The following discusses some major objectives of species, community and habitat management and appropriate management or research actions.

Identification of species for special management

Corals (keystone and umbrella species) are protected under the Great Barrier Reef Marine Park Act. A range of other Great Barrier Reef species are fully protected, or subject to size or bag limits under Great Barrier Reef Marine Park and State regulations. However, these have been identified on an ad hoc basis, and there has been no systematic attempt to identify species requiring special management.

Jones and Kaly (1996) identify five types of species deserving special conservation status:
(a) Ecological indicators (species which may provide an early warning of detrimental impacts on the community, e.g. *Acropora* spp. in inner and mid-shelf reefs)
(b) Keystone species (pivotal species upon which the diversity of a large component of the community depends, e.g. seagrasses, macroalgae, corals and their key herbivores and predators)
(c) Umbrella species (species with large area requirements, which given sufficient protected habitat area, will bring many other species under protection, e.g. seagrasses, macroalgae, corals, sponges and other colonial animals)
(d) Flagship species (popular species that serve as rallying points for major conservation initiatives, e.g. corals, dugongs, turtles)
(e) Vulnerable species (those which are actually prone to extinction: below).

Table 2. Ecologically sustainable use: from ideal to action

The following attempts to define principles implicit in the concept of ESU and develop from these practical management strategies and actions:

Some general principles of ESU and management implications...

1. The maintenance of ecosystem function must be considered as the primary objective of environmental management throughout the Great Barrier Reef. (Implications: this dictates a 'top down' approach to management, and complements the 'bottom up' species approach implicit in biodiversity conservation, below).

2. A large-scale or 'systems' approach to management is essential. (Implications: this dictates integrated land/sea management, and strategic planning and management in the coastal zone.)

3. Maintenance of environmental quality and ecosystem function is a prerequisite for management in aquatic environments. Implications: this dictates a priority on water quality management.)

Some management strategies and objectives...

1. Large protected areas which encompass land and sea systems need a precautionary approach to maintaining biodiversity, for reference areas and for fisheries refugia. (Land and sea protected areas should be integrated where possible, e.g. Cape York/Far Northern Section.)

2. The maintenance of water quality is of critical importance in all areas of the Great Barrier Reef Marine Park and entering and adjacent waters. (Integrated catchment management is a State and national priority).

3. Marine Protected Areas should be of a sufficiently size and of suitable spatial arrangement to ensure that their ecological function and connectivities (larvae and adults) are maintained.

4. Management (and therefore research and monitoring) should primarily focus on maintaining the ecologically important, functional groups, critical habitats, and 'keystone' and 'umbrella' species. *(see 'Maintenance of biodiversity' section (below))*

5. In the absence of scientific understanding of the Great Barrier Reef system, an empirical , precautionary approach to environmental management is required (e.g. monitoring indicator species in protected and unprotected areas; applying techniques which have worked in other areas; managing or prohibiting activities documented as harmful in other areas) .

6. Extractive activities occurring over significant areas (meso/macroscale) require application of precautionary principle (e.g. fisheries is the major extractive use of Great Barrier Reef is fisheries; fisheries globally (and particularly on coral reefs) have not been sustained; new (and existing?) fisheries should require an Environmental Impact Statement).

7. Management should focus on mechanisms to avoid/reduce meso-scale chronic and episodic threatening processes (e.g. oil or chemical spills from mainland cities, resorts, shipping).

8. Monitoring is the basic tool under scientific uncertainty (e.g. state of the environment reporting is needed to detect cumulative impacts of multiple or chronic 'minor' disturbances).

Identification of potentially vulnerable marine species

Great Barrier Reef Marine Park, State and Commonwealth legislation protect some perceived vulnerable and threatened species such as turtles, dugongs, cetaceans and seabirds. However, there has been no systematic attempt to identify criteria for vulnerable or endangered species on the Great Barrier Reef Marine Park. The very large number of species in the Great Barrier Reef Marine Park and the fact that many coral reef species are rare, but not necessarily endangered, greatly complicates the task.

Potentially vulnerable species may be identified based on empirical and theoretical considerations. Jones and Kaly (1996) identify several types of species as potentially vulnerable and other criteria have been added by the authors:

(a) Species with unusually restricted breeding sites. (Many highly mobile marine species converge on specific breeding grounds, representing only a small part of their geographic range, e.g. whales, turtles, seabirds, some fish. Here they are potentially vulnerable to overfishing or environmental disturbances.)

(b) Species that are very large, long-lived and/or of low fecundity. (Typically, these species are also naturally rare and aggregated, slow to mature and have consistently low recruitment. These characteristics make them prone to over-exploitation and slow to recover. Examples include giant clams; large, live-bearing fish such as sharks and rays; and most marine reptiles and mammals are particularly susceptible to over-exploitation.)

(c) Species subject to large-scale mass mortality. (A number of marine species exhibit catastrophic declines in abundances over a short period e.g. seagrasses subject to die-back, and mass mortality of marine mammals.)

(d) Species subject to prolonged recruitment failure. (While most marine species exhibit variable recruitment and 'year-class phenomena', this may occur over long periods in some species, e.g. potato cod).

(e) Species highly susceptible to environmental stresses. (These may be the first to become extinct locally, and may be the first to succumb to global threats such as ocean warming. They may be used as 'early warning' indicators of changes, e.g. sediments and nutrients may affect seagrasses and corals.)

(f) Species that are extreme habitat specialists. (For example, symbiotic species associated with a one or a few species of host, e.g. some anemone fish (*Amphiprion* spp); turtle and dugong barnacles (*Platylepas* spp.)

(g) Obligate supra-tidal, intertidal, estuarine and coastal embayment species. (These are potentially limited habitats and their susceptibility to human disturbances makes these vulnerable, e.g. to overharvesting for food, bait and curios, and oil and other surface layer contaminants.)

(h) Species subject to excessive exploitation. (A growing number of marine reptiles, mammals, fish and invertebrates in Australia have been over-exploited, e.g. turtles, dugongs, tunas.)

(i) Species subject to indirect, chronic or episodic disturbances or impacts. (e.g. by-catch from netting or trawling affects dugongs, turtles and shelf benthos.)

(j) Inshore species subject to eutrophication or sedimentation from terrestrial run-off. (e.g. seagrasses, inshore corals)

(k) Endemic species, particularly those with narrow ranges. (Most Great Barrier Reef mid- and outer-shelf species have a very wide Indo-Western Pacific distribution. Inner-shelf habitats appear to have a higher proportion of endemics e.g. the gastropod family Volutidae, some nudibranchs.)

While insufficient is known of the status of almost all species in the Great Barrier Reef Marine Park, the above criteria are useful in identifying such species. A matrix approach may be useful in identifying the most vulnerable species (table 3).

Table 3. Matrix for identifying potentially vulnerable species (see text 2.2. for legends a–j). Species with highest scores (x) may be most vulnerable.

Species	sci	abund	a	b	c	d	e	f	g	h	i	j	total
dugong	A	UC (decl)		xx	xx			x		x	x	x	8
green turtle	F	UC (decl?)	xx	xx		xx				xx	x		9
Irrawaddy dolphin	NR?			xx					x		x	4?	
tiger shark	N	UC?			xx							x	3?
Volutidae spp.	N	C–R?							x?			x	2?
Platylepas spp.	N	R	x	xx*	xx*			xxx		(xx)	(x)	(x)	12
seagrass (inshore)	A	A			xx		x		x	x		xx	7

Sci (scientific knowledge): A: adequate; F: fair; N: nil
Abund (abundance): A: abundant; C: common; UC: uncommon; R: rare; ?: unknown (guess)
Decl: declining population

Habitat/community conservation: practical unit for management

The ecosystem and species approaches meet at the habitat/community level, the most practical level for biodiversity conservation. While space prevents a detailed review of the research issues and possible management mechanisms, implications are briefly discussed.

Need for inventory of Great Barrier Reef Marine Park habitats and communities

No inventory of habitats and communities has been developed for the Great Barrier Reef Marine Park, despite their high priority within the Strategic Plan. Systematic benthic surveys were initially used to identify habitats and reef types in the first Capricorn Zoning Plan. However the large size of the later Marine Park Sections and time and funding constraints resulted in use of more a descriptive, 'Delphic' approach, based on the opinion of experienced researchers on patterns of community/reef types in the area. While systematic surveys have not been undertaken for the entire Great Barrier Reef Marine Park, the REEF GIS database being developed by the Great Barrier Reef Marine Park Authority and the AIMS monitoring database have descriptions of around 500 different reefs (e.g. Oliver et al. 1995) which could form the basis of a comprehensive inventory.

While protection in the Great Barrier Reef Marine Park to date has largely centred on coral reefs, the Great Barrier Reef Marine Park and the Great Barrier Reef World Heritage Area include many other communities: saltmarsh, mangroves, estuaries, hard and soft shores, seagrass beds, macroalgal assemblages and other inshore communities; virtually undescribed continental shelf hard and soft bottom benthic communities; the interconnecting shelf watermasses, plankton and nekton communities; coral reefs; islands; and the continental slope and adjacent waters benthic and planktonic communities of the Coral Sea.

Paradoxically, mid- and outer-shelf emergent coral reefs have been disproportionately more protected (because they are visible and 'glamorous') although they are probably under lesser threat, and may have a lower species diversity and low proportion of endemics than inshore areas.

Need for bioregionalisation
No comprehensive bioregionalisation has been developed for the Great Barrier Reef Marine Park, again despite its high priority within the Strategic Plan. The most important regionalisation used in zoning plans has been the cross-shelf (inner, mid, outer) zonation developed by AIMS, although a lack of consistency of the model in north-south direction has posed problems between Sections. A preliminary macroscale bioregionalisation of the Great Barrier Reef World Heritage Area has been independently proposed under the Ocean Rescue 2000 National Network of Marine Protected Areas (Thackway et al. 1995), but requires refinement and testing.

Need for research on community management strategies
Research is required to develop scientifically-based strategies for habitat and community management, particularly: keystone habitats and communities; optimal and minimal sizes of protected areas for each community type; migration/larval connectivities; and functional relationships. A systematic approach such as that suggested by Jones and Kaly (1996) for species management would be useful.

While adequate scientific understanding of the Great Barrier Reef system is a distant prospect, the Great Barrier Reef Marine Park Authority precautionary model for large marine protected areas for coral reefs should be equally applied to other habitats and communities within the Great Barrier Reef Marine Park and the Great Barrier Reef World Heritage Area.

Risk prioritisation as a basis for management response

At present there is no coherent system of prioritising the risks to the ecosystems and values of the World Heritage Area such that management resources can be effectively distributed and applied. This lack is compounded by the commonly held misapprehension that the Great Barrier Reef Marine Park Authority has a legislative role to manage all activities impacting on the ecological and socio-cultural values of the World Heritage Area or the Great Barrier Reef Marine Park. If we consider the principal potentially impacting activities to be fishing, shipping, terrestrial run-off, tourism and recreation (with global climate change as a poorly known contributor) it may be seen that for only tourism and recreation is the Great Barrier Reef Marine Park Authority the lead management agency in the Great Barrier Reef. While the Great Barrier Reef Marine Park Authority has a reserve power to intervene in the management of any of these activities where they are impacting on the ecology of the Great Barrier Reef this power has not been exercised. Thus the largest slice by far of management resources within the Great Barrier Reef Marine Park Authority goes to managing tourism with minimal resources going to managing the effects of fishing, terrestrial run-off or shipping.

The quantification and prioritisation of the threats to ecology and values of the World Heritage Area should be carried out in a formal way. The results of this can then be incorporated into the Strategic Plan to prioritise the management strategies developed in the Plan. The allocation of management responsibilities and resources can then be attempted to be made using a systematic approach.

SUMMARY AND CONCLUSIONS

It is concluded that the Great Barrier Reef Marine Park Authority lacks a coherent, scientific-based implementation plan for ESU and biodiversity conservation. The broad goals, objectives and strategies for biodiversity conservation are to be found in existing legislation, but policies and agreements have not been collated or synthesised into an ESU and biodiversity conservation policy and necessary implementation plans. This lack of a formal framework for ESU and biodiversity conservation has resulted in inconsistencies among Section zoning plans (e.g. the adjacent Far Northern Section and Cairns Section Zoning Plans are inconsistent in objectives and design), difficulties in evaluating zoning plans (e.g. in reviewing the Far Northern Section), an ad hoc approach to scientific research (e.g. many of the Strategic Plan 5-year research objectives have not been commenced), a continuing uncertainty on the status of all but a few species in the Great Barrier Reef Marine Park, and an ability to target management to the highest priority issues.

The development of a scientifically-based management plan for ESU/D and biodiversity conservation in the Great Barrier Reef is a high priority. This plan should synthesise the goals of ESU/D and biodiversity conservation, apply current scientific knowledge of the Great Barrier Reef system and theory of marine protected area design, and develop practical management objectives and prescriptions to be used in planning and management in the Great Barrier Reef Marine Park.

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SESSION 5

People and the Reef

Using geographic information systems for integrating socio-economic and cultural information into reef planning and management

D Benzaken and M Gilbert
Great Barrier Reef Marine Park Authority, PO Box 1379, Townsville Qld 4810

ABSTRACT

The integration of a wide range of socio-economic datasets into the Great Barrier Reef Marine Park Authority Geographic Information System is being used by the Great Barrier Reef Marine Park Authority to provide a greater understanding of reef use and values of the Great Barrier Reef Marine Park. Spatial analysis and modelling allows for the development of 'use catchments' and cognitive maps which can assist in planning and management decisions such as equitable resource allocation within the context of multiple use.

GIS provides a powerful tool which can integrate a range of disparate social datasets to provide a context for more concentrated research involving surveys for site specific information of use and perceptions of activities carried out in the Marine Park.

A case study of recreational use is presented to illustrate this approach. The Australian Bureau of Statistics Census data, the Department of Transport Boat Registration database, the Great Barrier Reef Marine Park Authority Representation database and a site specific survey conducted in the Ingham area following the reopening of Bramble Reef to line fishing were integrated and spatially analysed to produce maps of stakeholder use patterns, perceptions and value of the area.

INTRODUCTION

The management of the Great Barrier Reef Marine Park presents a challenge of protection and sustainable multiple use. Management of uses and users is primarily achieved by zoning of the Marine Park into areas of permitted activities, preparing management plans in consultation with users, strategic planning with stakeholders, assessment of impacts of major development and permitted activities, research and monitoring, and public education.

The management of reef use can be significantly assisted by the provision of information which describes the natural and socio-economic environments using a common framework. Geographic Information Systems (GIS) provide a powerful tool with which to integrate, analyse and display a range of disparate datasets and allow for the modelling of relevant aspects of socio-economic and environmental relationships as well as providing a context for more concentrated site-specific research. The use of GIS in socio-economic studies is relatively new but is being embraced by academics and organisations worldwide and in Australia, as a tool for the implementation of ecologically sustainable resource planning and management situations such as fisheries management (Stoffle et al. 1994) , tourism planning (Fagence 1990; Phillips and Tubridy 1994; Li 1987; Boyd et al. 1994; Oppermann and Brewer 1996), economic valuation of conservation areas (Eade and Moran 1996), mapping multiple perceptions of wilderness (Kliskey and Kearsey 1993), regional and ecosystem planning (Martin and Bracken 1993; Daplyn et al. 1994) and to describe and interpret patterns of use and values and their impact on the natural environment.

Over the years, the Great Barrier Reef Marine Park Authority has endeavoured to integrate existing datasets from its planning and research activities into the corporate GIS. Socio-economic datasets are at this stage limited although significant improvements have been achieved in the last two years with the reef-wide Data Returns dataset on tourism use, and the acquisition of demographic datasets such as the Australian Bureau of Statistics Census data.

The integration of a wide range of socio-economic datasets such as census data, visitor use statistics and socio-economic survey data into the Great Barrier Reef Marine Park Authority GIS provide the basic material for understanding spatial patterns of reef use. Socio-economic information obtained from users about their motivations for observed spatial and temporal patterns of use, provided insights into the dynamics of use of particular sites at different times. In particular spatial analysis allows for the development of 'use catchments' and cognitive maps for different user groups. A case study of recreational use in the Great Barrier Reef World Heritage Area is presented to illustrate this approach.

The Bramble Reef case study

Bramble Reef, located off-shore from the coastal town of Ingham, was closed to line fishing on the first of January 1992, following public perception of declining fish stocks, in particular coral trout (*Plectropomus leopardus*) and sweet lip (*Lethrinus miniatus*). A cross-sectoral advisory committee, (the Bramble Reef Replenishment Area Advisory Committee), was established to advise the Great Barrier Reef Marine Park Authority on the management of the closure. Target fish species populations were monitored by the Great Barrier Reef Marine Park Authority through its Effect of Fishing program. Following the recovery of fish stocks (Ayling and Ayling 1994), the reopening of Bramble reef was discussed by the Committee and a decision to reopen Bramble Reef to fishing was made by the Great Barrier Reef Marine Park Authority and scheduled for 1 July 1995. It was also agreed to monitor the environmental, social and economic impacts of the reopening. The Bramble Reef socio-economic study is one of a number of projects undertaken by the CRC Reef Research Centre.

Methodology

The Australian Bureau of Statistics Census data, Queensland Transport Boat Registration data, the Great Barrier Reef Marine Park Authority Representations data and site-specific surveys conducted in the Ingham area were integrated and spatially analysed to produce maps of stakeholder use patterns, perceptions and value of the area.

Population and boat registration data

Australian Bureau of Statistics C-data was obtained and converted to ArcInfo format for use in the Great Barrier Reef Marine Park Authority GIS. The spatial aggregation of the census data is approximately 200 household units (the smallest unit available), enabling it to be coarsely aggregated to compare with a variety of other socio-economic boundary coverages. The problems encountered of mismatch between different socio-economic and administrative boundaries in vector GIS is widespread and while the use of a raster GIS format can overcome some of these problems (see Martin and Bracken 1993), the financial constraints generally preclude the latter approach.

Private boat registration data was spatially referenced to a postcode coverage for the area adjacent to the Marine Park. This too has limitations in terms of discontiguous spatial representation of mapping units; however, it proved to be adequate at the scale of the Great Barrier Reef region. The boat registration data was also used to graph the increase in total boat registrations in the Ingham area from 1981 to 1995 (see figure 1 over).

Socio-economic surveys of Ingham residents

A number of surveys of Ingham residents and Ingham offshore users were carried out prior to, and following, the reopening of Bramble Reef. A range of user groups were surveyed including Recreational Users (fishers and non-fishers), Indigenous Users, Charter Boat Operators (Fishing, Diving and Tourist) and Commercial Fishing Operators. The survey design and instrument were developed and piloted in consultation with the members of the Advisory Committee. Face-to-face interviews were conducted between June and September 1995. Some 253 questionnaires were completed, most of them obtained from recreational and indigenous users. The small study area, combined with low numbers of resident commercial fishers and tourism operators, precluded meaningful results from the analysis of the commercial component of the data. Consequently, comparative analysis was carried out only between Recreational Users and Indigenous Users.

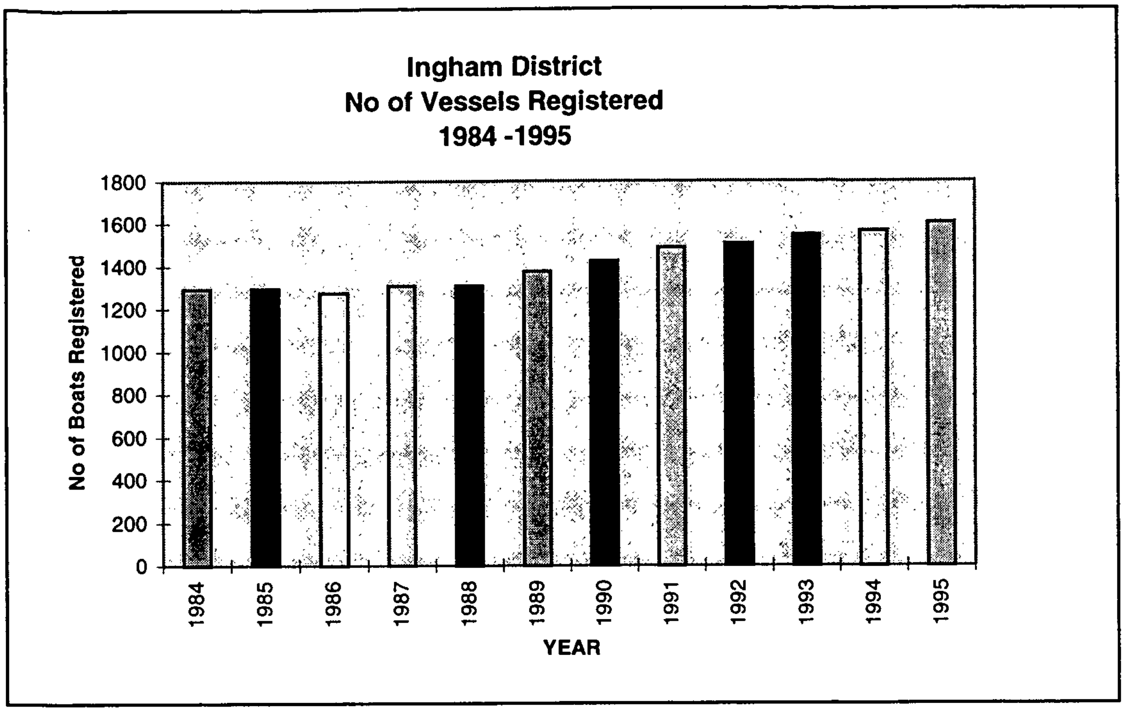

Figure 1. Total number of privately registered vessels for Ingham from 1984 to 1995
Source: Queensland Transport

The results of the Bramble Reef socio-economic survey were entered into the GIS to produce a series of thematic maps describing the spatial and temporal distribution and characteristics of human-use of the offshore Ingham waters. The attributes described included: the intensity and extent of use by recreational fishers and indigenous groups; average trip length per destination; average number of angler hours per trip per destination; harvested catch rate per angler hour (CPUE) per group, percentage of catch released; relative harvested CPUE (%) of total CPUE, and the predominant motivations cited for visiting each destination. The frequency of the size of vessels (length '< 5 m' and '5 m and over') used for visiting destinations were spatially referenced to assist in estimating the potential range of reef-going vessels in the total number of boats registered to the Ingham area (see figure 2).

The results of the Ingham survey were geo-coded to a coverage already held in the Great Barrier Reef Marine Park Authority GIS, which contained links to a corporate database recording public comments on proposed zoning for each unit. This Representations database provided a further source of historical information about the study area and its management as each comment recorded was categorised by user group type and the activities undertaken at the destination. The coverage had been generated from topographic features within the Marine Park, thereby avoiding the problems of 'ecological fallacy' (Martin and Bracken 1994) often encountered when overlaying environmental resource data with socio-economic boundary coverages. This approach provides the option to integrate a range of environmental data such as satellite images with human use of reefs for monitoring impacts on individual reefs as was carried out by Stoffle et al. (1994) for the coral reefs of the Dominican Republic.

RESULTS

Boat ownership and use of the offshore Ingham area

For the period 1984 to 1995 the Ingham District boat registrations increased 23.96%. Of the 1460 boats registered to postcode 4850 in January 1996, 290 were 5 metres and over in length, and 1170 boats were under 5 metres in length. Detailed research on vessel length and range travelled from boat ramps to destinations, as investigated in the Bramble Reef surveys, provides the potential to estimate the extent of recreational use by boat-owners living in the area adjacent to the Marine Park. The overlaying of 'use catchments' generated for major towns in the coastal zone can provide important information for marine park management of the extent of recreational use and impacts.

Patterns of use of the offshore Ingham area

Visitation frequency and trip length data from Recreational and Indigenous users combined was used to calculate a total number of trip hours recorded for each destination between June 1994 and July 1995. The total of 78 respondents with frequency information recorded 14 198 total trip hours for the offshore Ingham waters. Britomart Reef and southern Hinchinbrook Channel were the most used destinations recording over 1200 trip hours, with the northern section of the Hinchinbrook Channel and Trunk Reef recording the next highest use level. Combined with the total number of trips to destinations, the results would indicate that while trips to Hinchinbrook Channel are generally more frequent and shorter in duration, the innermost reefs of Britomart and Trunk Reef were receiving as much use, but in the form of longer, less frequent trips.

The study showed that indigenous (n = 39) and non-indigenous users (n = 183) differed in their use of the offshore Ingham area on a number of points. Indigenous 'catchments of use' were more contracted than those of non-indigenous users with an average trip length per destination visited of 6 hours or less versus 6 to 35 hours for non-indigenous users, and 92% of their time was spent fishing versus 88% for non-indigenous users. Indigenous use of the study area tended to concentrate more on the immediate island waters around Palm Island Group, the Hinchinbrook Channel and the innermost reefs of the outer Great Barrier Reef (see figure 3). Recreational use comprised a more widespread range encompassing remote outer-reefs, Islands including Palm Island Group, with the greatest number of visits recorded for Hinchinbrook Channel (see figure 4). While both groups were primarily engaged in fishing rather than non-fishing activities, there were marked differences in their fishing motivations. Indigenous fishers placed greater importance on catch size and catching big fish than on fishing for sport and escaping routine.

Mapping the 'use catchments' for both Recreational and Indigenous groups allows the identification of areas of possible use conflict between groups. Comments contained in the Representation database for destinations e.g. Hinchinbrook Channel, provide an historical perspective on current perceptions of group use. Conflicts between commercial and recreational fishing over the use of particular areas, were recorded in the representations submitted to the review of the Central Section (1987) but could not be matched with current data (other than anecdotal) as a result of the small sample size of commercial fishers in this study.

Profile of users

The average number of participants per boat were 2.48 and 3.14 persons for recreational and indigenous fishers, respectively. The survey included the hours spent undertaking a range of activities by all participants on the last trip recorded, and comparisons between activities at destinations was combined with information from the Great Barrier Reef Marine Park Authority representations database. Similar comparisons between groups and gender for time spent on activities overall were made but not spatially referenced.

Catch profile

Catch rates (HCPUE Total number of fish harvested per angler hour) were calculated for Indigenous and Recreational fishers and were mapped for each destination with the highest recorded catch rates of 3.15 for Indigenous and 2.03 for Recreational fishers. Hinchinbrook Channel recorded comparatively low catch rates for both groups. The relative harvested CPUE (%) was calculated and mapped to give an indication of the total number of fish harvested relative to the total number of fish caught. This combined with a map showing the percentage of fish released per destination illustrated an interesting overall profile of fishing in the offshore Ingham waters.

The species of fish caught and harvested per group per destination were also recorded and HCPUE rates for targeted fish such as coral trout and sweetlip were mapped for each destination. Comparisons between species ratio of total catch for inshore and reef environments were graphed. Due to the size of the sample however, the results need to be interpreted cautiously but the application demonstrated the usefulness of the method for future surveys on fishing in the Great Barrier Reef region.

DISCUSSION

The Bramble Reef Socio-economic Survey was a pilot study with a sample size of only 252 respondents. The authors acknowledge the limitations of the sample size and other data anomalies. Consequently, the interpretation of the results can only be regarded as general conclusions about patterns of use of the offshore Ingham. In particular, when the survey data is dis-aggregated over a wide-range of destinations as in this GIS project, the sample size at some destinations becomes too small to be reliable. This was the case for the spatial analysis of user's motivations for selecting particular destinations. Recommendations for the design of future surveys is documented elsewhere (Bramble Reef Report in progress). However, the application proved to be effective for spatially comparing results between different user groups and demonstrates the range of socio-cultural information which can be integrated into the GIS.

The spatial representation of reef use not only provides accurate information on the spatial distribution of use, but also in identifying destination characteristics, user perceptions of management, environmental quality and the value placed on particular locations by various stakeholder groups, whether direct or indirect users. This type of information can be used in conjunction with information from users obtained though the public participation process to document use (or value) of areas, in particular to assist in understanding conflict of use (or value). Numerous studies have shown that public participation favours the well-organised groups (and their demands) in the planning process. This information will assist in deciding on the most appropriate (acceptable) management regime given the nature of user expectations (and conflicts) for high-use areas. The combination of spatial data on use and destination value with spatial biophysical characteristics of the reef will assist in the negotiation of trade-offs to achieve conservation goals while allowing for reasonable use.

CONCLUSION

A GIS approach to the study of reef for planning and management allows for an accurate representation of use patterns that can be undertaken at a number of spatial scales. It is also an avenue to add value to external data sources by analysing them with a focus on the information needs of the Great Barrier Reef World Heritage Area. Conversely, the integration of locally collected data with regional, state and national datasets will provide context and broaden the scope and value of otherwise limited case study information. Finally, spatially referenced socio-economic data can be analysed with biophysical data of the Great Barrier Reef World Heritage Area to provide a better understanding of biophysical and socio-economic relationships.

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Heron Island reef flat: 15 years of change

Vicki J Harriott
School of Resource Science and Management, Southern Cross University, PO Box 157, Lismore NSW 2480

ABSTRACT

Dredging of the boat harbour at Heron Island in 1987 and subsequent alterations triggered concerns about possible impacts of sedimentation on adjacent reefal areas. Monitoring of impacts was hindered by the lack of suitable quantitative baseline data. Here, the results of a series of transects across Heron Island reef flat adjacent to the boat harbour in 1977–78, were compared with similar surveys in 1994. The abundance of holothurian species and cover of substrata such as sand and live coral were compared between the two times for 4 zones. Holothurian density was lower in 1994 than in 1977–78, with declines in abundance of *Holothuria atra* on the inner reef flat and *Stichopus chloronotus* on the reef crest. On the reef crest, cover of sand decreased while cover of live coral increased. The results indicate that the sedimentation associated with the dredging apparently did not detrimentally impact reef flat corals, nor was abundance of sand higher in 1994 than in 1977–78. There was no increase in holothurian density associated with the dredging events, as has occurred in other areas impacted by combined sedimentation and eutrophication. The most significant factor in the changes is attributed to the building of walls adjacent to the harbour between 1978 and 1994 which apparently raised the mean low water level on the reef flat.

INTRODUCTION

Heron Island in the Capricorn–Bunker Group on the southern Great Barrier Reef is a site of great scientific and general interest because of its long history of habitation and scientific study. The reef flat at Heron Reef has been subjected to many human impacts, such as reef-walking (Liddle and Kay 1987) and scientific experiments. Since 1945, the construction and alteration of the boat harbour have affected the drainage pattern and distribution of sediments on the reef flat (Fisk 1991; Gourlay and Jell 1993; Lawn and Preker 1993).

Major modifications to the harbour in 1987 and in subsequent years, including enlargement and deepening of the boat swing-basin, were perceived to have a significant impact on the reef flat. The alterations produced an extensive sediment plume which swept over the reef flat and into the lagoon on the incoming tide (Fisk 1991; Gourlay and Jell 1993; Lawn and Preker 1993), and fine sediments from excavated material deposited on the beach adjacent to the harbour leached into the water for many years. Despite the existence of many biological studies of Heron reef flat, there were few data sets detailed enough to determine whether significant changes had occurred as a consequence of the dredging and harbour alterations.

This paper examines whether changes in the holothurian populations and habitat types of Heron reef flat have occurred over a 15-year period, by comparing the results of unpublished surveys in 1977–78 (Harriott 1980) with recent (1994) surveys. In sites such as Kanehoe Bay in Hawaii, populations of some holothurian species increased as a result of extensive eutrophication and sedimentation (Banner 1974), so holothurian populations may act as an indicator of altered water quality and sediment regimes. If dredging resulted in eutrophication and an increase in sediment on the reef flat, it would be predicted that holothurian populations and cover of sand might be higher in the recent surveys, and that cover of live coral might have declined in recent years as a result of chronic low-level sedimentation.

METHODS

Holothurian populations and habitat type were surveyed between May 1977 and April 1978, for transects from the low tide mark to the reef crest at Heron Island approximately 50 m south-east of the boat harbour. The results for 8 transects were pooled as replicates for time T_1. Between 25 and 30 January 1994 (time T_2), 8 similar transects were completed in the same area of the reef flat. In both surveys, the sampling unit was 2 m x 2 m quadrats. For each quadrat, holothurians were counted and habitat categorised as percentage cover of sand, rubble, boulder, consolidated dead coral platform, live coral and soft coral.

In the early surveys, 2 of the 8 transects were sampled contiguously (120–123 quadrats per transect), while for 6 transects, quadrats were placed 10 m apart (22–24 quadrats per transect). In 1994, one transect was sampled contiguously (122 quadrats), and 7 transects, were sampled every alternate 2 m (66–74 quadrats per transect). The larger sample sizes in 1994 reduced the variability of the data relative to the earlier surveys, and increased the likelihood that smaller changes could be detected in future samples.

The densities of the cryptic species *Holothuria impatiens, H. hilla, Stichopus horrens* and *Dicucumaria africana* were extremely variable and their visibility was dependent on weather conditions at the time of sampling, so these species were excluded from the analyses comparing holothurian densities between times. For each transect, the density of each holothurian species per quadrat (= 4 m^2) and percentage cover of each habitat type were compared between times using T-test. For percentage habitat categories, each analysis was done using both untransformed and arcsin-transformed data. The conclusions were identical, so results are presented here only for the untransformed data.

To examine zonation patterns of holothurians, and their variation over time, all transects were divided into the following zones (after Cribb 1973 and Jell and Flood 1978): *Zone 1*: Inner reef flat: dominated by sand, little living coral (approximately 30% of transect); *Zone 2*: Middle reef flat, sand-coral subzone: abundant boulders, some live coral (approximately 35% of transect); *Zone 3*: Outer reef flat, coral-algal subzone: more live coral, sand in channels between patches of rock and coral (approximately 20% of transect); *Zone 4*: Reef crest, outer edge of reef (approximately 15% of transect).

Holothurian density and habitat cover per zone were analysed using 2-way ANOVA examining the effect of zone and time on total density of all non-cryptic holothurian species, density of *H. atra, H. leucospilota, H. edulis* and *S. chloronotus*, and percentage cover of the habitat categories: sand, rubble, boulder, consolidated platform, and live coral. In cases where the 2-way ANOVA showed significant interaction terms between the main factors, the results were re-analysed for each zone, using a series of t-tests, comparing times T_1 and T_2.

RESULTS

Holothuria atra was the most abundant species, representing more than 50% of total holothurian density in 1994 (figure 1). The total densities of *H. leucospilota, H. edulis* and pooled species were significantly lower in the 1994 sample than in 1977–78 ($p = 0.03, 0.03, < 0.01$). There was a significant difference between times for the cover of all substrate types except rubble. There was a significant decline in the cover of sand ($p = 0.03$), and an increase in rocky substrata and live coral cover between the two samples ($p = 0.02, 0.02$) (figure 2).

Results of the 2 way ANOVAs, examining the effect of zone and time on each variable (table 1) showed that for *H. leucospilota*, zone was a significant factor, while for *H. edulis* time was a significant factor. For the other 3 categories, there was a significant interaction between the factors zone and time. When the effect of time was examine separately for each zone for these three categories, densities of holothurians differed significantly with time in Zone 1 for *H. atra*, in Zone 4 for *S. chloronotus*, and in Zones 1 and 2 for pooled holothurians. In each case, density was lower in the 1994 sample.

For rubble, zone was a significant factor. For all other habitat categories, there were significant interactions between the factors zone and time. When the results were analysed separately for each zone, there was significantly less sand in the reef crest zone in the 1994 sample than in the earlier samples (34% cf. 2.4%). Live coral was significantly higher in the reef crest zone in 1994 (16.7% cf. 41.1%), but was not significantly different in any other zone.

Table 1. Results of 2-way ANOVAs testing for the effects of zone and time on holothurian density and habitat type. P(F) is presented for each factor and for the interaction term. P(F) < 0.05 represents a significant effect.

	HA	HL	HE	SC	Pooled	A	B	C	D	E
ZONE	<.01	<.01	0.19	<.01	<.01	<.01	<.01	<.01	<.01	<.01
TIME	0.08	0.12	0.04	0.06	<.01	<.01	0.07	0.2	<.01	<.01
INTERACTION	0.02	0.12	0.26	<.01	0.02	<.01	0.27	0.01	<.01	<.01

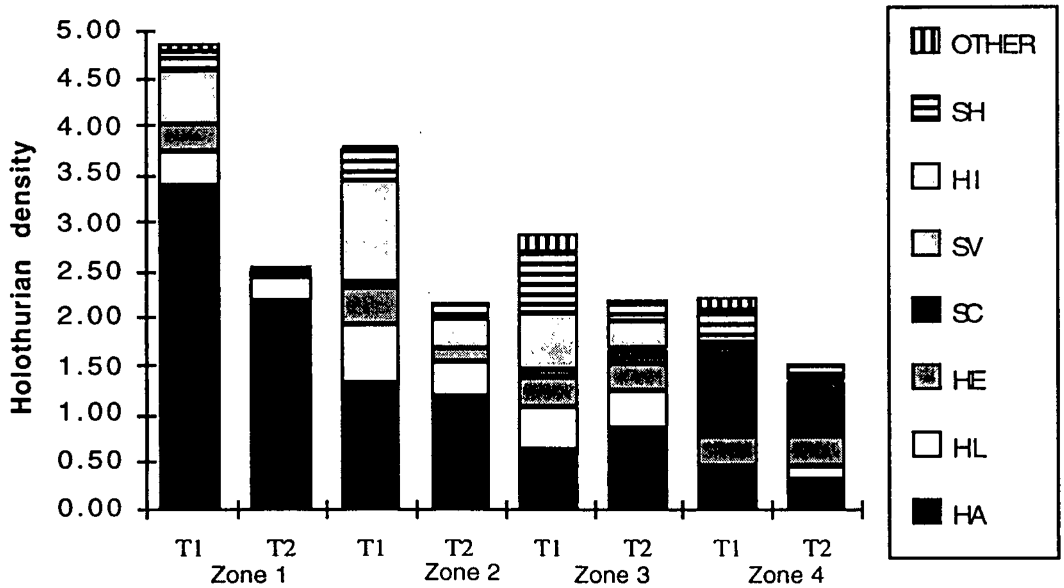

Figure 1. Density per quadrat of holothurians in Zones 1–4 at time T_1 (1977–78) and T_2 (1994). Codes for legend are HA= *Holothuria atra;* HL= *H. leucospilota;* HE= *H. edulis*; SC= *Stichopus chloronotus;* SV= *S. variegatus*; HI= *H. impatiens*; SH= *S. horrens.*

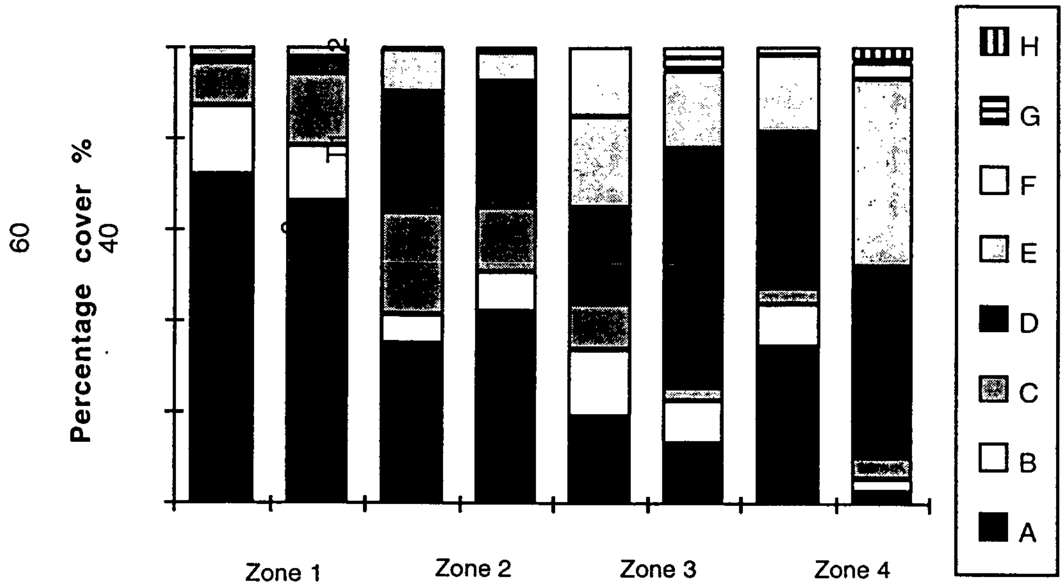

Figure 2. Percentage cover of habitat types in Zones 1–4 at time T_1 (1977–78) and T_2 (1994). Codes for legend are A= sand; B= rubble; C= boulder; D= consolidated dead-coral platform; E= live coral; F= dead coral; G= soft coral; H= *Palythoa*.

DISCUSSION

There was a significant decrease in overall holothurian density on Heron Island reef flat between 1977–78 and in 1994, with holothurian densities in the inner reef flat in 1994 just over 50% of their 1977–78 value. The decrease was attributable to a decrease in density of *H. atra* in the inner reef flat zone, a decrease in *S. chloronotus* in the reef crest zone, and an overall decrease in the abundance of *H. edulis* and *H. leucospilota*. Habitat analysis showed an overall decline in cover of sand, attributable to a decrease in sand on the reef crest from 34.2% to 2.4%. There was an increase in hard coral rock substrate in the outer reef flat, and an increase in live coral on the reef crest.

These results are not consistent with the results which might have been predicted as a outcome of the dredging operation, which resulted in the visible movement of sediment plumes across the reef flat for several years. There was no increase in sand cover on the inner reef flat, and no decline in hard coral cover which might be attributable to impacts from dredging.

Holothurian abundance was lower in 1994 than 15 years earlier. No increases in holothurian abundances similar to those associated with eutrophication and sedimentation at other sites (Banner 1974) have occurred. Lack of data for the intervening period means it is impossible to determine whether the decline in holothurian abundances reflects natural population fluctuations, or whether they were caused by an alteration in the environment as a result of the dredging operation or other causes e.g. cyclones. There are few published reports of population dynamics of holothurian populations.

Gourlay and Jell (1993) note that there is significant natural variation in sediment distribution on the Heron reef flat as a result of oceanic conditions, and that alterations to the natural patterns have occurred as a result of the harbour dredging. Interpretation of the effects of the dredging are complicated by natural impacts, such as the major effects of cyclones, in particular, cyclone Fran (Gourlay and Jell 1993) and cyclone Rewa, which passed through the region in the weeks before the 1994 surveys. They also record that repairs to the harbour bund wall associated with the harbour dredging have altered the flow patterns for the ebbing tide draining from the reef flat. It is possible that some combination of these factors have altered the grain sizes or organic content of reef flat sediment so that fewer holothurians can be supported.

The most dramatic changes recorded after the 16 year interval were a large decline in cover of sand, and increase in coral cover in the reef crest zone. Lawn and Preker (1993) reported that the outer reef flat was less influenced by silt plumes than other parts of the reef flat, so any deleterious effects of sedimentation on corals was likely to be less significant there than at other sites. There is also evidence that water flow patterns on the reef flat have been significantly altered as a result of re-building of the harbour walls, raising the water level in the area adjacent to the boat harbour. This would allow increased upward growth of corals which had previously died when the water level dropped since the 1950s. A significant increase in coral cover on the outer reef flat was also reported by Fisk (1991). The increase in coral cover is likely to be temporary, until the coral reaches the new low tide level, when the tops of the corals are likely to die again.

ACKNOWLEDGMENTS

I thank Simon Banks for field assistance in 1994, and the Heron Island Research Station and Queensland University for the use of facilities. This project was funded by the Great Barrier Reef Marine Park Authority.

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Recreational fishers in Shoalwater Bay and adjacent waters: motivations and attitudes

GR Jennings
Tourism and Leisure Studies, Faculty of Arts, Central Queensland University, Rockhampton Qld 4702

ABSTRACT

Recreational fishing is reported as a popular leisure time activity in national parks and wilderness areas (Borschmann 1987). While the desire to catch a fish is the primary goal of recreational fishers, there are non-catch related motivations associated with the experience (Dovers 1994). Non-catch related motivations may include a desire to escape from the everyday environment, a need to experience freedom and a need for rest and relaxation within a natural 'wilderness' environment. There are also social aspects associated with recreational fishing such as being with friends and family (PA Management Consultants 1984).

Data collected in a recent mail survey of registered boat owners from Gladstone, Rockhampton, Yeppoon, Marlborough, St Lawrence, Sarina and Mackay found similar motivation patterns. The mail survey was part of a larger study of recreational users and their usage patterns of Shoalwater Bay and adjacent waters.

The mail survey also asked users about their attitudes towards various activities which might be conducted within the study area. A majority expressed concern about commercial extractive activities. This concern reflected the conflict of interests associated with the use of marine based environments for recreational and commercial activities (Gartside 1986; Kenchington 1993; Dovers 1994) and the continuous debate between recreational and commercial fishers regarding who is responsible for diminishing fishing stocks (Gartside 1986; Dovers 1994).

From a management perspective, the registered boat owners noted the desire to experience a 'wilderness' setting while participating in outdoor activities and the need for the '*preservation of* [the] *environmental quality*' (Jackson 1986) of Shoalwater Bay and adjacent waters.

INTRODUCTION

To date, very few studies have focused on the recreational usage patterns of the marine areas of Shoalwater Bay; in fact Gutteridge Haskins and Davey (1996) suggest none exist. Several studies of land usage patterns have been conducted as part of the *Commonwealth Commission of Inquiry: Shoalwater Bay, Capricornia Coast, Queensland*: A G B McNair conducted a study of central Queensland residents and residents residing elsewhere in Queensland regarding their attitudes towards various land use issues related to the Shoalwater Bay Military Training Area; while Wood, Thompson, McIntyre and Killion (1994) developed a theoretical recreational and tourism opportunity spectrum for the Shoalwater Bay Military Training Area.

In order to obtain information on recreational marine usage of Shoalwater Bay and adjacent waters, a study was commissioned by the Great Barrier Reef Marine Park Authority. Part of the study investigated user motivations and attitudes. This paper will present and discuss the findings regarding the motivations and attitudes of recreational users, specifically fishers of Shoalwater Bay and adjacent waters as determined by a mail survey of registered boat owners residing in Gladstone, Rockhampton, Yeppoon, Marlborough, St Lawrence, Sarina and Mackay.

Recreational fishing is viewed as a popular leisure time activity in national parks and wilderness areas (Borschmann 1987). Dovers (1994) highlights that while the desire to catch a fish is the primary goal of recreational fishers, there are non-catch related motivations associated with the experience. The importance of non-catch related motivations as part of the overall recreational fishing experience is also discussed by Fedler and Ditton (1994) in their 1978 to 1991 review of American recreational fishers. Johnson and Orbach (1986) noted in an American study that non-catch related motivations included *'escape, freedom, relaxation and personal liberty'* as well as the desire to experience a *'frontier spirit'*. Such non-catch related motivations are also reported by various researchers in the Australian context. PA Management Consultants (1984) found in a national Australian household study conducted during July 1984, that to *'relax and unwind, to be outdoors'* to enjoy the company of others, to experience the *'thrill/contest of catching fish'* and to obtain a source of food were the main reasons people reported for engaging in recreational fishing. Gartside (1986) reported similar motivations ranging from a sense of *'escapism'* from daily life and work, as well as *'enjoyment of the environment'*.

A social aspect of recreational fishing was also reported by PA Management Consultants (1984) who stated that men favoured fishing with friends over fishing with their families, whilst women favoured fishing with their families over with their friends.

METHOD

The Shoalwater Bay study area was defined as those waters located between the latitudes of 22°08'S to 23°00'S and longitudes of 150°02'E to 151°02'E. See figure 1.

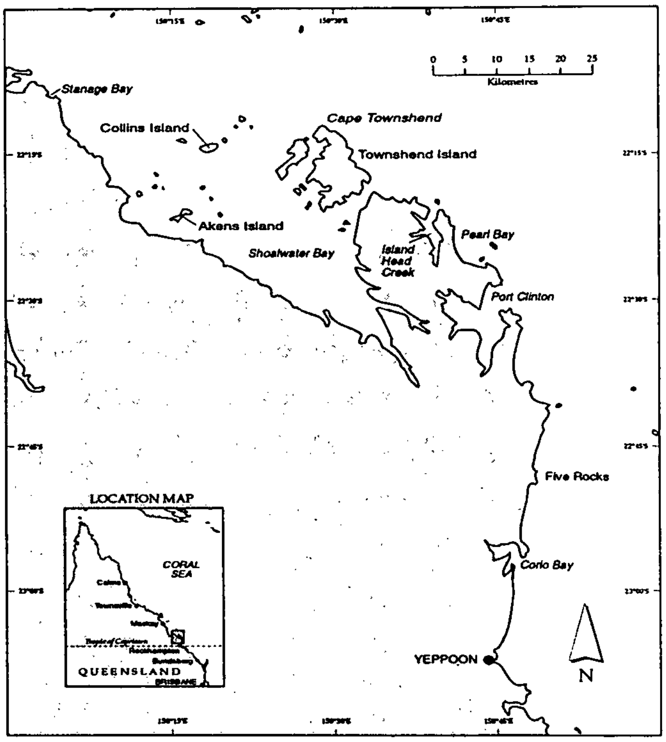

Figure 1. Shoalwater Bay Study Area
Source: Great Barrier Reef Marine Park Authority

The mail survey component of the Shoalwater Bay and adjacent waters study targeted local recreational users who were registered boat owners of either motor or sail driven vessels. Expert opinion was used to identify the drawing areas in order to classify 'local' users. The experts contacted had either long histories as users or managers of the area or held executive positions in recreational clubs. According to expert opinion, local users were deemed to be those users located in coastal towns and cities along or east of the Pacific Highway between Mackay in the north and Gladstone in the south. The largest drawing areas were considered to be Yeppoon followed by Rockhampton. The sample for the mail survey was framed from boat registration records held by the Queensland Department of Transport. The sampling frame was received in late March 1996 and was up-to-date for the preceding six month period. The sampling frame was proportionately stratified based on experts' opinions regarding usage of the Shoalwater Bay area by recreationalists from Mackay, Sarina, St Lawrence, Marlborough, Yeppoon, Rockhampton and Gladstone. After the proportions were determined for each of the locations, each location was further proportionally stratified by suburbs. The overall sample size was set at 1200 as this would provide a 95% confidence interval for a finding of 50% of ± 3.0% (Veal 1992).

Each person included in the sample was mailed a package which included a survey with a reply paid envelope. Each survey included a cover page, asked twenty questions and utilised maps to orient the respondent to the Shoalwater Bay area. To improve the response rate, a reminder card was sent to all survey recipients approximately one week after the survey was posted. Survey recipients were advised in the initial cover letter accompanying the survey that a reminder card would be used. The reminder served as both a thank you and as a reminder to those who had not yet returned the survey. It should be noted that surveys and reminders for Rockhampton residents did not arrive a week apart as mail deliveries did not occur on two days of one week due to two public holidays resulting in some reminder cards arriving one or two days after receipt of the survey.

Of the 1200 surveys sent out, 50 were returned as a result of incorrect addresses and 50 telephone calls were received from people indicating that they did not use the area and would not be returning their surveys. Details of the latter were recorded on survey sheets and included in the analysis. In all, 400 surveys were completed and returned, giving a response rate of 33 percent. The proportions used in the stratified sampling were reflected in the completed and returned surveys. The response rate needs to be considered when discussing the results in relation to all recreational boat owners within the study area.

The returned surveys were coded, entered and analysed using the computer program SPSS.

RESULTS

Of the 400 respondents to the survey, 256 respondents indicated that they were users of the area, while 142 indicated that they did not use the area for recreational purposes and 2 respondents did not provide data regarding usage of the study area. Of the 256 users of the area, 245 respondents engaged in recreational fishing, that is 95.7% of users were fishers of the area. Some users indicated that they also engaged in other activities such as boating, camping, and sightseeing.

The reasons why the recreational users chose Shoalwater Bay and the adjacent waters as a recreational setting were related to the quality of the fish stocks (53.1%), followed by the amenity provided by the area (34.8%). When discussing the amenity of the area, users noted the scenic amenity, the wilderness settings, the peace, the quiet and the solitude. The proximity of the study area to mail survey respondents' residence was noted by 23.8% of the users.

Whilst the opportunity to be with family and friends was noted specifically by three respondents, mail survey respondents reported that family and friends accompanied them on trips to the study area. The mode response for the type of passenger who accompanied the mail survey respondent was friends (68.4%) with family accompanying 62.1% of the mail survey respondents.

Survey respondents were also asked their opinions about various activities listed on the *GBRMPA Shoalwater Bay BRA Q120 map*. The activities listed were bait netting and gathering, camping, recreational collecting, commercial collecting, crabbing and oyster gathering, diving, commercial line fishing, recreational line fishing, research activities, boating activities, tourist activities, tourist and educational facilities/programs, spearfishing, commercial netting, trawling, and indigenous hunting, fishing and collecting. To this list were added sightseeing, photography, snorkelling. The study area was broken up into five sections in order to canvas the opinions of respondents. The sections were the northern section of Shoalwater Bay, the southern section of Shoalwater Bay, Island Head Creek and environs, Port Clinton and environs, and Cape Clinton to Little Corio Bay.

In responding to the type of activities which the respondents thought were suitable for each of the areas, users and non-users were asked to comment. The following data represents the responses from approximately 78–85% of respondents to the survey as some respondents did not provide data in various sections. In Section A, the northern section of Shoalwater Bay, the following activities were considered to be unsuitable: trawling (68.3% of respondents); commercial collecting (66.5% of respondents); commercial netting (66.8% of respondents); and commercial line fishing (49.3% of respondents). Indigenous fishing, hunting and collecting received an almost equally divided response with 41.2% of respondents noting that it should be allowed while 36.8% considered that it should not be allowed in Section A.

In Section B, the southern section of Shoalwater Bay, the activities which the mail survey respondents considered should not be allowed were trawling (70.5% of respondents), commercial collecting (67.8% of respondents), commercial netting (67.8% of respondents), commercial line fishing (53% of respondents), and spearfishing (52.5% of respondents). Respondents were also divided between the appropriateness of indigenous hunting, fishing and collecting within this section (37.8% of respondents for and 37.8% against the activity).

Commercial collecting (66.5% of respondents), trawling (64.5% of respondents), commercial netting (64% of respondents), commercial line fishing (49.5% of respondents), and spearfishing (45.8% of respondents) were considered as inappropriate for Section C, Island Head Creek and environs. While beliefs regarding the appropriateness of indigenous hunting were nearly divided (37.9% thought the activity was inappropriate and 39.5% believed the activity should be permitted in the section).

As in the previous sections, Section D, Port Clinton and environs, trawling (69.3% of respondents), commercial netting (67.8% of respondents), commercial collecting (67.5% of respondents), commercial fishing (53.3% of respondents) and spearfishing (50.5% of respondents) were considered inappropriate. Again there was division regarding the suitability of indigenous activities being conducted in the Section area (39% thought it was appropriate and 37% thought it was inappropriate).

The trends evident in Sections A to D were reflected in mail survey respondents' attitudes regarding the various activities appropriate for Section E, Cape Clinton to Little Corio Bay. Trawling (70% of respondents), commercial netting (73.3% of respondents), commercial collecting (68.2% of respondents), commercial collecting (68.2% of respondents), commercial line fishing (56.8% of respondents) and spearfishing (53.5% of respondents) were considered inappropriate, however, indigenous activities were marginally considered more appropriate in this section (41.3% of respondents thought it was appropriate and 39.5% thought it was inappropriate).

Comments made by the mail survey respondents were related primarily to keeping out commercial fishers from the study area (46.0% of respondents). A range of activity controls were also suggested by 21.5% of respondents.

DISCUSSION

The mail survey respondents indicated that the primary recreational activity pursued in Shoalwater Bay and adjacent waters was recreational fishing. The main reasons for the use of Shoalwater Bay and adjacent waters for recreational fishing were the quality of the fish stocks, the amenity of the area, the area's proximity to the user's place of residence and the provision of safe anchorages. The first two reasons or motivations supported those reported by Dovers (1994) who stated that the primary goal of recreational fishers was to catch a fish followed by non-catch related motivations. The non-catch related motivations reported in this study reflected the literature: to relax in the outdoors, to enjoy the environment, to get away from every day life and work (PA Management Consultants 1984; Gartside 1986; Johnson and Orbach 1986).

Friends and family were reported as the two main categories of passengers who accompanied the user on her or his recreational trip in Shoalwater Bay and adjacent waters. This pattern reflected one of the non-catch related motivations of recreational fishing which was reported by PA Management Consultants (1984), that was to enjoy the company of others as well as the trend that men preferred the company of friends over family. The mode for gender for mail survey respondents was men who comprised 89.5%, women 5.0% and missing data 5.5%.

It is apparent that recreational users considered most commercial operations were inappropriate for the Sections A to E. This is further emphasised by the comments made by the respondents in regard to their choices of suitable and unsuitable activities for each of the Sections. These comments related to keeping the commercial fishers out followed by suggestions for activity controls in Shoalwater Bay and adjacent waters. It should also be noted that other extractive activities such as spearfishing and indigenous activities received either negative attitudes or mixed attitudes relating to the conduct of those activities in the study area. The negative attitude to other extractive activities apart from recreational fishing highlighted the point made by Jaakson (1988) that having to share an area had the ability to detract from users' satisfaction. It also reiterated the points made by Gartside (1986), Kenchington (1993) and Dovers (1994) regarding a conflict of interests between commercial and recreational activities and the continuous debate over who is responsible for diminishing fish stocks.

In conclusion, recreational users of Shoalwater Bay and the adjacent waters were primarily fishers, who used the area because of the quality of the fish stocks and the desire to experience a 'wilderness' setting while participating in outdoor activities in the company of friends and family. These users expressed the need for the '*preservation of* [the] *environmental quality*' (Jackson 1986) of Shoalwater Bay and adjacent waters. From their perspective, the preservation and/or maintenance of the quality of the fish stocks and the setting was best achieved through the exclusion of commercial operations. Having solicited this information on recreational users' motivations and attitudes, managers now need to provide such recreational experiences within the recreational and tourism opportunity spectrum to be developed for Shoalwater Bay and the adjacent waters whilst simultaneously considering the perspectives of commercial fishing operators.

ACKNOWLEDGMENTS

The study of *Recreational Usage Patterns of Shoalwater Bay and Adjacent Waters* was funded by the Great Barrier Reef Marine Park Authority and supported by Central Queensland University. Personnel from the Queensland Department of Environment and Queensland Department of Transport provided data and/or feedback during the course of the study. Thanks are also extended to the recreational users of Shoalwater Bay who chose to participate in the study and to Ray Berkelmans at the Great Barrier Reef Marine Park Authority and to Les Killion and Jillian Litster at Central Queensland University who provided comments and suggestions regarding this paper in its draft stages as well as Leon Jackson at the Great Barrier Reef Marine Park Authority who prepared map 1.

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Heron Island, Great Barrier Reef: an environmental history in outline

DT Neil
Department of Geographical Sciences and Planning, The University of Queensland Qld 4072

ABSTRACT

The environmental history of Heron Island, and its adjacent reef, is traced through several overlapping phases: Geomorphic and Ecologic Development of the System, Discovery and Scientific Awakening, Exploitation, Settlement, Environmentalism and Management, and Sustainable Use or Sustained Damage. First observations of the island were recorded on 1843, exploitation of turtle populations occurred in the late 1920s with associated species losses and introductions. Settlement of the island commenced with resort establishment in 1932. Disruption of hydrodynamic, geomorphic and ecologic processes has occurred since that time. A conflict exists between the demands of commercial management, the sustainability of ecological and geomorphic processes, and the residual historical legacy of past mismanagement. Until this conflict is more adequately resolved, the island's geomorphic and ecologic future remains uncertain.

INTRODUCTION

The paper examines the evolving relationship between Heron Island's biophysical environment and resources, and the people who use them. The approach used is that of *environmental history*. It is applied to Heron Island using the conceptual framework of Worster (1988), that is, an exploration of the three themes of i) the nature of the island, ii) the interaction of the socio-economic realm with the island, and iii) the changing values that help fashion the nature of that interaction. Dovers (1994) explains this approach as an endeavour to explain '...how we got to where we are: why is the environment we live in like it is?'. Previous examples of the application, or partial application, of this approach for eastern Australian seascapes include those of Fisher (1994) for Moreton Bay, south-east Queensland, and of Bowen (1994) for the Great Barrier Reef region. The environmental history of Heron Island, and its adjacent reef, is traced through several, often overlapping, phases:

i. *Geomorphic and Ecologic Development of the System*
ii. *Discovery and Scientific Awakening*
iii. *Exploitation*
iv. *Settlement*
v. *Environmentalism and Management*
vi. *Sustainable Use or Sustained Damage?*

Each of these is discussed in turn below.

Geomorphic and ecological development of the system (6.5 ka – present)

Development of the Heron Island/Reef system followed Holocene sea level rise and stabilisation, arguably with each reef and island having an individual geomorphic and ecological trajectory. The island has moved through a continuum of successional stages from an unvegetated sandbank to, at the time of discovery, a 13 ha sand cay dominated by closed canopy *Pisonia grandis* forest. The times of island formation, of initial plant colonisation, and of development of the present *Pisonia grandis* forest with associated avifauna, are uncertain.

Discovery and scientific awakening (1843–1951)

Whaling captain Ebenezer Bunker sailed through the Capricorn-Bunker Group in 1803, observing the abundance of turtles which prompted him to write to the Sydney Gazette in 1827 advocating the exploitation of green turtle, bêche-de-mer and pearl oyster (Gill 1988).

King (1827) noted that the islands 'abound with turtle and bêche-de-mer [which] will at some time become of considerable importance to the coastal trade of New South Wales'. Jukes (1847) provided the first description of the characteristics, in 1843, of the coral cover on the reef flat adjacent to the island and of the island's beach rock, vegetation and birdlife, some of which provides a basis for comparison with conditions over a century later. Calls for a greater scientific understanding of the Great Barrier Reef commenced with Saville-Kent in 1890, and several expeditions to the Capricorn Group in the first few decades of this century (e.g. Royal Australian Ornithologists' Union, 1910; Royal Zoological Society of NSW, 1925) which provided the foundations of scientific knowledge of these reefs and reef islands. An important part of this scientific awakening was the Royal Society's Great Barrier Reef Expedition at Low Isles in 1928–29, the first sustained scientific investigation of the Great Barrier Reef. Heron Island was considered for this expedition but rejected, in part because of the difficulties of accessing the island across the reef flat. Moorhouse's (1933) investigation of turtle hunting at Heron Island at this time was important in documenting the unsustainability of the unregulated exploitation which was occurring, although the demise of the turtle cannery is generally considered to be due to economic and marketing factors rather than to management initiatives or short supply. The Heron Island bore was drilled in 1937 to 231 m with the general intention of increased understanding the development of the Great Barrier Reef (Richards and Hill 1946); however, despite the acquisition of much valuable information, its specific purpose was not achieved (Hopley 1982). Perhaps the culmination of this phase was the establishment of the Heron Island Research Station by the Great Barrier Reef Committee in 1951.

Exploitation (1925–1929)

Exploitation of guano and bêche-de-mer, and the degradation of vegetation caused by lighthouse keepers and goats, affected several areas within the Great Barrier Reef province in the second half of the 19th century. The absence of guano from Heron Island spared it the worst of this exploitation. However, establishment of a turtle soup cannery in 1925 impacted on the Heron Island turtle population and the associated introduction of several species (including cats and rats) also affected the fauna, including turtle hatchlings and both tree- and ground-nesting birds.

Opportunistic harvest of Capricorn/Bunker island turtles to provision sailing ships occurred from the early 19th century (Limpus et al. 1984). On Heron Island, a turtle cannery operated during the latter half of the 1920s. Operations were limited to the summer breeding season from early November to February (Moorhouse 1933). Moorhouse reported that 'During the 1928–1929 season, so scarce did the turtles become towards the end of the season that periodic visits had to be made to the neighbouring islands in order to maintain sufficient animals to keep the factory in active operation' and added that the season's animals were 'wiped out'. The effects of this harvest were aggravated by '...the policy of turning turtles before they have laid...adhered to by all persons met with, factory proprietors as well as ordinary fisherman' (Moorhouse 1933). The green turtle (*Chelonia mydas*) was the only species exploited for food on a large scale, other species being regarded as unpalatable. However, the hawksbill (*Eretmochelys imbricata*) is valued for its shell and was taken on the reef flat by turtle hunters at North West Island (Musgrave and Whitley 1926). This probably occurred at Heron Island also.

Indirect effects of the Heron Island turtle cannery included faunal introductions. Moorhouse (1933) reported that 'On Heron Island...the common house cat...has so multiplied that it now forms a real menace to the young turtles, for each cat frequently takes seven or eight turtles for a meal and eats the heads only'. Cats also impact on the avifauna. They were probably introduced to North West Island in the 1890s by the guano miners there (Cribb 1969). Cats on North West Island fed mainly on Wedgetailed Shearwaters during summer and their presence deterred other ground-nesting species (Walker 1988). Stomach contents analysed mostly contained seabird remains as well as insects (cockroach, centipede; Domm and Messersmith 1990). Campbell and White (1910) and MacGillivray (1926) noted the predation of Wedgetailed Shearwaters by cats, Campbell and White adding that cats were 'responsible for great havoc' amongst the Noddys. Observations from North West Island are likely to be applicable to Heron Island also. Local extinction of Buff banded rails on both Heron and North West Islands was attributed to cat predation (Cooper 1948; Campbell and White 1910). Apparently, rats were also responsible for predation on turtle hatchlings on Heron Island (Norman 1967). Cockroaches were introduced before 1928

(Nebe 1928) and the presence of weeds on Heron Island was observed as early as 1927 (Macgillivray and Rodway 1931).

Although a wide range of adverse impacts had clearly occurred within a few years of first occupation of Heron Island in 1925, a positive note is that all of the Capricorn Group islands were bird sanctuaries by 1927 (Napier 1934).

Settlement (1932 – present)

Apart from the seasonally occupied and short-lived turtle cannery, settlement of Heron Island began with establishment of a resort in 1932, followed by the research station in 1951. These uses resulted in a wide variety of impacts including loss of vegetation, exotic species introductions, local extinctions of native species, habitat loss and modification, changes to geomorphic processes and soil characteristics, and changes in hydrodynamic patterns and species distributions on the adjacent reef flat.

Although initially on a small scale, continued expansion of the facilities of the resort, research station, and National Parks facilities has led to the loss of natural vegetation, with 10% of the island occupied by buildings and a further 30% by roads, lawns, walkways, garages etc. (Walker 1991d). Vegetation loss is significant as the total area of *Pisonia* forest in Australia is only 160 ha (Walker 1991b), of which about half is on North West Island, near Heron. The 4 ha of *Pisonia* forest cleared for buildings and roads on Heron Island (Walker 1991b), although perhaps insignificant in itself, represents 2.5% of the total area of *Pisonia* forest in Australia. *Ficus obliqua* var. *petiolaris* may have been lost from Heron Island due to clearing for building sites (Cribb 1992). Although weeds were first introduced to the island during the exploitation phase, the proportion of the island flora which has been (deliberately or inadvertently) introduced to the island has continued to increase. By 1961, Gillham (1963) observed that introduced plants accounted for 10% of the total number of species on the island (46). By 1975 the proportion had risen to 29% (Heatwole 1984) and Chaloupka and Domm (1986) report that about 50% of the 51 species on the island in 1984 were introduced. An observation generally omitted in subsequent reports is that of Cooper (1948) who reported two flourishing clumps of prickly pear (*Opuntia* spp.) about 6 m in diameter and 1.5 m high in the woodland fringe vegetation.

Island disturbance due to human occupation has resulted in the loss of breeding populations of Pied Oystercatchers and Black-naped Terns from Heron Island (Anon. 1990). The demise of ground-nesting terns was reported as early as 1946 (Cooper 1948) and attributed to the presence of the resort. White-breasted Sea-eagles have not nested on Heron Island since 1965 (Anon. 1990), and the nest beside the turtle factory in 1925 (MacGillivray 1928) had disappeared by 1946 (Cooper 1948).

Turtle exploitation did not cease with the demise of the cannery. Turtle was served to the resort guests as soup and as steaks (Roughley 1936). (Seabird eggs were also on the menu (Walker 1991a)). Roughley's visit to Heron was during the winter of 1935, showing that, unlike the cannery, the turtle fishery for resort use, and probably for some commercial shipments to Brisbane, occurred throughout the year. Nesting Green turtles from the region were shipped to Brisbane for soup manufacture and retail meat sales on a continuous annual basis until 1950 (Limpus et al. 1984). Other exploitation associated with the resort included collecting from the reef flat, the Heron Island volute coming 'close to extinction a few years ago' (Hiscock 1966).

One of the most contentious issues in reef management relates to evidence of eutrophication in Great Barrier Reef waters and its possible consequences (e.g. Walker 1991c; Bell and Gabric 1991; Kinsey 1991). Large populations of seabirds roost and nest on the island (Barnes and Hill 1989), contributing a substantial quantity of nutrients to the porous island soils (Allaway and Ashford 1984). Septic and sewerage systems further contribute to the nutrient loadings, although representing a small proportion (< 20%) of the total. Expansion of resort capacity and a dramatic increase in the population of the most numerous seabird (Black Noddy) using the island (Barnes and Hill 1989) imply a marked increase in nutrient loadings. However, the combination of the island's soil characteristics and the rate of nutrient input suggests that there is no imminent danger of the island's assimilation capacity being exceeded (Staunton-Smith 1992). There remains some debate as to the pathways and transport times of nutrients reaching reef waters. Although chemical pollution of the island seems unlikely to be a major problem, examples include fuel leakage to the soil from rusting 44 gallon drums (pers. obsv. February, 1992) and soil and groundwater pollution from oils and paints (Anon. 1990).

Although the need to address the problem of garbage generation at Great Barrier Reef resorts was highlighted by Ryland (1969) a further two decades passed before appropriate action was taken at Heron Island. An estimated 280 t of solid waste is generated by the resort each year. On a per capita basis the rate of solid waste generation at the resort is greater than at the research station and greater than that of a mainland city. Food waste represents a greater proportion of solid waste at the resort than on the mainland (Hunter 1990). In recent years significant changes have taken place in waste management on the island. Food wastes used to be dumped in the channel between Heron and Wistari Reefs. Subsequently they were dumped at sea (a minimum of 500 m seaward of the reef; on some occasions, only to be washed back onto the islands' beaches) and, more recently, food scraps have been frozen, stored and returned to the mainland for disposal. Increased availability of food, including garbage, from anthropogenic sources, has altered the population size, density and distribution patterns of some avian species (e.g. Silver gulls (Walker 1988); Silvereyes (Catterall et al. 1982)) which, in the case of gulls, decreases the breeding success of other species.

The effects of reef walking at Heron Island are largely unknown. All coral species examined by Liddle and Kay (1987) were tolerant of reef walking damage, although resistance to breakage varied between species and according to colony morphology. Large quantities of sediment (> 800 mg L^{-1}) may be resuspended by reef walkers (Neil 1990) and further research on faunal impacts is warranted.

The difficulty of boat access to Heron Island was described by Yonge (1930). Attempts to rectify this commenced with the scuttling of the ship *Protector* adjacent to the reef edge and blasting a cutting through the reef rim (late 1940s), channel dredging (from the reef rim to the island) and swing basin and blockwall construction (late 1960s), maintenance dredging and blockwall repair (frequently in 1970s and 80s), channel deepening and swing basin enlargement (1987) and construction of a new bundwall (1993). Impacts of these works include: lowering of reef flat water levels and increased tidal velocities (Gourlay and Flood 1981; Gourlay 1983), permanent loss of sediment from the unstable leeward end of the sand cay (Flood 1986), deposition of sediments on the beach rock, the inner and outer reef flat, reef rim and reef slope during periods of dredging and from sediments winnowed from erosion of the dredge spoil dump constructed after the 1987 dredging works (Gourlay 1991a,b; Gourlay and Jell 1993), increased exposure of the beach rock on the northern and southern beaches which, with seawall construction, inhibits nesting by turtles, inhibits their return to the sea after nesting and can result in high mortality rates of hatchlings attempting to reach the sea from nests landward of exposed beach rock, coral mortality (Endean 1976), changes in the density and composition of benthic fauna adjacent to the channel (Neil 1987), and loss of the volute gastropod *Cymbiolacca pulchra* after the 1987 dredging program (Catterall et al. 1992 (by two years later volute densities had largely recovered). It is likely that numerous other impacts have occurred which will remain undocumented.

Alternatives to boat access include helicopter, seaplanes and conventional aircraft. The helicopter service has required reclamation for a helipad and the construction of additional sea walls. Seaplane services, which operated to the island at various times during the post-WW II period, have been discontinued. Environmental effects are undocumented. In 1971, resort representatives proposed an airstrip on the island, suggesting that it could be built on the resort side of the island with minimum damage to the island's vegetation and away from the nesting grounds of the mutton birds (Courier Mail June 15, 1971). Furthermore, there were 'six islands within 12 miles of Heron, capable of taking any birds displaced by the airstrip' (Courier Mail June 22, 1971). Conservation groups opposed the proposal.

Environmentalism and management (1960s to present)

Imposition of management regulations in Great Barrier Reef waters began with regulation of the pearl and bêche-de-mer fisheries (1888), protection of marine fauna on foreshores and surrounding reefs of some Great Barrier Reef islands, including Heron, by the Fish and Oyster Acts (1914 to 1945), and protection of green turtles in Queensland (1950). Locally, the terrestrial environment of Heron Island was declared a National Park in 1940. Parallel with this increased management interest was a growth in community awareness (through magazines (e.g. *Walkabout*), books (e.g. Roughley's *Wonders of the Great Barrier Reef* (1936); Dakin's *Great Barrier Reef* (1950)), film and, later, television) of the nature and values of the Great Barrier Reef. A new wave of exploitation through mining and oil drilling was imminent in the 1960s, with a State government intent on resource exploitation and development regardless of the consequences. This new wave of exploitation was thwarted by a coincidence of the rise of environmentalism (e.g. Wildlife Preservation Society of Queensland, Littoral Society (now Australian Marine Conservation Society), Australian Conservation Foundation), of strong community opinion, and of relatively enlightened Commonwealth governments of both political persuasions. This important era is reviewed by Bowen (1994) and others.

At a local scale, scientific interests and resort owners successfully lobbied for the establishment of a Heron Wistari Marine National Park (1974), and at the regional scale the Great Barrier Reef Marine Park was established in 1975 and the Capricorn Section of the Park, including Heron Island, was proclaimed in 1979. A National Parks base was established on the island in 1983. Heron Reef was originally declared Marine National Park 'A' which permits fishing, boating, recreational activities and non-manipulative research and prohibits mining, oil drilling and spear-fishing. More recently, Marine National Park 'B' status (additional prohibitions and controls on collecting, fishing, tourist and educational facilities) was applied to the reef in the immediate vicinity of the island in order to protect those areas readily accessible to resort guests and researchers.

Through the 1980s and early 1990s, and within the constraints of federal and state legislation, Heron Island is managed independently by the resort, research station and national parks organisations, and cooperatively by the Heron Island Management Committee, which consists of a representative of each of the three organisations. A management plan for the island was agreed to by the three parties in September, 1983 with a number of revisions to account for changes in resort and research station occupancy rates and user profiles, and the establishment of the national parks service complex on the island.

The *environmentalism and management* phase of Heron Island's environmental history has seen significant changes in attitudes to and practice of environmental management on Heron Island. Evidence of this includes the eradication of most of the exotic fauna, construction of bundwalls to reduce tidal flows to the boat channel, introduction of waste recycling schemes, cessation of sea dumping of food scraps, reduction of anthropogenic food sources for wildlife, initiation of 'clean-up days', improved communication of ecological sensitivity to island users, establishment of a public education centre, sponsorship of research scholarships and support for monitoring programs by resort management, increased presence of the managing agency and establishment of the Management Plan.

Sustainable use or sustained damage? (the present)

For more than a decade, Heron Island has been well protected by both terrestrial and marine legislation and management. Some marked improvements have occurred, as noted above. Nevertheless, adverse impacts continue, in part due to failure to rectify past mismanagement and also to continued expansion and upgrading of facilities on the island. Inadequate environmental management occurs with respect to both ecological and geomorphic processes and management provisions. Examples include: the proportion of introduced flora continues to rise, a significant proportion of the islands coastline is unavailable to nesting turtles due to sea walls and other structures, the continuing absence of numerous avian species previously recorded as nesting on the island, erosion of the island due to sediment transport to the boat channel has not been solved by the recently constructed (1993–94) bundwalls, and bulldozing of occupied Wedgetailed Shearwater nesting burrows for building construction has occurred. The management plan addresses most of the issues of importance to island management.

However, there are shortcomings. Although the management plan deals with the interrelationships between island development and beach processes, it fails to adequately address the implications of island development and management for the adjacent reef flat. The management plan provides guidelines, designs and standards for management but provides no mechanism for enforcement, no penalty for breaches (which have occurred in relation to a number of guidelines) and no contingency plans to deal with environmental hazards (e.g. reef flat sedimentation after failure of an inadequately designed and constructed tailings dam during the 1987 channel dredging operations). The impacts of some aspects of the use of Heron Island and its adjacent reef flat remain uncertain. These include the effects of reef walking and the extent and long-term effect of disturbance of nesting sea turtles by tourists. Given the ongoing effects of human presence and activities on Heron Island outlined above, the status of the island at this point in its environmental history could better be described as sustained damage, rather than as sustainable use.

CONCLUSIONS

At Heron Island a ternary tension is evident between the demands of commercial management, the sustainability of ecological and geomorphic processes, and the residual historical legacy of past mismanagement. While many of the most severe and glaring abuses of the past have been rectified, particularly those associated with the *exploitation* phase, there remains the need to correct those problems which have been created during the *settlement* phase. Until this is achieved, it seems unlikely that Heron Island can move to the next phase in its environmental history. Gammage (1994) rejects the notion of sustainable development, and argues that the issue for future Australian environmental management is not sustainable development, but sustainable damage. While this is generally true of post-European in settlement Australia, at Heron Island the opportunity exists to move beyond sustainable damage if the regulators, managers and users of the island work towards this goal.

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SESSION 6

Reef connectedness

Habitat optima of soft corals on the central Great Barrier Reef: niche characterisation using regression tree analysis

Katharina E Fabricius[1] *and Glenn De'ath*[2]
[1] *CRC Reef Research Centre and AIMS, PMB No. 3, Townsville Qld 4810*
[2] *CRC Reef Research Centre and TESAG, James Cook University Qld 4811*

ABSTRACT

Soft corals are often cast as the villains that invade unoccupied reef substrata, thereby excluding reef-building corals and retarding reef growth. This study seeks to determine the optimal environmental conditions for soft coral abundance and richness of genera. We demonstrate distinct cross-shelf gradients in soft coral assemblages, and also less pronounced changes in abundance along other environmental gradients. Depth, wave exposure, slope, flow, sediment levels, and interactions between these factors affect abundances of taxa.

We discuss the rapid survey technique as a field method that can detect subtle spatial changes in communities. Regression trees are presented as a statistical technique ideal for revealing the complex interactions between environmental factors which affect the distribution of taxa. Regression trees are easy to use and simple to interpret. They can be used to characterise combinations of environmental variables related to different abundance levels, and thus determine the most favourable (and most avoided) habitats for taxa, and identify patterns of niche separation. Rapid surveys, combined with regression trees, are a powerful and efficient combination for community analyses, well suited to both scientific and managerial application.

INTRODUCTION

Previous studies of soft coral assemblages have demonstrated that distinct assemblages are found in certain types of reefs across the shelf (Dinesen 1983). Distribution and abundance of taxa on Davies Reef, central Great Barrier Reef, were strongly related to the physical environment (Fabricius et al. 1995; Fabricius and De'ath, in press). In contrast, abundances remained unaltered in areas where space availability was enhanced after crown-of-thorns starfish outbreaks (Fabricius, in press). The latter studies were carried out on mid-shelf and outer-shelf reefs using a combination of line intercept and belt transects. In the present investigation, rapid surveys were used to assess soft coral assemblages from near-shore to outer-shelf reefs between Townsville and Innisfail. Belt transects have been used successfully in detailed analyses of relationships between taxa and microscale to mesoscale environmental parameters, whereas the use of rapid surveys for studies other than large-scale studies have not been widely accepted, in spite of successful applications (e.g. Done 1982). Recording a single soft coral belt transect of 25 x 0.5 m takes 20 to 80 minutes. In the same time, rapid surveys covering hundreds of square meters and 5 depth zones can be carried out (personal observation). Moreover, rare taxa are more likely to be observed in rapid surveys than in belt transects, as their probability of occurrence in a small area is low, and thus communities with many rare taxa may be better represented. In this paper, we characterise large-scale and mesoscale patterns in the distribution of soft coral families and individual genera, and we present regression trees as a powerful, yet easily interpretable statistical technique capable of detecting changes in abundances caused by complex interactions between environmental factors.

FIELD METHODS

Rapid surveys were carried out on a total of 278 sites at 71 locations on 22 reefs across the continental shelf. Inner-shelf sites were represented in greatest numbers in order to complement earlier studies (inner-shelf: 165 sites on 15 reefs, mid-shelf: 39 sites on 4 reefs, outer-shelf: 74 sites on 3 reefs). The area surveyed ranged from latitude 17.00°S to 19.20°S, and longitude 146.00°E to 147.50°E. At each location, the reef was surveyed at the following depth zones: 18–13 m, 13–8 m, 8–3 m, 3–1 m and on the reef flat.

The following data were recorded during swims on scuba of 10–15 min within each site:

- Abundances of all soft coral genera, estimated on a scale of 0 to 5, using the following rating scale: 0 = absent, 1 = one or few colonies (0+ to 0.2% cover), 2 = uncommon (0.2+ to 0.5%), 3 = moderately common (0.5+ to 3%), 4 = common (3+ to 20%), and 5 = dominant (> 20%).
- Per cent total cover of soft corals, hard corals, turf and macro algae, and unconsolidated substratum (sand and rubble).
- Physical variables were estimated during the time of surveys: flow speed (cm s^{-1}), wave exposure (rated on a 5-point scale between 0.0 to 1.0), slope angle (degrees), sediment deposits (rated on a 4-point scale of 0 to 3)

STATISTICAL METHODS

The relationships between abundances of taxonomic groups and regional characteristics (shelf position, reefs, location within reefs), and local physical conditions (flow rates, wave exposure, depth, slope angle, and sediment deposits on the benthos), and their interactions, were analysed with univariate statistics, principal components analysis, and regression trees.

Classification and regression trees are a modern statistical technique which explains the variation of a single response variable in terms of several explanatory variables (Breiman et al. 1985; Chambers and Hastie 1992). The response variable may be either categorical (classification trees) or quantitative (regression trees); we will deal only with the latter. The explanatory variables may be either categorical and/or quantitative. The tree is constructed by repeated binary splitting of the data, each split being based on the value of the explanatory variable which maximises the difference between the two resulting sets of response values. At the end of the procedure the data are partitioned into groups (leaves of the tree), each of which may be simply characterised by the values of the variables which formed the divisions.

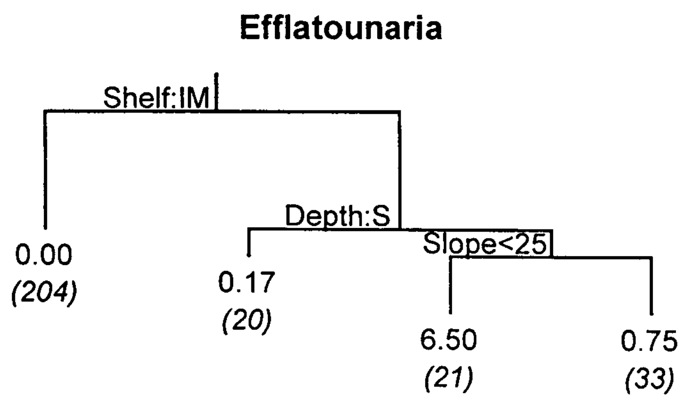

Figure 1. Outcome of a regression tree analysis on the soft coral genus *Efflatounaria*

Consider the simple example in figure 1. The response variable is the percentage cover of *Efflatounaria*, a genus of soft coral. The explanatory variables are cross-shelf position (categories: inner, mid and outer), depth (categories: shallow, medium and deep), and slope (quantitative: range 0–90). The first division is based on shelf, with inner- and mid-reefs in the left branch having a mean cover of 0.0 (n = 204). This group of data is not subsequently divided (all data are 0!) and forms a terminal node or leaf. The right branch, consisting of all outer-reefs, is now divided into shallow depths to the left, and medium and deep depths to the right. This process is repeated until the tree is completed with four leaves as shown.

The four groups can be characterised as follows:

Group	Definition	Mean cover	Size
1	Shelf: inner and mid reefs	0.00	204
2	Shelf: outer reefs; Depth: shallow	0.17	20
3	Shelf: outer reefs; Depth: medium to deep; Slope: < 25	6.50	21
4	Shelf: outer reefs; Depth: medium to deep; Slope: ≥ 25	0.75	33

The advantages of regression trees include:

- Simplicity of interpretation. Each group is characterised by the mean value of the response variable, its size, and its defining variables and their values.
- Detection of complex interactions, often difficult with linear models, is automatic since left and right branches are independent.
- Missing values can be handled easily.

There are some disadvantages:

- The technique has not been widely used in the ecological literature and requires explanation.
- Inference for trees is not as well developed as for more traditional models.

RESULTS

A total of 31 soft coral genera was identified in surveys of 278 sites on the central Great Barrier Reef. Over all reefs, the richness (number of genera) averaged 8.1 per site, with an average of 11.7 on mid-shelf reefs, compared to 7.2 on the inner-shelf and 8.1 on the outer-shelf reefs (figure 2). The soft coral family Alcyoniidae dominated on the inner-shelf reefs, whereas all families, but in particular members of the families Xeniidae and Nephtheidae, were represented on the mid-shelf and outer-shelf reefs (figure 3). Gorgonian abundance was generally low except on some mid-shelf reefs.

Soft coral cover was highest on inner-shelf reefs (20%). It was 12% on mid-shelf reefs, and 13% on outer-shelf reefs. The zone of highest cover within each shelf position shifted downslope with increasing distance from the coast (figure 2). It was highest in shallow water on the inner-shelf sites, and at depths greater than 8 m on the outer-shelf reefs where wave exposure and water clarity are greater. In contrast, mean richness in genera increased at all positions on the shelf with depth.

The proportion of soft corals to total coral cover was greatest on inner-shelf reefs, and independent of depth (figure 2). In contrast, on the outer-shelf reefs this ratio increased with increasing depth, due to the combined effect of a depth-dependent increase in the cover of soft corals and decrease in hard corals.

These summaries of cover and richness values along gradients of depth and distance to the coast served as first insight into patterns of distribution. Naturally, other environmental variables, such as wave action, sediment load, flow and slope angle, contributed to the distribution patterns. However, principal components analysis on the 18 most common taxa displayed a distinct cross-shelf pattern in the assemblages, indicating that changes in communities across the shelf were more consistent than changes due to any other single environmental variable (figure 4). The sites clustered strongly as inner-shelf, mid-shelf and outer-shelf sites.

The distinct cross-shelf pattern was due to the restricted distribution of several taxa (figure 4). Among the 16 most common genera, *Asterospicularia* and *Efflatounaria* were typical outer-shelf genera. In contrast, *Paralemnalia, Lemnalia, Capnella* and *Plexaura* were found on mid- and outer-shelf reefs, but only very rarely on inner-shelf reefs. Whereas *Pachyclavularia, Parerythropodium, Alcyonium* and *Clavularia* were almost exclusively restricted to inner-shelf reefs. Only a few genera occurred in all three shelf positions, these being *Sarcophyton, Sinularia, Nephthea, Lobophytum, Briareum* and *Xenia*. Abundance differences across the shelf in these taxa were also strong (e.g. highest abundances of *Sarcophyton* and *Briareum* on the inner-shelf reefs, and *Nephthea* and *Xenia* on the mid-shelf and outer-shelf). Moreover, two of the most common *Sinularia* species, *S. flexibilis* and *S. capitalis*, dominated the inner-shelf reefs, but were rarely found on mid-shelf reefs and never occurred on the outer-shelf.

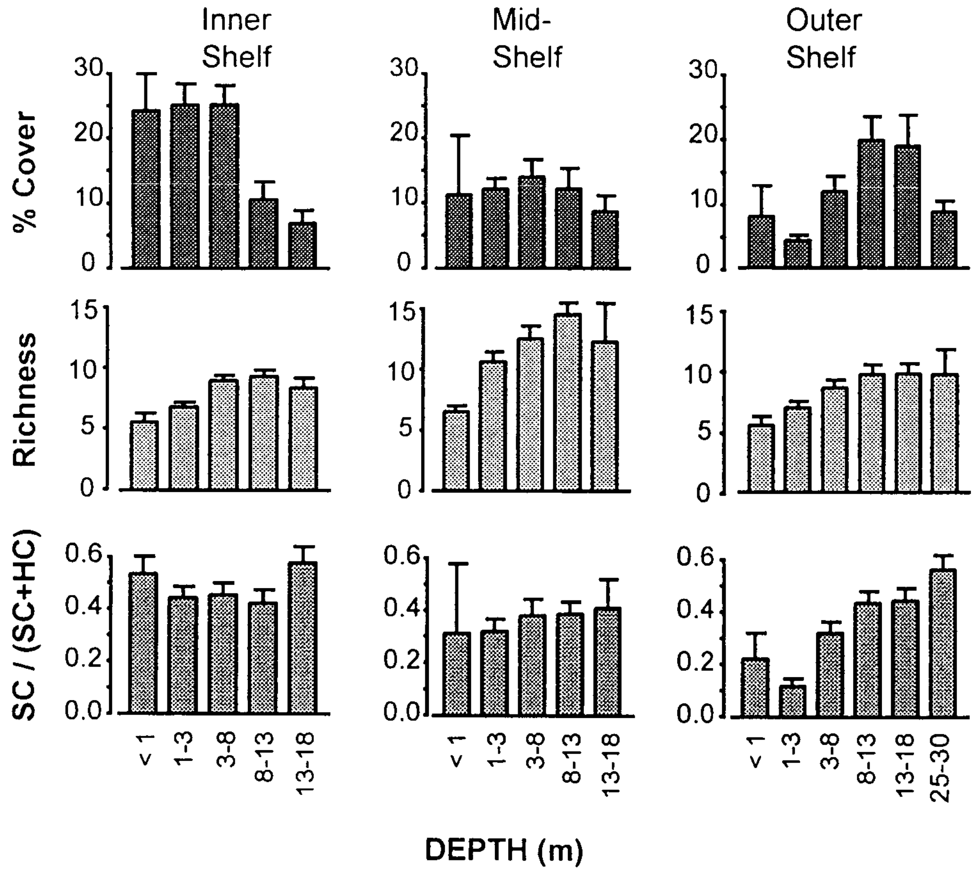

Figure 2. Depth related gradients in soft coral cover, richness in genera and the proportion of soft coral cover to total coral cover (SC/(SC+HC)) across the continental shelf. Error bars indicate 1 SE.

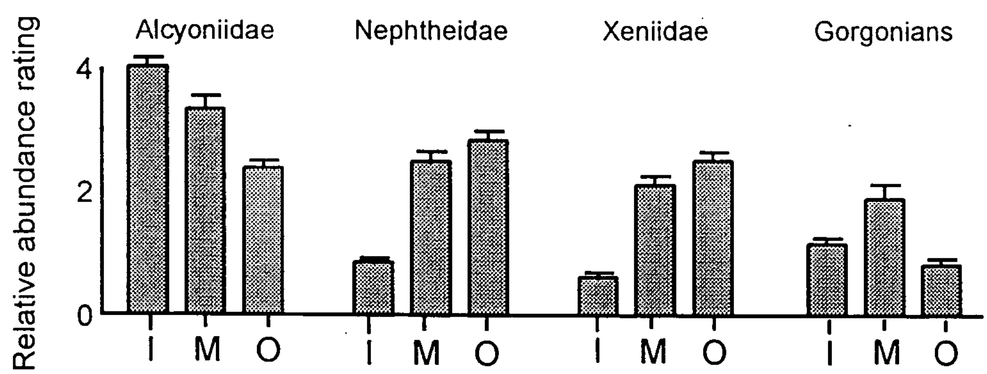

Figure 3. Relative abundance of families on inner-shelf (I), mid-shelf (M) and outer-shelf (O) reefs. Error bars indicate 1 SE.

When inner-shelf sites were analysed separately using the most common inner-shelf taxa, depth gradients were strongly evident (figure 6). Each of the taxa shown in the principal components biplot, favoured a particular depth. For example, *Briareum, Clavularia*, and the alcyoniid genera *Lobophytum* and *Sinularia capitalis* characterised the upper 3 m zone, whereas the greatest abundances of *Alcyonium* and *Pachyclavularia* occurred at 13–18 m. The plot also shows that higher soft coral cover occurred in shallow compared to deeper zones.

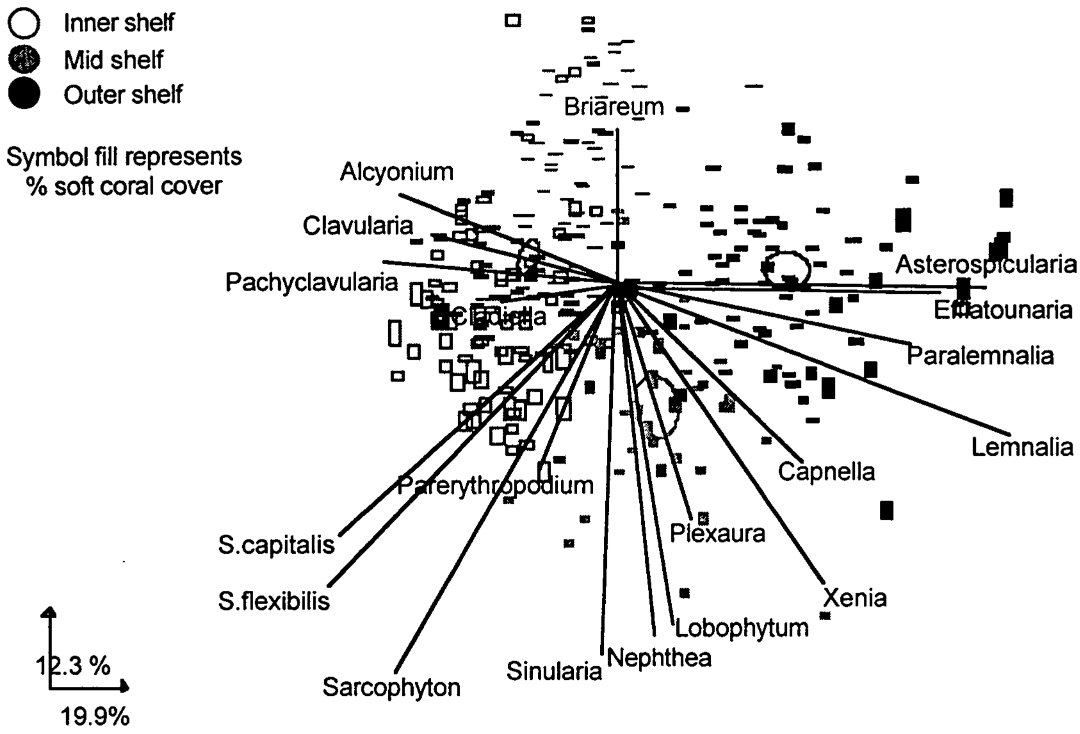

Figure 4. Principal components biplot on the 18 most common soft coral taxa. The sites (rectangles) are arranged according to their similarity in soft coral assemblages. Species vectors point towards the sites with higher abundances. Ellipses indicate 90% CI for the group means.

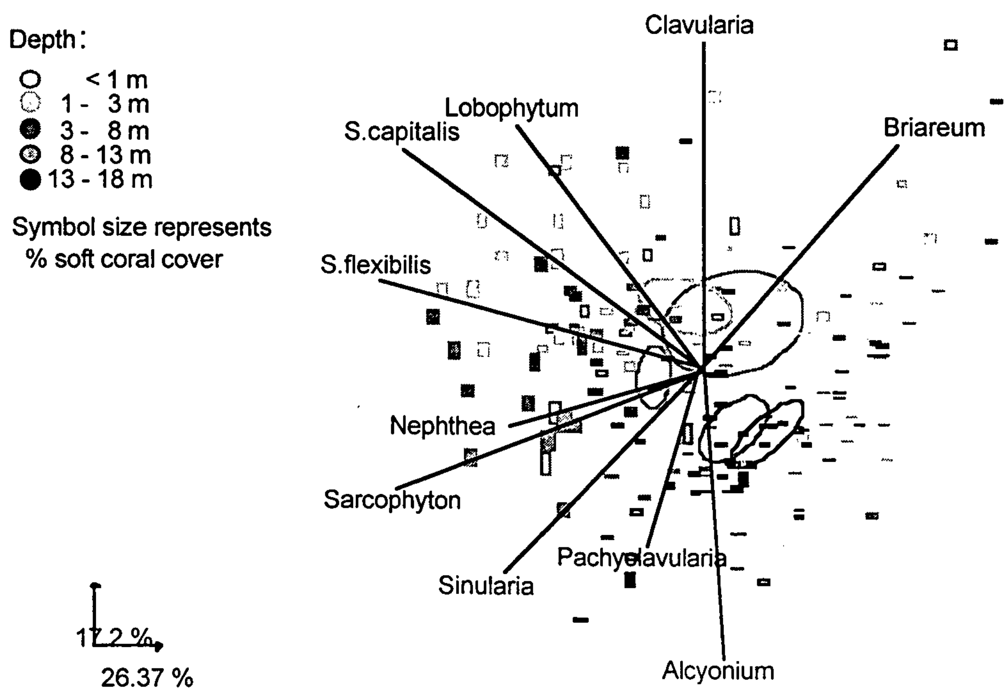

Figure 5. Principal components biplot of near-shore sites on the central Great Barrier Reef, indicating a consistent depth-gradient in terms of composition of the soft coral assemblages (different taxa representing different depth zones) and relative abundances. Ellipses indicate 90% CI for the group means.

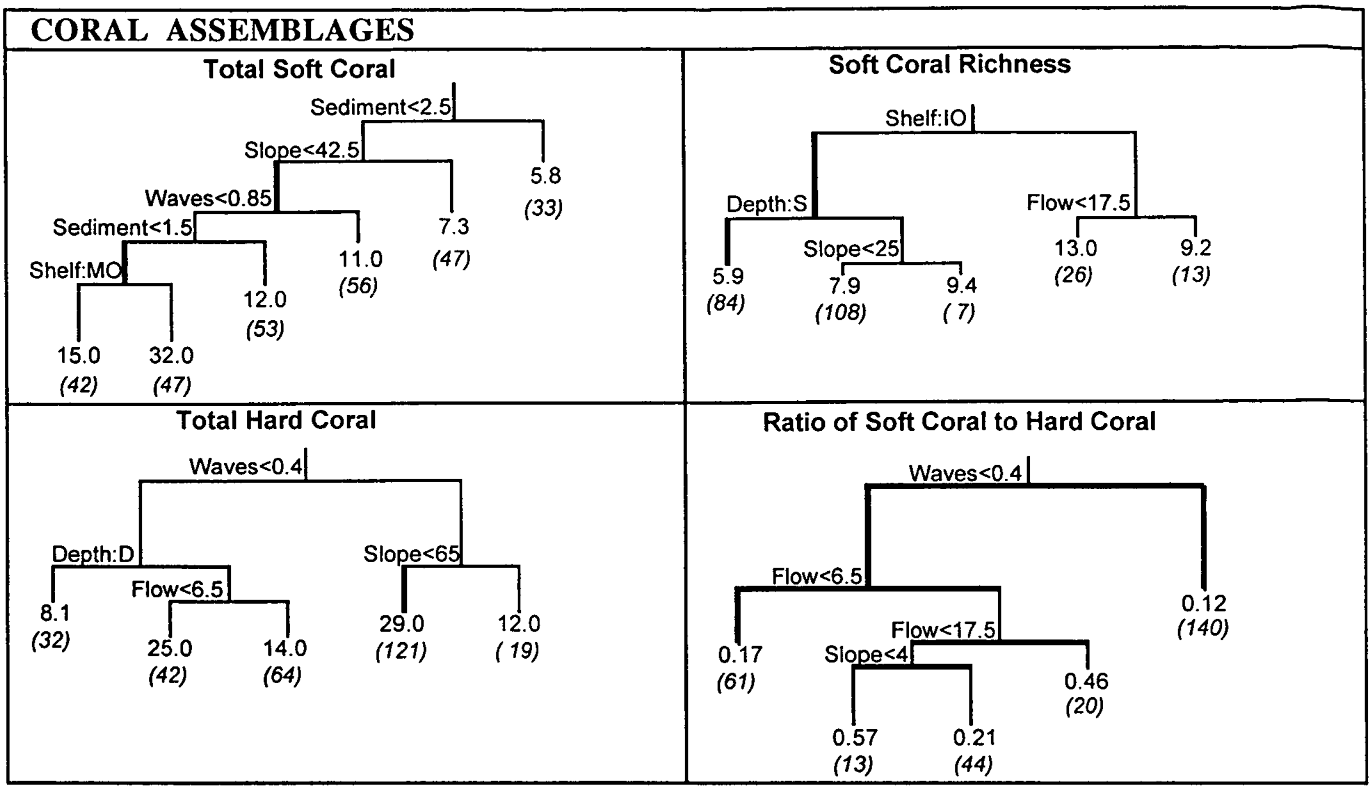

Figure 6. Regression trees of the characteristics of the coral assemblages

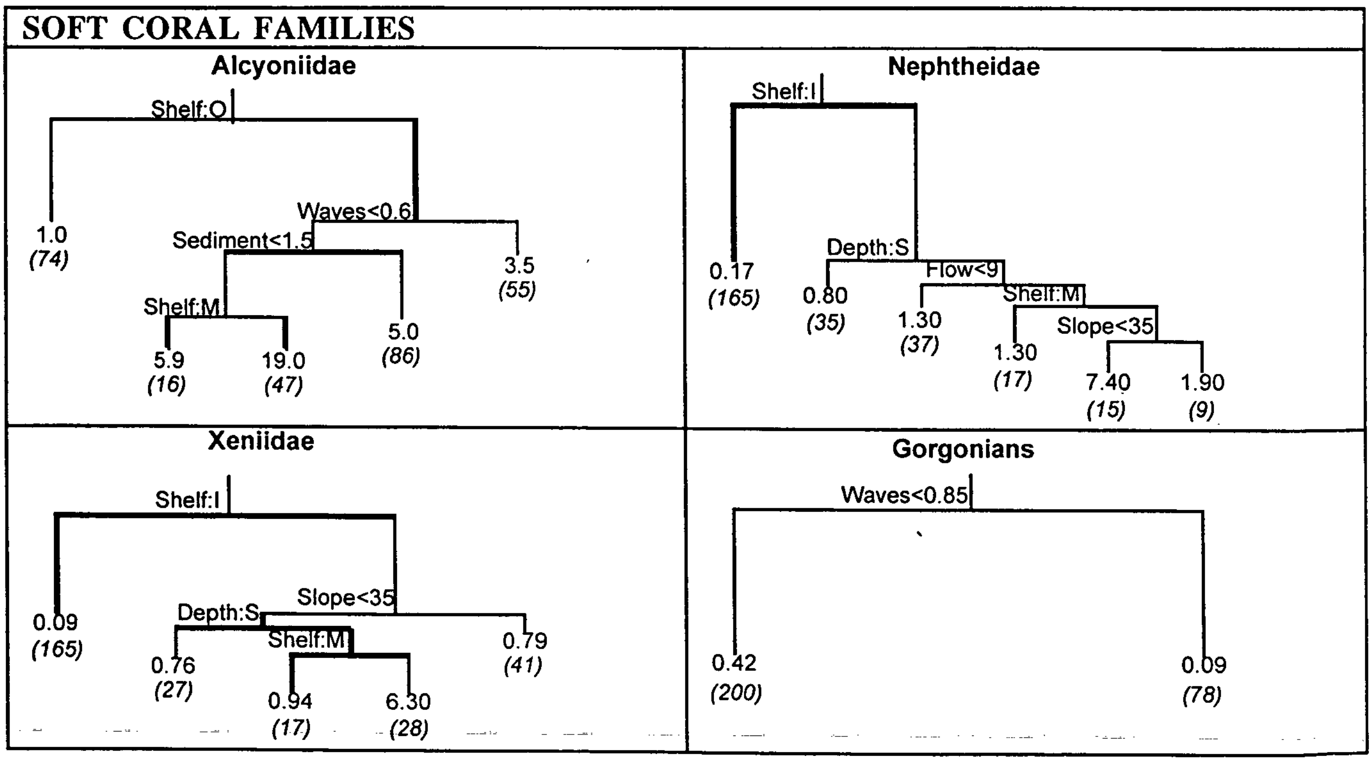

Figure 7. Regression trees of the three most common soft coral families, and of gorgonians

The regression tree analyses of characteristics of coral assemblages (figure 6) revealed the following patterns:

- **Total soft coral cover:** Highest (mean = 32%) on inner-shelf sites with low sediment load, a slope angle of < 42°, and moderate to weak wave exposure.
- **Soft coral richness:** Number of genera per site was highest (13) on mid-shelf sites with moderate to low flow. On inner- and outer-shelf sites, richness was very low at shallow depths, and moderate at depths > 3 m.
- **Total hard coral cover:** On wave-exposed sites, cover was highest (29%) on 121 sites with slopes < 65°. On wave-protected sites, cover was lowest at depth > 13 m and was highest on more shallow sites with low flow.
- **Ratio of soft coral to hard coral cover:** Highest ratio (0.57) on wave-protected sites where flow was moderate and where the reef formed horizontal terraces. Very low in wave-exposed habitats.

For the families, the regression tree analyses (figure 7) showed the following habitat characteristics favoured and avoided by the different families:

- **Alcyoniidae:** Highest abundance (19%) on 47 inner-shelf sites with moderate to low wave exposure and low sediment deposits.
- **Nephtheidae:** Very rare on inner-shelf sites. Most abundant (7.4%) at depth > 3 m with fast flow, on outer-shelf sites where the slope angle was < 35°.
- **Xeniidae:** Very rare on inner-shelf sites. Most abundant (6.3%) on medium to deep depths on outer-shelf sites with gradual slopes.
- **Gorgonians:** Very low abundances on wave-exposed sites, and evenly distributed elsewhere.

DISCUSSION

The composition of soft coral assemblages changed drastically across the continental shelf. The most conspicuous feature was the high proportion of genera with spatially restricted distributions. Almost 70% of the 16 most common genera were only found at one or two of the three cross-shelf positions (6 occurred in one position, 5 were restricted to 2 positions, and only 5 genera occurred at all positions). Highest richness was found on the mid-shelf reefs, as some of the inner-shelf and outer-shelf taxa extended their distribution into this intermediate region. In contrast to the taxonomic composition, the overall soft coral cover changed little across the shelf, due to the varying habitat optima for the different families. The Alcyoniidae dominated the inner-shelf region, whereas the Xeniidae and Nephtheidae were most common on the outer-shelf. For the families, shelf position and not one of the physical factors was the strongest separator of the groups in the regression trees. Within shelf groups, depth, flow, sediment and wave exposure also strongly influenced the distribution of the families, though to a varying extent at different shelf positions. Contrary to earlier assumptions (Dinesen 1983), there was no simple inverse relationship between the cover of soft and hard corals. Instead, the ratio between these two benthic groups was strongly habitat-specific.

The rapid survey technique was able to detect subtle changes in abundances and composition of soft coral assemblages along environmental gradients. This technique enables large areas of reef to be surveyed in a highly cost and time effective manner, particularly so when distributions of taxa are very variable or a large proportion of taxa are rare. In these cases, the more traditional belt and line transect methods are likely to result in data which inadequately represent the reef community. Regression trees, as used in this paper, proved ideal for the detection of complex environmental interactions, which would have been difficult to reveal in the more usual linear model analysis. Another advantage of this method is that findings can be represented in an simple, yet ecologically meaningful way. To conclude, rapid surveys, in combination with regression tree analysis are a powerful procedure for benthos community analyses, well suited to both scientific and managerial application.

ACKNOWLEDGMENT

The study was funded by the CRC Reef Research Centre.

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SESSION 7

Managing the Great Barrier Reef World Heritage Area

The Global Coral Reef Monitoring Network: building on Australian research and development

CR Wilkinson
Global Coral Reef Monitoring Network, c/- Australian Institute of Marine Science, PMB No. 3, Townsville MC Qld 4810

ABSTRACT

The Global Coral Reef Monitoring Network was established as a response to large-scale damage and destruction of coral reefs around the world. The impetus arose out of the International Coral Reef Initiative, in which Australia has been a driving force since its inception in 1994. The Network, co-sponsored by IOC(UNESCO), UNEP and IUCN and co-hosted by AIMS and ICLARM (Manila), aims to improve the conservation, management and sustainable uses of coral reefs. It will establish a global network, which integrates current efforts to document the biophysical status and trends in the ecosystems and socioeconomic uses of the resources. More importantly, the GCRMN will build capacity in countries with coral reefs, through training and provision of equipment, to monitor the status and trends in their reefs. The GCRMN aims to provide high-quality data on the status of coral reefs for the preparation of predictive global change models as part of the GOOS Coastal Zone Module, as well as providing and disseminating monitoring results to parties responsible for environmental management. The goal is to provide accessible data directly to decision makers and the user public. Monitoring will be based on methods developed in collaboration by AIMS with Asian countries as part of the ASEAN–Australia Living Coastal Resources project (1984–94).

INTRODUCTION

The Global Coral Reef Monitoring Network (GCRMN) has been established to provide data for better management of coral reefs, by harnessing the interest and skills of all users in reef assessment and management. Two major products are envisaged: data on reef status and trends; and people trained to observe reefs closely for cause and effect relationships.

The GCRMN is a component activity of the International Coral Reef Initiative (ICRI), to provide Research and Monitoring information on coral reefs and related ecosystems for more efficient management and long-term conservation (ICRI 1995). The GCRMN is supported by the Intergovernmental Oceanographic Commission of UNESCO, the United Nations Environment Programme and the World Conservation Union (IOC–UNEP–IUCN) and hosted by the Australian Institute of Marine Science and the International Center for Living Aquatic Resources Management (AIMS and ICLARM). Advice will be provided by a widely representative Scientific and Technical Advisory Committee (GCRMN–STAC).

The first concerted effort to document coral reef status and damage by S.M. Wells and others (UNEP/IUCN 1988) reported widespread damage, but found that for significant areas of the reef world, there were no valid data, other than occasional anecdotal observations. The need for long-term coral reef monitoring was the major conclusion at two recent international meetings. At a workshop on coral bleaching and global change in June 1991 (D'Elia et al. 1991) and another in June 1993, featuring collected case histories on effects of stress on coral reefs (Ginsburg 1994), it was recognised that many reefs were being severely damaged by a variety of natural and anthropogenic stress, but data were insufficient to be precise on the extent. This was evident when predictions were attempted on the future of coral reef ecosystems under the growing pressures of human use of reefs (Wilkinson 1993).

To determine long-term patterns over broad scales, monitoring must be both extensive spatially, as well as inclusive of many different reef habitats and states. Much previous monitoring has started with the 'Hughes paradox' – many scientists started monitoring healthy reefs with high coral cover; rarely did they monitor devastated or damaged reefs with low cover (Hughes 1994a). Thus, many studies reported a decline in coral cover.

To be effective, reef monitoring must encompass the ecological and temporal scales of organism life cycles and rare episodic events, like tropical storms or predator plagues (Hughes 1994a). A few long-term monitoring studies revealed widely different conclusions. Jamaican reefs showed virtually no change in coral cover for approximately 20 years (Goreau 1959), but during the last 16 years there has been a steady decline in coral cover (from 30–80% to < 5%), paralleled by increases in algal cover (Hughes 1989, 1994b). These long-term studies of both algal and coral populations demonstrated the magnitude of changes and the predominant agent responsible – gross over-fishing.

During a 16-year study on the central Great Barrier Reef, Done (1992; Done, in press), demonstrated distinct cycles in the coral communities with a periodicity of approximately 12 years, corresponding to outbreaks of *Acanthaster planci*. During a 30-year study on Heron Island, southern Great Barrier Reef, Connell (1978; Connell, in press) showed marked changes in coral cover and species composition, corresponding to irregular tropical storms. Monitoring of reefs in Kaneohe Bay, Hawaii showed a steady decline due to nutrient pollution, interspersed with periodic community crashes due to freshwater inundation, until the coral community recovered when the sewage was diverted offshore (Smith et al. 1981; Jokiel et al. 1993)

Selective 'short-term' sub-samples within these widely separated studies show very conflicting stories. For example, between 1983 to 1988: Jamaican reefs were gradually declining in coral cover; on the central Great Barrier Reef, reefs were in the initial stages of recovery from almost complete coral loss; on Heron Island, coral cover on the protected crest was declining, but increasing on an exposed crest; and Kaneohe reefs were recovering rapidly. Thus, any attempts of global comparisons based on few, widely dispersed studies are meaningless.

These studies are, however, valuable for management of these locations, and only indirectly applicable to global reef management. Thus, the GCRMN will supplement these detailed studies, using the model of long-term monitoring along the length of the Great Barrier Reef to provide management authorities with valid information of reef status and trends (Oliver et al. 1995). This Australian project was also a model for similar monitoring in Southeast Asia during the ASEAN–Australia Living Coastal Resources project (Chou 1994).

Background to the Global Coral Reef Monitoring Network

The concept of global coral reef monitoring has been discussed in international forums for many years. International environmental agencies assembled a 'group of experts' in Monaco in December 1991, to discuss growing evidence of damage and reef and mangrove monitoring (IOC 1991). This group recommended a pilot scale monitoring project using methods developed during the ASEAN–Australia Living Coastal Resources project (UNEP 1993; English et al. 1994).

At the 7th International Coral Reef Symposium in Guam, 1992, the Global Coral Reef Task Team supported a global monitoring project using the methods recommended (IOC 1992a). Many coral reef scientists and managers reported their willingness to participate in proposed global reef monitoring (IOC 1992b). However, funding was not available to initiate action.

The Global Task Team provided the focus for the GCRMN, stating that the major, imminent threats to coral reefs were anthropogenic, with climate change as a longer-term threat, but an immediate one to coral island communities (Wilkinson and Buddemeier 1994).

A United States Coral Reef Initiative was launched at the UN Global Conference on Sustainable Development of Small Islands Developing States in Barbados in 1994 as a response to the problems facing coral reef countries and to maintain the emphasis on reefs expressed in Agenda 21 of the 1992 UNCED meeting (Crosby et al. 1995). Soon after, another 7 countries (Australia, France, Japan, Jamaica, Philippines, Sweden and the UK) joined the USA to form the International Coral Reef Initiative (ICRI) at the First Conference of Parties of the Convention on Biological Diversity in Bahamas in 1994. ICRI held a major international meeting in Dumaguete City, Philippines, in mid-1995, which established the GCRMN, and appointed a Coordinator to be administered by the IOC, using US State Department funds.

Objectives of the Global Coral Reef Monitoring Network

The GCRMN aims to improve management and sustainable conservation of coral reefs for people by assessing the status and trends in the reefs and how people use and value the resources. It will do this by providing many people with the capacity to assess their own resources, within a global network, and to spread the word on reef status and trends. These will be achieved through strategic objectives that link existing organisations and people to monitor biophysical and social, cultural and economic aspects of coral reefs within interacting Regional Networks. This will involve strengthening the existing capacity to examine reefs by providing a consistent monitoring program, that will identify trends in coral reefs and discriminate between natural, anthropogenic, and climatic changes. The results will be disseminated widely at local, regional, and global scales as annual reports on coral reef status and trends to assist environmental management agencies implement sustainable use and conservation of reefs. The data will also aid preparation of predictive global climate change models for the GOOS Coastal Zone Module.

Operating Principles of the Global Coral Reef Monitoring Network

The GCRMN *will* emphasise the involvement of local communities in monitoring with equal emphasis on biophysical as well as social, cultural and economic data. Wherever possible, the GCRMN will use existing organisations and networks, integrate existing monitoring programmes, and maintain flexibility to incorporate different methods of monitoring, other than the standard methodology. Much of the monitoring will be in current or planned Marine Protected Areas and adjacent unprotected areas. The Network will be responsive to reef users and provide information back in an understandable format.

Strategies of the Global Coral Reef Monitoring Network

The GCRMN will monitor the current status and future trends in coral reefs and their use through 6 independent ICRI regions: Western Indian Ocean and East African States (island states and countries of East Africa); the Middle East Gulfs (countries bordering the Red Sea to the Persian/Arabian Gulf); South Asia (India, Sri Lanka and Maldives); East Asian Seas (countries from Burma/Myanmar and Japan to Indonesia and the Philippines); the Pacific Island states; and the Caribbean and Intra-Americas, including countries with reefs bordering the Atlantic Ocean.

Within each region, there may be one or more GCRMN Sub-Nodes to coordinate training, monitoring and data management for the 3 to 8 participating countries. For example, Mauritius will be a GCRMN Sub-Node for Western Indian Ocean countries, and Kenya will be another for East African States.

Each Sub-Node will employ a team of trainers and database operators to train other trainers and assist in database operations in adjacent countries. Funding for each Sub-Node will be requested from country, development bank or agency donors, with the responsibility for monitoring devolving to the countries after about 5 years.

The GCRMN will have three interlinked levels: local communities (fishers, schools, colleges, and tourists) monitoring broad areas with less detail; moderate coverage at higher resolution and detail by tertiary trained personnel in Government environment or fisheries departments and universities; and high resolution assessment over small scales by scientists and institutes currently monitoring reefs for research. Considerable monitoring is in progress by institutes around the world and the GCRMN will request these bodies cooperate with developing countries to introduce monitoring. Sub-Node and country trainers will monitor key national sites while providing training to local communities.
A wide range of reef types will be monitored along line transects, assessing easily recognisable lifeforms and fish, especially commercial or recreational species. As people gain more experience, monitoring will be upgraded to species level using the same methods. Local communities will be questioned on their use and knowledge of reef resources and how management may be improved.

Existing or planned Marine Protected Areas (MPAs) will be amongst the main monitoring sites, to provide data on the resources and effectiveness of management. This will be coordinated with the World Bank, IUCN/CNPPA, GBRMPA Global Representative System of Marine Protected Areas project (Kelleher et al. 1995) for site selection and questions asked by management.

Monitoring data will be used to generate annual, country, regional and global summaries of reef status and all data will be stored in ReefBase (ICLARM, Manila).

Two special monitoring projects will be supported by the GCRMN: a pilot programme undertaken simultaneously by research institutes around the world to give a snapshot of reef status; and the development of a tourist monitoring programme, coordinated through tourist operators.

Methods

The GCRMN will feature simultaneous gathering of biophysical, social, cultural and economic data. Biophysical monitoring will be based on a 'standard methodology': manta tow (or equivalent for a broad perspective); line intercept transect with initial identification at 'lifeform' level (or equivalent transect method); and fish censusing, with emphasis on fisher target species and indicator fish, like butterfly (chaetodont) fish (English et al. 1994). Socioeconomic parameters will focus on use of reef resources and community knowledge and attitudes to reef management, along with demographic data and legal and economic parameters.

Monitoring Sites

Countries and GCRMN Sub-Nodes will recommend sites for monitoring based on local requirements and recommendations adapted from the Monaco meeting (IOC 1991). These include assessing: 'pristine' reefs remote from human populations compared to reefs under a range of human impacts; reef flats, reef slopes, both windward and leeward; reefs at geographic extremes e.g. high latitudes, within high and low salinity concentrations; reefs from high to low biodiversity; reefs experiencing the range of storm effects (from equatorial reefs to tropical storm belts at latitudes of more than 7°), the range of oceanic turbulence and current influences, and the range of land run-off; sites monitored in the past, especially those with continuous monitoring data or monitored many years ago; reefs in Marine Protected Areas and adjacent, unprotected reefs; and reefs that have been extensively damaged (natural or human causes). This last category is particularly important to determine the ability of reefs to recover and will require methods aimed at detecting the survival of newly recruited corals.

These sites should cover the complete geomorphologic range of reef types and locations, from fringing reefs close to land to oceanic atolls. The sites should permit discrimination of changes and trends between natural coral reef impacts (storms, fresh water run-off) to global climate change (sea level rise, increased temperatures and radiation, changes in rainfall and current patterns) and anthropogenic pressures (pollution, increased sediment loads and over-exploitation).

Outputs of the Global Coral Reef Monitoring Network

There will be tangible and intangible outputs: data on reef status and trends generated by communities, governments and research institutes; **methods manuals,** annual **reports and major reports coinciding with** the International Coral Reef Symposia every 4 years; **an interactive, international network** of trained people monitoring coral reefs; and **greater awareness by** users, public, governments and international agencies, **of the need for reef** management and **conservation.**

DISCUSSION

The GCRMN is an ambitious project aimed at providing data to enhance reef management. The methods and protocols have been largely drawn from studies performed in Australia during the past 15 years. The degree of success will largely depend on the international community providing funds to support reef monitoring, as there is considerable willingness amongst a large reef user and research community to assist. Simultaneously there will be other projects providing more data, including monitoring by tourists and volunteer divers.

A novel approach has been undertaken by Birkeland and Randall (in press), of relocating sites that had been surveyed previously in Samoa in 1917 and 1973. The GCRMN will benefit from similar studies in progress to provide additional long-term data to the surveys that the GCRMN will add, starting from now.

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Section 2

Abstracts of Poster Presentations Not Produced as a Paper

Effects of anthropogenic eutrophication on micro-organisms and nutrients in coral reef waters

GJ Gast, WJ Steinhoff and RPM Bak
Netherlands Institute for Sea Research, PO Box 59, 1790 AB Den Burg, The Netherlands

ABSTRACT

Input of organic matter and nutrients stimulates growth of micro-organisms. Anthropogenic eutrophication by raw sewage discharge and run-off, resulting from urban development, is primarily used by bacteria. As different reef organisms use microbes in varying degrees as nitrogen and/or carbon source, shifts in microbial abundances in the coral reef water column, caused by eutrophication, could possibly lead to changes in coral reef benthos composition. From February 1994 till March 1995 we monitored microbial community and nutrients in coral reef waters over a eutrophication gradient along the island Curaçao in the Southern Caribbean. We included an oceanic station as a control on the watermass passing the island.

We found enhanced levels of dissolved inorganic nitrogen, mainly nitrate, in reef water, which originates from the reef. Increased bacterial production occurred in reef water when current and surge were calm enough to allow bacteria to use carbon (i.e. mucus) excreted by reef benthos. Sewage discharge led to increased bacterial production, elevated concentrations of nutrients and a changed phytoplankton composition in reef waters, depending on the physical circumstances. In the harbour, where water exchange is low, the microbial loop processed the heavy eutrophication. Energy and nutrients were passed on to higher trophic levels in this top–down controlled ecosystem. Run-off enhanced bacterial growth and caused a temporary escape of bacteria from their consumers.

Suspended particulate matter: an important energy source for corals on nearshore reefs?

KRN Anthony and BL Willis
Department of Marine Biology, James Cook University of North Queensland Qld 4811

ABSTRACT

High concentrations of suspended particulate matter (SPM) on nearshore reefs are generally assumed to constitute a negative component of coral energy budgets. However, the extent to which corals can utilise SPM as an energy source has not previously been quantified. Feeding studies investigating the effects of SPM concentration on rates of ingestion and assimilation (using ^{14}C) in three common coral species (*Pocillopora damicornis, Montipora digitata* and *Porites cylindrica*) show that rates of SPM ingestion increase exponentially as a function of concentration for all three species. Rates of ingestion did not reach levels of saturation within the range 1–30 mg SPM L^{-1}, the range of concentrations typically found across the Great Barrier Reef Lagoon. *M. digitata* reached a maximum rate of ingestion at 50 mg SPM L^{-1} (21 ± 0.9 [SE] μg SPM cm^{-2} h^{-1}), but showed reduced ingestion rates at 100 mg SPM L^{-1}. *M digitata* and *P. cylindrica* showed significantly higher rates of ingestion and assimilation than *P. damicornis* when expressed per unit surface area, but this pattern was reversed when expressed per unit biomass of tissues. Up to 80 % of the ingested SPM was assimilated at low concentrations (1–8 mg SPM L^{-1}), but decreased to 50% at 30 mg SPM L^{-1}. High assimilation efficiencies and the exponential relationship between particulate feeding and SPM concentration demonstrate the importance of heterotrophy to corals in high-sediment environments, and may explain the energetic basis for coral growth in highly turbid waters on nearshore reefs.

Growth of *Sargassum baccularia*, a macroalga dominant on Great Barrier Reef nearshore reefs, is promoted by short-term nutrient pulses

B Schaffelke and DW Klumpp
Australian Institute of Marine Science, PMB No. 3, Townsville MC Qld 4810

ABSTRACT

Large brown algae are distinct and dominant members of shallow water communities on nearshore reefs of the Great Barrier Reef. There is increasing concern that biomass produced by these seaweeds may compete with corals directly for space or indirectly by altering nutrient pathways. We studied the responses of *Sargassum baccularia,* the most dominant species in terms of macroalgal biomass, to experimentally enhanced nutrients. Most of the inputs of nutrients into Great Barrier Reef waters are episodic (e.g. by rainfall and riverine input). We simulated the availability of enhanced nutrients by short-term (24 h) pulses of ammonium and phosphate, 5- to 50-fold above background level. After pulses, plants were returned to natural nutrient levels in the field or in outdoor aquaria. Nutrient pulses significantly increased the internal nitrogen and phosphorus stores, which then promoted a significant enhancement in growth and productivity of *S. baccularia.* A 24 h nutrient pulse enhanced growth rates by 40–60% compared to controls and sustained this rate for about two weeks.

Our results suggest that increases in water column nutrients as transient spikes of very short duration may distinctly favour *Sargassum* species in competition with other benthic organisms on nearshore reefs. The pronounced response we observed to nutrients applied on top of background levels of Great Barrier Reef nearshore waters may predict a promotion of macroalgal growth if nutrient stocks increase.

Diver–minke whale interactions on the northern Great Barrier Reef

***PW Arnold*[1] *and RA Birtles*[2]**

[1] *Museum of Tropical Queensland, Townsville Qld 4810*

[2] *Department of Tourism, James Cook University of North Queensland Qld 4811*

ABSTRACT

Underwater encounters with dwarf minke whales (*Balaenoptera acutorostrata*) regularly occur from dive charter vessels operating between Port Douglas and Lizard Island during winter months. Preliminary information on spatial and temporal distribution of whales, pod size and mean contact time is available, based on sightings provided by charter operators and direct observations. Ongoing studies include the effects of underwater encounters on both divers and whales (part of a larger study by Birtles and Valentine on SCUBA diver experiences, focusing on wildlife–human interactions on the Great Barrier Reef), assessment of protocol used for swimming with whales, photo-identification of individual whales and demographics of the whales which approach divers.

Environmental and ecological controls on the in situ population growth rates and distribution of small phytoplankton inhabiting shelf waters of the Great Barrier Reef

N Crosbie

Australian Institute of Marine Science, PMB No. 3, Townsville MC Qld 4810

ABSTRACT

Concerns exist about the potential for negative impacts on the Great Barrier Reef via indirect effects of nutrient loading. As phytoplankton are central to the process of biological mediation of water quality, knowledge of their response to nutrient loading is of premium management importance. In particular, high-quality information on in situ growth rates of phytoplankton is sort in order to determine the response of the phytoplankton community to nutrient loading, with a view to predicting impacts to the reef benthos and pelagial via grazing upon nutrient-stimulated phytoplankton populations.

In situ growth rates of picophytoplankton (*Synechococcus* and *Prochlorococcus*) and other small phytoplankton (mostly small diatom species) were measured by the diffusion chamber approach of Furnas (Limnol. Oceanog. 36: 13–29) under inshore and offshore conditions (Cairns region, Great Barrier Reef), with counts obtained by flow cytometry or by the Utermohl method. The results are discussed in relation to physical and ecological forcing factors, and cross-shelf distribution patterns of small phytoplankton.

Detritus and the Great Barrier Reef: quality and quantity over time and space

M Dommisse and M Furnas
Australian Institute of Marine Science, PMB No. 3, Townsville MC Qld 4810 and the CRC Reef Research Centre, Townsville Qld 4811

ABSTRACT

The proximate composition and quantity of detrital material potentially falling onto reef surfaces was studied in selected regions of the Great Barrier Reef to assess its nutritional value and quantitative role in the recycling of nutrient materials (carbon, nitrogen, phosphorus) into reef environments. Detritus samples were collected approximately every six weeks from Cannon Bay, Great Palm Island (18°S, 146°E) to examine temporal changes in the proximate composition and abundance of the detrital pool. Spatial changes in the detrital pool were examined by sampling cross-shelf from Double Island, Cairns (17°S, 140°E) to reef 20-334 in the Pompey Island group (20°S, 150°E). Analyses of detritus consisted of total particulate organic carbon (TPOC); total particulate carbon (TPC); total particulate nitrogen (TPN); total particulate phosphorus (TPP); chlorophyll *a* (Chl*a*) and pheophytin (Phe) measurements. Ratios between elements and constituents were used to determine the potential nutritional value of detritus – TPOC:TPC to establish the lability of detritus and TPC:TPN and TPC:TPP to determine the nutritional value of nutrients packaged into detrital material. TPOC:Chl*a* and Chl*a*:Phe ratios were used to estimate the contribution of microalgae to detrital material.

Relationships between the distribution and abundance of sessile epibenthos in inter reefal areas of Torres Strait and seabed current stress and bedload partings

BG Long[1], CR Pitcher[1], L Bode[2] and LB Mason[2]
[1] *CSIRO Division of Fisheries, Cleveland Qld 4163*
[2] *Marine Modelling Unit, James Cook University of North Queensland Qld 4811*

ABSTRACT

The abundance of sessile epibenthos and substratum type in inter reefal areas of central Torres Strait was estimated along 2 x 500 m transects by SCUBA divers at 510 sites during a field survey in 1989. The seabed current stress at 1' intervals over Torres Strait was estimated by numerical modelling of the dominant tidal currents in the Strait. The distribution and abundance of sessile epibenthos of inter reefal areas of central Torres Strait was significantly correlated to both sea bed current stress and substratum type ($r^2 = 0.55$; $P < 0.0001$). The amount of exposed rocks and rubble and the abundance of sessile epibenthos was highest along a line from Cape York, Australia to Boigu Island in the western part of the study area and from Cape York along the Warrior reef complex to Daru Island in the eastern part of the study area. These areas also corresponded to bedload parting zones in Torres Strait; areas of high seabed current stress with tidal scouring. A regression model between seabed current stress and epibenthos abundance was also developed to predict the abundance of sessile epibenthos throughout Torres Strait as information on substratum type is often unavailable. In eastern Torres Strait where no benthos data were collected in 1989, the model predicted that epibenthos would be mostly absent in the inter reefal areas except for two areas south of the Hibernia Pass and an area east of Darnley Island. This prediction has been confirmed by a recent survey of the sea bed in eastern Torres Strait. These results have important implications for optimising sampling programs and enhancing the capability for mapping the distribution and abundance of inter reefal benthos.

Terrigenous and suspended sediments influences the distribution and abundance of seagrass and corals on coral reefs in Torres Strait

BG Long, TD Skewes and DM Dennis
CSIRO Division of Fisheries, Cleveland Qld 4163

ABSTRACT

The percentage cover of seagrass was estimated along 2 m x 20 m transects by SCUBA divers at 1212 sites on 45 reefs in Torres Strait. The percentage cover of live coral was estimated along 2 m wide transects at 317 sites perpendicular to the reef slope on 43 reefs. The percentage cover of seagrass, averaged by reef, was significantly correlated with inverse distance from the mouth of the Fly and Mai Rivers in Papua New Guinea and the geometric centroid of a group of islands around Thursday Island near the Australian mainland ($r^2 = 0.84$; $P < 0.0001$). The percentage cover of seagrass on the tops of the reefs was highest on the Warrior and Orman reefs in the north west of Torres Strait and absent on the ribbon reefs on the outer Barrier Reef and decreased in a south-easterly direction. Similarly the percentage cover of live coral, averaged by reef, was significantly correlated with inverse distance from the Fly and Mai Rivers and the Thursday Island centroid ($r^2 = 0.82$; $P < 0.0001$). In contrast to seagrass, however, the percentage cover of live coral along the edge of the reefs was highest on the ribbon reefs and was lowest on the Orman and Warrior reefs. The patterns of distribution and abundance of percentage cover of seagrass and corals mirrored patterns in the concentration of suspended silicates in the surface waters of eastern Torres Strait which are brought in by river water. These results indicate that factors associated with river run-off may have a significant influence on the distribution and abundance of seagrass and live coral on the reefs of Torres Strait.

Interactions between dugongs and gill-netting in Shoalwater Bay

T Preen
Department of Tropical Environment Studies and Geography, James Cook University of North Queensland Qld 4811

ABSTRACT

In just eight years dugong populations have declined by more than 50% along three-quarters of the length of the Great Barrier Reef Marine Park. If the mortality of dugongs can be reduced to near natural levels, recovery of the dugong populations will take many decades. If mortality is not reduced, dugongs, which were one of the prominent features of the Great Barrier Reef's World Heritage listing, will be driven to local extinction along most of the Queensland coast.

Gill-netting is recognised as one of the key threats to the survival of dugongs in Queensland and world-wide. In Shoalwater Bay, one of the two most important dugong habitats in the Great Barrier Reef Marine Park south of Cooktown, gill-netting is likely to be the main cause of the 50% population decline.

The interactions between dugongs and gill-nets must be understood if the impact of gill-netting on dugong populations is to be reduced. This project is using satellite transmitters to track the movement patterns of dugongs in the Shoalwater Bay area. Seven dugongs have been tagged in Shoalwater Bay and three have been tagged in Port Clinton. Five key grazing areas have been identified to date. Dugongs utilise sub-tidal seagrass beds in relatively open areas, extensive inter-tidal seagrass beds, and tiny, linear strips of seagrass along the edges of mangrove creeks. Tagged dugongs regularly move throughout Shoalwater Bay and Port Clinton as they travel between favoured feeding areas. Some dugongs also move out of the region occasionally. Three dugongs have travelled at least 200 km from where they were tagged.

Professional fishermen that work in Shoalwater Bay and Port Clinton will be interviewed about gill-netting practices and patterns in the area. This information will be used to interpret the information on habitat use and movements by dugongs with the aim of identifying strategies that may allow for the survival of gill-netting and the survival of dugongs.

Appropriate spatial scales for marine fishery reserves for management of coral trout, *Plectropomus leopardus*, on the Great Barrier Reef

CR Davies
Department of Marine Biology, James Cook University of North Queensland Qld 4811
Present address: Effects of Line Fishing Project, CRC Reef Research Centre, James Cook University of North Queensland, Townsville Qld 4811

ABSTRACT

The concept of Marine Fishery Reserves, or permanent spatial closures, has received substantial attention as a potential management tool for exploited stocks of demersal reef fish. A fundamental assumption underlying the use of spatial closures is that there is limited exchange of adults among separate management units. The aim of this study was to test this assumption for the common coral trout, *Plectropomus leopardus*. *P. leopardus* is a medium size serranid which is highly valued by fishers on the Great Barrier Reef. The Great Barrier Reef Marine Park is managed by a zoning system which allows fishing in some zones while excluding it from others, effectively implementing a spatial closure management strategy on the fishery. The spatial scale of the zones vary, from a section of a reef to groups of several reefs. The objectives of this study were to determine: i) The extent of movement of post-settlement *P. leopardus* within and among individual coral reefs, ii) Whether there was a temporal pattern of movement associated with the spawning activity of *P. leopardus*.

A total of 4627 *P. leopardus* were tagged and released on five reefs in the central Great Barrier Reef from five tag–release occasions over 22 months. Four hundred and forty three individuals were recaptured; 300 by commercial and recreational fishers and 143 from four research tag-recovery cruises. Ninety-nine per cent of the research returns were recaptured on the reef of release. One inter-reef movement was recorded between two adjacent reefs (from a reef open to fishing to a reef closed to fishing). The research returns indicated that the extent of inter-reef movement was negligible. In contrast, there was considerable movement within individual reefs. On average 35% of the *P. leopardus* returned from the research tag-recovery cruises had moved out of the 1.5–2.5 km section of reef perimeter in which they had been released. The extent of movement varied among reefs, and appeared to be related to movement to or from spawning aggregations.

In contrast to the negligible level of movement among reefs from the research returns, 36% of public returns were nominally returned from reefs other than the one on which they were released. The majority of movements among reefs from public returns were from the reef closed to fishing to the next adjacent reef (which was open to fishing). This disparity in the extent of movement of *P. leopardus* between the public and research returns appears to have been the result of infringement and misreporting of location of capture. The majority of public returns which were nominally recaptured on a different reef to that of their release were returned by one fisher. The available anecdotal evidence suggests that these fish were actually recaptured on the reef on which they were released.

These results indicate that the level of movement of *P. leopardus* among individual reefs is negligible. The extent of movement of *P. leopardus* within individual reefs, however, was found to be high. This suggests that partial reef closures may not effectively protect populations of reef fish, such as *P. leopardus*, and that the minimum spatial scale for Marine Fishery Reserve design should be an individual reef.

Design of experimental manipulations of line fishing and area closures on the Great Barrier Reef

BD Mapstone[1], RA Campbell[2], ADM Smith[2] and CR Davies[1]
[1] CRC Reef Research Centre located at James Cook University of North Queensland Qld 4811
[2] Department of Marine Biology, James Cook University of North Queensland Qld 4811

ABSTRACT

Fishing remains the major extractive industry in the Great Barrier Reef Region. Diverse commercial and recreational fisheries are widespread, and constitute multi-million dollar industries in the region. Biological information about species targeted by fishing is necessary but not sufficient to successfully manage the fisheries and ecosystem. Controlled experimental manipulations of fishing pressure and management options have been recommended previously as the most effective mechanisms for assessing empirically the responses of targeted stocks, other reef organisms, and fishing practice to changes in fishing pressure. Such information is not currently available for the Great Barrier Reef reef line fisheries, but will be critical to future decisions about management of Great Barrier Reef recreational and commercial fisheries. We used computer simulations to model the population dynamics of the of the main target species of recreational and commercial reef-line fisheries (*Plectropomus leopardus*), and fishing and closure strategies to assess the potential for such experiments to produce unequivocal results. We have now implemented a large scale experiment that is affordable, feasible, and has a high probability of producing clear signals about the relationships between catch rate, fishing dynamics, and stock density, and provides direct tests of the effectiveness of area closures as a fishery/stock management strategy on the Great Barrier Reef.

Our computer simulations considered 18 variables that were most likely to produce nuisance perversities in the experimental data. We set the variations in variable values beyond the extremes seen in existing field data. The results indicate that large scale experiments utilising whole coral reefs as units of experimental manipulation can be designed such that the resulting field data will have good statistical power (> 0.8) to detect moderate effects of fishing on catch rates and stock density and to measure responses of fished stocks to protection form further fishing. Under the 'best case' scenario many alternative designs would be feasible, but under the most extreme perversities in our simulations only experiments involving 24 reefs or more would be likely to produce useful results.

The experimental work must be supported operationally by the commercial and recreational fishing communities and supported administratively and legally by the relevant management agencies. This support has been obtained through an extensive consultation and liaison programme, which included input from all sectors on reef-selection, refinement of experimental design, and experimental implementation.

The experimental design involves four clusters of six reefs each, spread over 7° of latitude between Cape Flattery in the north and the Swain Reefs in the south of the Great Barrier Reef. Two treatment regimes and one control regime are applied within each cluster. The controls incorporate two reefs per cluster that have been closed to fishing historically and remain closed during the experiment, and which provide our best estimates of background environmental changes that are not related to fishing. The two treatment regimes consist of i) hard fishing over one year on two reefs per cluster that have been closed to fishing, and which are re-closed after the fishing manipulation and ii) increased fishing pressure on two reefs per cluster that have been open to fishing historically, but are closed for five years after manipulation.

The effect of re-opening Bramble Reef to bottom fishing on fishing behaviour and catch rates of commercial and recreational line fishers

BD Mapstone[1], CR Davies[1], JB Higgs[2] and DJ Welch[1]
[1] CRC Reef Research Centre located at James Cook University of North Queensland Qld 4811
[2] Department of Marine Biology, James Cook University of North Queensland Qld 4811

ABSTRACT

Bramble Reef is the closest mid-shelf reef to the mainland in the Central Section of the Great Barrier Reef Marine Park. It was closed to bottom fishing on 1 January 1992 in response to concern within the fishing community that the reef fish stocks had declined to an unacceptable level. It re-opened to fishing on 1 July 1995.

The re-opening of Bramble reef provided an opportunity to study the effects of reef closure and re-opening on catch rates, fish stocks, and the behaviour of fishers. It also presented the ideal opportunity to develop a study to test, around a focused issue, a number of catch and effort sampling methodologies.

The study involved collecting catch and effort information from one month prior, and for two months after, the opening of Bramble reef using 6 methodologies: i) traditional; and ii) 'bus route' style boat ramp surveys; iii) fishing diaries maintained by recreational anglers; iv) roving creel surveys; and, catch surveys conducted by: v) commercial fishers; and vi) club boat anglers.

Fishing effort at Bramble Reef on opening day was high, with more recreational (64) than commercial (26–40) fishers present. The recreational anglers were in 19 boats, whilst the commercial fishers were based on 14 primary vessels, with 26 dories. Effort by both recreational and commercial fishers dropped sharply after opening day. Over the remaining eight days there were on average two recreational boats and 5 commercial primary vessels (15 dories) on Bramble Reef on each day. Fishing at Bramble and nearby reefs was negligible by either fishing sector between late July and September because of persistent strong winds.

Recreational catch rates exhibited no clear trends over the duration of the study. Catch rates were highly variable, and both good and poor catches were reported on opening day and throughout July. The same was true of an adjacent reef, which has always been open to fishing. Catch rates from research surveys on a commercial fishing vessel declined rapidly on Bramble Reef after the re-opening. Catch rates immediately prior to 1 July were approximately twice as great on Bramble Reef as on control reefs, but within two weeks of re-opening catch rates at Bramble Reef had dropped to very similar levels to catch rates on control reefs. Data from the commercial fleet indicate that other commercial vessels experienced rapid drops in catch rates on Bramble Reef in the first few days it was open to fishing. Catch rates from Bramble Reef are now similar to catch rates on other reefs.

One of the major features of this program was the inter-departmental and community cooperation that it involved. Agencies involved in the study included the CRC Reef Research Centre, James Cook University, Great Barrier Reef Marine Park Authority, Department of Primary Industry, and substantial staff commitments in the field by Queensland Department of Environment Marine Parks and Queensland Boating and Fisheries Patrol. The research was substantially assisted by the cooperation of the recreational and commercial fishing sectors.

Pulvinaria urbicola Cockerell on *Pisonia grandis* at Tryon Island

JA Olds[1], RJ Elder[2], RM Charles[3], JR Platten[4] and KL Bell[5]
[1] *Queensland Department of Environment, Rockhampton Qld 4701*
[2&5] *Queensland Department of Primary Industries, Rockhampton Qld 4701*
[3&4] *Toolooa State High School, Gladstone Qld 4680*

ABSTRACT

The *Pisonia grandis* forest on Tryon Island, a coral cay at the northern end of the Capricorn Group of islands, has been severely infested with scale insects. The infestation of *Pulvinaria urbicola* Cockerell, was first noticed on the island in 1993 and has since defoliated most of the island's *P. grandis.*

Following its discovery on Tryon Island, *P. urbicola* has been recorded in low numbers on *P. grandis* on several other Capricornia Cays National Park islands. It has a large host range having been recorded on Capsicum, Carnation, Dahlia and Lantana and it is widespread throughout the Pacific. It appears, however, that this is its first recorded occurrence on *P. grandis*, a tree which principally grows in the high phosphate soils of coral cays.

The insect survives primarily on the host plant's sap (phloem) causing defoliation and eventually death in severe infestations. *P. urbicola* has several natural enemies including various species of parasitic wasp and predatory lady beetles, some of which have been recorded on Tryon Island.

To monitor the infestation, its predators and parasites and its effect on the Tryon Island's vegetation, a joint project between Queensland Department of Environment, Queensland Department of Primary Industries and Queensland Department of Education was developed. The Department of Environment manages the project, the Department of Primary Industries provides entomological and analytical expertise and Toolooa State High School assists in data collection and collation.

The monitoring project will continue into the future in an effort to understand the role of this insect in the development of coral cay vegetation.

At this point in time, the infestation is slowly subsiding due to a decreasing food source and increasing pressure from naturally occurring parasitic wasps. The vegetation has changed dramatically from an island with a closed canopy forest of predominantly *P. grandis* with little understory, to a more open forest, comprising a double story of typical coral cay vegetation other than *P. grandis*.

A strategic approach to ensuring that fishing in the Great Barrier Reef Marine Park is ecologically sustainable

J Robertson and M Russell
Great Barrier Reef Marine Park Authority, PO Box 1379, Townsville Qld 4810

ABSTRACT

Under the multiple use management regime for the Great Barrier Reef Marine Park, fishing is the largest extractive activity. Fishing is considered a reasonable use of the Great Barrier Reef Marine Park, but concerns over its ecological impacts have raised doubts about the ecological sustainability of the different fishing sectors. In an attempt to gain a better understanding of the effects of fishing on reef ecosystems, a strategic approach has been adopted which consist of a number of strategies. These strategies include large-scale manipulative research being conducted in fished and unfished areas of the Great Barrier Reef Marine Park; a spatial and temporal description of effort distributions of the different fishing sectors to identify high use areas and a more concise description and evaluation of whether representative habitats are adequately protected under the current zoning plan for the Great Barrier Reef Marine Park. The approach also ensures through a number of mechanisms the integration of fisheries and ecosystem management, the recognition of indigenous peoples in resource management, and the protection of critical habitats and endangered species.

Spawning periodicity of coral trout, *Plectropomus leopardus* (Pisces: Serranidae), on the northern Great Barrier Reef

MA Samoilys
Department of Primary Industries, PO Box 1085, Townsville Qld 4810

ABSTRACT

Plectropomus leopardus in the dominant species in the recreational and commercial day fisheries on the Great Barrier Reef. The periodicity of spawning of coral trout was studied at two reefs on the Great Barrier Reef over four years. Fish were monitoring by visual surveys, and by tagging. Coral trout aggregated and spawned from September to November, on the new moon, at the same aggregation sites each time. Aggregations dispersed between new moons. Some individuals returned for subsequent aggregations. Spawning occurred at dusk. Maximum numbers of fish in aggregations represented a 19-fold increase in density. Males established temporary territories at aggregation sites from which they courted females and to which they returned during subsequent aggregations. The predictability of coral trout spawning aggregations makes them both vulnerable to overfishing, and amenable to specialised management via seasonal and/or area closures.

Response of the coral-associated crustacean fauna of scleractinian corals to increased sedimentation: a prospective study

TM Sin
James Cook University of North Queensland Qld 4811

ABSTRACT

Scleractinian corals of the families Acroporidae and Pocilloporidae have a wide variety of macro-invertebrate commensal epifauna, some of which are obligate and highly specific. Although the abundance and diversity of this fauna have been linked with host coral size and health, the extent of the commensal-habitat relationship is not clear. In addition, studies on the responses of the commensal fauna to environmental disturbance have not accounted for the relationship with the physical and biological parameters of the host. This study presents the results of an investigation into this relationship, and the experimental design for a prospective study on the effects of increased sediment loading on both the host coral and the associated crustacean fauna. The structure and composition of the obligate commensal macrofauna of six species of branching scleractinian coral at Orpheus Island were found to be significantly correlated to host species, volume and rugosity. There was high host specificity at the family level between brachyuran crabs of the genera *Tetralia* and *Trapezia*, which inhabited acroporid and pocilloporid corals respectively. As these are obligate commensals which feed on mucus secreted by the coral host, I suggest that increased sediment loads would impact these organisms before a gross response in the host is detectable. I propose to test this hypothesis using a series of field and laboratory experiments based on the Beyond BACI (Before-After-Control-Impact) design for impact assessment.

The role of benthic mega-invertebrates in nutrient cycles on coral reefs: echinoderm density, population size and estimated population excretion rates on Rib Reef

S Uthicke and DW Klumpp
Australian Institute of Marine Science, PMB No. 3, Townsville MC Qld 4810

ABSTRACT

As a first step to elucidate the role of benthic invertebrates in nutrient cycles we determined the population size and calculated excretion rates of the most common mega-invertebrates on the reef flat of Rib Reef. Due to the nearly circular shape of Rib Reef, the area of several distinct zones on this reef could be conveniently calculated as a function of the radius. Two holothurian species *Holothuria atra* (103 000 individuals on the reef), *Stichopus chloronotus* (96 000 individuals) and the asteroid *Linckia laevigata* (31 000 individuals) were by far the most dominant members in this community. The daily excretion rates for the combined population of the two holothurian species added up to 40 530 mmol ammonium, 115 mmol nitrate, 4780 mmol dissolved organic nitrogen and 760 mmol phosphate. A conservative calculation showed that approximately 12 t of sediments are bioturbated by the holothurian population on Rib Reef on a daily basis. This bioturbation activity will result in further nutrient availability by releasing nutrient enriched sediment water; this aspect has yet to be quantified. The significance of the amount of nutrients released by holothurians in the context of overall nutrient pools of the model reef is being investigated. For example, in future studies we will quantify the response of reef producers to enhanced nutrient availability derived from holothurian presence and feeding activity.

Oceanic forcing of currents in the Great Barrier Reef: initial model studies

L Bode[1], LB Mason[2], and DM Burrage[3]
[1] Department of Mathematics and Statistics, James Cook University of North Queensland Qld 4811
[2] Department of Civil and Systems Engineering, James Cook University of North Queensland Qld 4811
[3] Australian Institute of Marine Science, PMB No. 3, Townsville MC Qld 4810

ABSTRACT

Recent modelling of larval transport in the Great Barrier Reef region has emphasised the importance of oceanic forcing (e.g. the East Australian Current (EAC)) to long-term movement of water-borne substances on the continental shelf. Although the magnitude of currents induced on the shelf by the EAC is generally weaker than those caused by winds or tides, the net long-term displacements which they produce can be significant. Currents meter moorings on the upper continental shelf slope, off Jewell and Myrmidon Reefs, have demonstrated significant low frequency variability in current strength and direction, and in the position where the incoming South Equatorial Current bifurcates against the continental margin. In the present work, a two-stage approach is used to develop models that can identify the major spatial and temporal features of ocean/shelf interactions, and which can transfer the effects of ocean currents onto the shelf in a realistic manner. In the first, a high resolution, three-dimensional stratified model of the western Coral Sea has been nested within a global model, to elucidate the basic structure of the regional circulation. In the second, an economical barotropic model has been developed, that: i) mimics the general structure of observed and modelled low frequency ocean currents on and near the shelf; ii) can be forced by readily available sea level data; iii) can transfer open boundary information to fine-grid, shelf-scale circulation models within the Great Barrier Reef. Preliminary results using both approaches have reproduced many of the observed features of the circulation and its variability.

Managing recreation and tourism in the Whitsundays

BM Barnett[1] and CC Thomas[2]
[1] Queensland Department of Environment, PO Box 5391, Townsville Qld 4810
[2] Great Barrier Reef Marine Park Authority, PO Box 1379, Townsville Qld 4810

ABSTRACT

The Whitsunday region is one of the most important holiday destinations in the Great Barrier Reef World Heritage Area. Visitors are attracted by the outstanding scenery of the islands, reefs and surrounding waters. Commercial operations cater for a range of recreational activities based on island and reef destinations, sites which are also accessible to private boat owners.

A substantial increase in tourism and tourist development in the Whitsundays has occurred since the 1960s, with a current growth rate of 3% per annum. Great Barrier Reef Marine Park Authority visitation records for 1994–95 accounted for a total of 487 000 visitor days in the Whitsundays, or 28% of the total commercial visitation to the Great Barrier Reef Marine Park.

The Great Barrier Reef Marine Park Authority and the Queensland Department of Environment are currently working together, in consultation with users, to finalise management plans for the Whitsunday island national parks and the marine parks.

Many of the issues identified during the planning process relate to the high levels of recreation and tourism use, including anchor damage, high visitor numbers and crowding, displacement of users, and unused permit allocation.

The plan will focus on protecting the area's special values whilst providing for a range of commercial and recreational opportunities. Strategies will be applied to manage areas of intensive and high use whilst maintaining other areas for moderate and low use, with appropriate levels of facilities. Sites of significant conservation and cultural value will be managed more intensively as 'restricted access areas'.

Detailed site plans are being prepared for sensitive sites requiring special management in the form of 'no anchoring areas' and public moorings to manage anchor damage.

Managing the effects of tourism use in the Great Barrier Reef World Heritage Area

Z Dinesen
Great Barrier Reef Marine Park Authority, PO Box 1379, Townsville Qld 4810

ABSTRACT

The Authority's objectives in managing tourism use in the Great Barrier Reef are to identify and mitigate the effects of tourism on natural, cultural, heritage and use values; to provide for a variety of uses and tourist experiences; to allow for continued growth and diversity in the tourism industry; to encourage a diverse and nature-based tourism industry; and to improve visitor understanding of the Great Barrier Reef and its management.

Tourism is the major commercial use of the Marine Park, worth over A$1 billion per annum. Over 80% of tourism use is focused in the Cairns and Whitsunday areas which constitute about 3.5% of the Marine Park. The ecological impacts of tourism include coral damage from anchoring and disturbance to nesting seabirds and turtles. Most ecological impacts of tourism activities within the Marine Park are relatively small-scale and confined to intensively used tourist destinations, but appropriate controls are also necessary to ensure that damage does not occur. particularly at sites of key conservation value. Social and cultural impacts include loss of amenity (e.g. crowding, permanent structures); displacement of historical users; and effects on cultural values of indigenous peoples.

The major elements of the Authority's tourism use management strategy now being developed and implemented are discussed.

A coastal resource atlas for the Great Barrier Reef: report on a pilot study

SJ Gardiner[1], JG Blackman[1] and J Day[2]
[1] Queensland Department of Environment, Conservation Strategy Branch, Wetland Inventory Team, Northern Regional Centre, Old Quarantine Station, Pallarenda Qld 4810
[2] Queensland Department of Environment, Coastal Management Branch, Northern Regional Centre, Old Quarantine Station, Pallarenda Qld 4810

ABSTRACT

Timely and appropriate information is essential for the efficient management of our coastal and marine resources. This need is more pressing as legislative responsibilities increase, e.g. the *Coastal Protection and Management Act 1995* requires the collation of information for the Statewide Coastal Plan and Regional Coastal Management Plans. Once such information is available, it can be used for numerous tasks ranging from park planning and management to rapid responses in emergency situations, such as oil spills.

In response to the need for improved coastal information a coastal resource atlas pilot project has recently been undertaken. The project demonstrated the value of a geographic information system (GIS) approach to information gathering, manipulation and output. An ArcInfo vector GIS format was used to organise the collection and presentation of information. A current thematic mapper satellite image of the area was added as a backdrop to the vector data. This was an important information source in its own right, and also assisted in the visualisation and validation of all vector data sets.

The outcome has provided the basis for a versatile digital coastal atlas. Information is structured within five distinct 'environments' (physical, biological, jurisdictional/cadastral, developed/managed, and cultural). The GIS approach allows information to be used at different scales, and different combinations of data to be displayed or used to produce customised hardcopy maps and tables. It also allows interactive computer sessions and has multiple applications in management and planning. The poster depicts this approach to coastal resource mapping which has general application throughout the Great Barrier Reef and adjoining coastal areas.

'No anchoring areas' – a management strategy being applied in the Whitsundays

A joint poster by the Queensland Department of Environment, the Great Barrier Reef Marine Park Authority and the Order of Underwater Coral Heroes (OUCH)

ABSTRACT

The number of vessels operating in the Whitsundays has increased considerably in recent years. There are more private vessels, more charter vessels and more bare-boats available for charter. This means there is greater anchoring pressure around Whitsunday fringing reefs.

There are presently 566 charter vessels with Marine Park permits valid for the Whitsunday area (as at September 1996). Two hundred and eleven of these charter vessels are bare-boats. Three hundred and fifty of these charter vessels were used in 1995, of which 172 were bare-boats. There are also 1443 private vessels registered in the Proserpine (Whitsunday) area of which 274 are longer than 6 m.

Anchoring practices are not always the best. Visitors to the area can have minimal boating experience or lack experience in a coral reef environment. In addition some boat owners or operators do not show due care when anchoring.

Anchor damage to corals is already obvious in some high-use bays. In other bays a precautionary approach is needed to ensure the potential for similar reef degradation is reduced. This is of increasing importance as human use increases.

The fringing reefs in a number of high-use bays have been surveyed by the OUCH (Order of Underwater Coral Heroes) Volunteers. This mapping has been carried out in conjunction with the Department of Environment and the Great Barrier Reef Marine Park Authority. These maps have then been used to optimise the positioning of Reef Protection Markers. Monitoring of bays with 'no anchoring areas' has also commenced.

'Reef Protection Markers' are white pyramid shaped buoys, identified by blue Marine Parks stickers. 'Reef Protection Markers' delineate the seaward boundary of a 'no anchoring area'.

Eight bays presently have 'Reef Protection Markers' installed with more bays proposed. Most vessels appear to be complying with these 'no-anchoring areas', however there are always a few exceptions.

There are a number of costs associated with this 'no-anchoring' strategy. These costs include initial surveys, installation of markers and public moorings, and ongoing maintenance and monitoring. The OUCH Volunteers have put in considerable time and effort, reducing these costs.

As with every management strategy, considerable public consultation has been required to ensure the effort will have long-term value and ongoing public support. 'No-anchor areas' are a practical solution for reducing reef degradation and are an example of successful joint cooperation between a community group and management agencies.

The primary goal of the Great Barrier Reef Marine Park Authority is to protect the natural values of the Marine Park

J Phillips
Great Barrier Reef Marine Park Authority, PO Box 1379, Townsville Qld 4810

ABSTRACT

The principal components of a conservation strategy which are necessary to achieve the vision are:a system of strictly protected ecologically representative areas

- protection of threatened species and communities
- protection of significant local or site-specific conservation values
- control of threatening processes
- ecologically sustainable use

In 1996–97 the major focus of the conservation program is on threatened species and representative areas. The control of threatening processes is specifically addressed in separate programs such as Fishing, Water Quality (including the downstream effects of catchment use), Coastal Development and ports, Shipping and Oil spills, and Tourism and Recreation.

In 1996–97 the major focus of the conservation program is on threatened species and representative areas. The Authority is undertaking a review of the adequacy of the present system of strictly protected zones in the Great Barrier Reef Marine Park. A structured program is being developed jointly with stakeholders, scientists and managers with the aim of achieving long-term protection of an adequate and representative proportion of habitat types and biological communities of the Great Barrier Reef.

The threatened species and communities program is focused on vertebrate species at present. Priority has currently been given to protection of dugong, marine turtles, and seabirds.

Marine harvest refugia as a tool for inshore fish population enhancement – some examples from Australia and elsewhere

DA Pollard
New South Wales Fisheries Research Institute, PO Box 21, Cronulla NSW 2230

ABSTRACT

In summarising and discussing the biological and ecological principles behind the concept of marine harvest refugia, this poster suggests that serious consideration must be given to the proposition that the only long-term solution to the problem of sustainable inshore fisheries management may lie in the total protection from consumptive exploitation of relatively large areas of the inshore marine environment and its living resources. The establishment of such extensive 'marine harvest refugia' coupled with the use where necessary of more conventional but less holistic fisheries management measures in surrounding exploited areas, should help to replenish the fishable stocks in these latter areas through protection of adult spawning stocks and of juvenile fish in their nursery habitats. Apart from providing continuous recruitment of potentially harvestable resources to these surrounding fished areas, such harvest refugia would also be available for a wide variety of other generally non-consumptive (e.g. recreational, educational, scientific and aesthetic) uses, with existing conflicts between resource production potential and these more passive uses being greatly reduced.

Recognising Indigenous interests in the Great Barrier Reef World Heritage Area

D Saylor, L Sommer and G Smith
Great Barrier Reef Marine Park Authority, PO Box 1379, Townsville Qld 4810

ABSTRACT

Aboriginal and Torres Strait people have a long association with the Great Barrier Reef. Today, Aboriginal and Torres Strait people reside in urban centres, rural areas and remote communities along the coast adjacent to the Great Barrier Reef. Both groups of people maintain a continuing relationship with the marine environment and see the marine area as an integral part of their identity. Use of marine resources is regarded as essential to and inextricable from their lifestyles and culture. People possess a duty of care for the marine environment, and hold aspirations for continued economic benefit from the marine environment.

Interests and aspirations of Aboriginal and Torres Strait Islander people in the Great Barrier Reef World Heritage Area are wide-ranging and deal with every aspect of management and use of the Area. Indigenous interests fall into four main areas: cultural connections, lifestyles and economy, natural and cultural resource management, and information and research.

The Great Barrier Reef Marine Park Authority has a demonstrated a commitment to the recognition of Aboriginal and Torres Strait peoples' interests in the Great Barrier Reef World Heritage Area. A number of projects are being undertaken throughout the Great Barrier Reef World Heritage Area to involve Aboriginal and Torres Strait people in management of the area. Initiatives include training programs for Community Rangers at Yarrabah, Palm Island and Cape York communities; development of management strategies in Cape York, protection of culture and heritage values of indigenous people throughout the World Heritage Area and agreements on the conservation of endangered species.

Do scraping, tissue and breakage injuries have the same impact? A case study for two scleractinian corals, *Acropora hyacinthus* and *Montipora tuberculosa*

V Hall

Department of Marine Biology, James Cook University of North Queensland Qld 4811

ABSTRACT

Corals are frequently injured by natural processes and human activities. Three common injury types are generated by these processes and include tissue removal, scraping injuries and breakage. The aim of this study was to determine if the impact of these common injury types was similar. Injuries were artificially reproduced onto colonies of *Acropora hyacinthus* and *Montipora tuberculosa* and their regeneration monitored. Recovery was similar for both species over 12 days while there was a five-fold difference in the amount of regeneration recorded between treatments. Recovery was greatest for the scraping injury, intermediate for breakage, and low for tissue removal. Regeneration of the different injury types was gradual and involved several developmental stages, the composition of which was recorded 12 and 24 days after injury. Generally, the regenerated area of the wound consisted mainly of undifferentiated tissue and skeleton after 12 days, with the development of polyps increasing markedly by 24 days. The amount of recovery increased with time. Unregenerated areas of the injury were colonised by algae. Algal cover was high for the tissue injury, low to intermediate for the scraping injury, and very low for the breakage injury. The results of this study are important for reef management since different types of damage can be linked to particular human activities.

Developing a reliable coral reef monitoring program for use by community groups, tourist operators and visitors on the Great Barrier Reef

BM Musso and G Inglis
Department of Tropical Environment Studies and Geography and CRC Reef Research Centre, James Cook University of North Queensland Qld 4811

ABSTRACT

Public involvement in environmental monitoring is becoming a key element of many management programs throughout Australia, in both terrestrial and marine/coastal environments. Participation of community groups and industry offers a chance to expand the resources available for monitoring and provides an effective way to increase public awareness and stewardship. Criticism has been raised about such programs on the basis of low reliability of the data collected by non-professional personnel. However, careful planning, rigorous testing of the techniques used by non-professionals and quality control procedures may minimise these problems and ensure the validity of the program.

A 12-month pilot project was initiated to investigate the feasibility and data quality of volunteer-based coral reef monitoring programs. A low-cost and user-friendly protocol for monitoring coral assemblages is trialed in the field with a number of volunteer organisations. The aim is to assess the relative accuracy of volunteer-derived data and the consistency of identification of reef organisms among non-professionals. Preliminary results show that dive experience is important in determining inter-observer variability, with data collected by divers with 30 or less hours having a significantly larger spread than data collected by divers with over 100 hours experience. Furthermore, non-professionals tend to over-estimate total coral cover when compared to scientists and some lifeform categories used in the monitoring are consistently erroneously identified by volunteers. Additional objectives currently being addressed include a comparison of the precision of a range of methods used to monitor coral assemblages when used by scientists and volunteers, and the effect of different levels of training on the quality of volunteer-derived data.

Major outcomes of this study include the development of minimum standards for volunteer-based monitoring on coral reefs. The long-term objective is the establishment of a network of volunteer organisations (including tourist operators, dive clubs and community groups) which will adopt standardised field techniques, data management and quality control procedures to monitor the reefs they visit regularly.

Impacts of tourist pontoons on the Great Barrier Reef

V Nelson[1] *and B Mapstone*[2]
[1] *LeProvost, Dames and Moore, PO Box 251, Spring Hill Qld 4004*
[2] *CRC Reef Research Centre, James Cook University of North Queensland Qld 4811*

ABSTRACT

Tourism has become the most important economic activity in the Great Barrier Reef Marine Park over the past decade. Moored pontoons have become a common base from which to 'show off' the Great Barrier Reef to tourists, providing activities such as snorkelling, SCUBA diving, fishing (in some cases), glass-bottom boat and semi-submersible tours and fish feeding. This poster presents a synthesis of the ecological impacts of the pontoon itself and the effects of snorkelling, diving and fish feeding activities associated with pontoons. At early pontoon installations there were large decreases in coral cover underneath the structure, but more recent pontoons have been moored over sand, avoiding any impacts on coral. The impacts of snorkelling and diving varied greatly among pontoons, with coral cover decreasing relative to controls at some pontoons and increasing at others. Damage to corals was greater at snorkelling and dive sites than at controls in programmes where damage was quantified. The long-term ecological consequences of chronic damage to coral colonies are not known, but may include reductions in fecundity, survival and growth. Fish aggregations varied in size and composition among pontoons but appeared to have no impact on local fish populations or cause depletions in populations elsewhere. These results must be interpreted cautiously, however, because of the variable quality of pontoon monitoring programmes. Nevertheless, pontoons appear to have a relatively benign effect on benthic and fish assemblages on the Great Barrier Reef while providing tourists an unparalleled opportunity to view and learn about the reef.

The Cod Hole: potato cod numbers decreasing

LL Vail and AK Hoggett
Lizard Island Research Station, PMB 37, Cairns Qld 4870

ABSTRACT

The Cod Hole is an internationally famous recreational dive site on the Great Barrier Reef (14°40'S, 145°40'E). The main attraction of this small area is the numerous large potato cod (*Epinephelus tukulas* Morgans) which allow divers to approach closely. Over four years (April 1992 to April 1996), data have been collected by divemasters on the Lizard Island Charters dive vessel *Volare* during their frequent visits to the site: levels of human usage, number of potato cod and other large fishes present, and any injuries observed on the large fish. Observations have been made on 392 occasions.

Data collected in this way do not estimate total human usage accurately because regular commercial operators can and do arrange their schedules to minimise crowding at the site. However, the data on fish numbers do provide a good estimate of the number of cod available to be seen by a diver and it is this statistic, to a large extent, that measures the tourism value of the site. Mean and maximum numbers of cod seen per visit are now about half that of four years ago. Anecdotal and other historical data show a strong negative correlation between numbers of potato cod at the Cod Hole with human abuse of the fish. The drop in numbers revealed by this survey is a cause for concern.

Patterns of skeleton formation in coral recruits: can species be identified?

AH Baird
Department of Marine Biology, James Cook University of North Queensland Qld 4811

ABSTRACT

Patterns of reef connectivity are often inferred from patterns of coral recruitment to artificial substratum. However, the generality of recruitment studies is limited by problems in identifying coral recruits, with most authors unwilling to identify recruits beyond the family level. In this study, patterns of skeletogenisis of juveniles of the two brooding pocilloporids, *Seriatopora hystrix* and *Stylophora pistillata* were compared to determine whether the spat of these species could be reliably separated. Cohorts of larvae were collected from adults of each species in the laboratory, settled out then subsampled at periods of 1, 2, 4 and 8 weeks. Spat were examined under light and scanning electron microscope to compare the morphology of the skeleton. While differences in the ultrastructure of the skeleton of these species were present, these differences are not readily apparent under light microscope. Consequently the taxonomic resolution claimed in many studies of coral recruitment appears unjustified.

Ecology of *Drupella* at Heron and Wistari reefs

I Fellegara
Zoology Department, The University of Queensland Qld 4072

ABSTRACT

Drupella have been reported to have caused large coral damage during outbreaks. During this study, *Drupella* population was surveyed over a two-year period; during which time it was low and stable. *Drupella rugosa* was the most abundant species followed by *D. cornus*, *D. eburnea* and *D. fragum*. They preferred different habitats; however, they were often found coexisting on the same coral colony. Juvenile *D. rugosa* and *D. eburnea* were often found coexisting with adults too. Adult and juvenile of all *Drupella* species fed preferably on *Acropora* species; whereas *D. cornus* had a wider range of coral preferences feeding both on *Acropora* and *Montipora*. Multiple-choice feeding experiments confirmed the differences in food selection among *Drupella* species. Feeding-aggregation experiments showed that *D. rugosa* tended to aggregate more than *D. cornus*. These results suggest that the presence of different coral species and the feeding behaviour of *Drupella* may be important factors involved in the numeric explosions of different *Drupella* species in different areas.

Chronic damage to corals from fish: corallivory by chaetodontids

MS Pratchett
Department of Marine Biology, James Cook University of North Queensland Qld 4811

ABSTRACT

Scleractinian corals constitute the primary food source of most butterflyfish. Grazing on coral by chaetodontids is likely to be energetically costly, and affect coral growth, reproduction and longevity. Similarly, selective feeding is likely to influence community dynamics. Butterflyfish on the northern Great Barrier Reef spent more than 75% of their active time feeding. Feeding rates were significantly different between butterflyfish species. *Chaetodon baronessa* had the highest feeding rate (696 bites per hour) and *C. vagabundus* had the lowest (316 bites per hour). All butterflyfish were selective in their diet, but the primary prey differed between species. *Chaetodon baronessa* and *C. trifascialis* feed almost exclusively (> 80%) on *Acropora hyacinthus*. *Chaetodon plebius* fed mainly on *Pocillopora damicornis*, while *C. auriga* and *C. vagabundus* consumed non-coral prey. Overall, feeding pressures from butterflyfish were greatest on the competitively dominant coral *Acropora hyacinthus*. Butterflyfish may thereby limit *A. hyacinthus* from monopolising tropical shallow reefs and maintain a more diverse coral assemblage of less competitive species.

Interspecific variation in dispersal of the pelagic stages of reef fishes: will general models of reef connectivity be unrealistic?

IC Stobutzki
Department of Marine Biology, James Cook University of North Queensland Qld 4811

ABSTRACT

The active control of dispersal by the pelagic stages of reef fishes is possible by directional swimming. It has been previously demonstrated that swimming abilities vary greatly among families, which will influence the degree of control they can exert over their dispersal. Here the variation in sustained swimming ability between species was examined, within two reef fish families (Chaetodontidae and Pomacentridae). This will be integral in explaining differences in their ecology and demography. Both families showed a wide range in swimming abilities, within the pomacentrids average distances covered by species ranged from 22.74 km to 49.33 km, while in the chaetodontids distances ranged from 45.67 km to 92.55 km. Differences in swimming ability were related to size and pelagic larval duration within the Pomacentridae, but not within the Chaetodontidae. The results suggest that these within family differences will influence the relative importance of passive versus active dispersal. For less competent swimmers the degree of connectivity between reefs is more likely to be determined by current patterns, while other species may be able to override these. This highlights the need to look directly at the abilities of individual species, as general models of dispersal are unlikely to be realistic.

Annual changes in coral cover over a broad geographic scale on the Great Barrier Reef

HPA Sweatman and R Ninio
Australian Institute of Marine Science, PMB No. 3, Townsville MC Qld 4810

ABSTRACT

The long-term monitoring program of the Australian Institute of Marine Science has the aim of detecting changes in reef biota and so providing a context for assessing human and other impacts. Data are collected on reef fishes, sessile benthos, *Acanthaster planci* and dissolved nutrients in annual sampling from 54 reefs which have been surveyed for the last 2–4 years. Sampling is distributed at several spatial scales: the reefs were chosen from six latitudinal sectors and a range of position across the continental shelf. In this program, sessile benthic organisms are sampled using underwater video on fixed 50 m transects at three sites within each reef.

Per cent hard coral cover is a commonly used index of reef condition. Annual estimates of hard coral cover varied by as much as 20% at individual sites (5 x 50 m transects), reflecting in part sampling error associated with precise relocation of the transects. In the absence of disturbance, coral cover should increase through recruitment and colony growth. When reefs that were known to support high densities of *A. planci* and where coral cover consequently declined, were excluded, the average annual increase in coral cover at a reef level was about 3%. There was no simple relationship between existing coral cover and subsequent increases.

Recruitment in reef fishes of commercial significance: implications for reef connectivity and population management on the Great Barrier Reef

GG Wilson

Department of Marine Biology, James Cook University of North Queensland Qld 4811

ABSTRACT

Emperor (*Lethrinus*) and snapper (*Lutjanus*) species attract substantial management interest as fisheries targets within the Great Barrier Reef Marine Park, yet details of their population replenishment remain poorly documented. Spatio-temporal patterns of recruitment, and subsequent growth, were examined in an assemblage of these species at Green Island, central Great Barrier Reef. Population replenishment was indicated as a biphasic process, whereby 'post-larval' recruitment to nursery areas precedes dispersal to 'adult' habitats at 80–100 mm SL. *Lethrinus* recruitment was characterised by a strict association with seagrasses (nine species), with protracted recruitment seasons and comparatively high densities in 'common' species. By contrast, *Lutjanus* recruits displayed a greater diversity of habitat preferences (seagrass, two species; open soft-sediments, one species; both habitats, one species), narrower recruitment seasons, and low recruit-densities. Analyses of microhabitat associations within nursery areas indicated a *Lethrinus* attraction towards the seagrass canopy *per se*, while *Lutjanus* recruits relied upon small, non-vegetative structures for diurnal shelter. Age-at-size information (*Lethrinus genivittatus, L. harak, L. xanthochilus*; *Lutjanus fulviflamma*), and above observations of dispersal-size, suggests a seagrass/sand residency as brief as 3–5 months for *Lethrinus* species and 3–4 months for *Lutjanus fulviflamma.*

In concert, these data are consistent with a model of rapid progression through the juvenile period in both genera. For species such as *Lethrinus*, the paucity of shallow seagrass beds at regional scales along the Great Barrier Reef suggests that single, isolated reefs are critical to regional population replenishment. Specifically, this implies substantial connectivity between 'nursery' and nearby reefs.

Movements of the common coral trout, *Plectropomus leopardus* (Serranidae), in relation to spawning aggregations

DC Zeller
Department of Marine Biology, James Cook University of North Queensland Qld 4811

ABSTRACT

Using ultrasonic telemetry, this project investigated movement patterns of the common coral trout *Plectropomus leopardus* in relation to annual spawning aggregation events. The main objectives were to locate spawning aggregation sites around Lizard Island (northern Great Barrier Reef) and determine movement patterns of *P. leopardus* during the spawning period. Individual coral trout were tracked for periods of two weeks to six months during 1993–1995. Four spawning aggregation sites were identified and monitored during this period. Thirty-one per cent of all transmitter equipped fish participated in one or more spawning events. Distances moved by individual fish to aggregation sites ranged from hundreds of meters to over five kilometres. Residency at the aggregation sites varied, ranging from single night attendance, or repeated daily return movements, to long-term occupancy. While generally sedentary with established and stable home ranges, individual coral trout do move considerable distances to participate at spawning aggregations. These findings have implications for the proposed use of Marine Protected Areas as a fisheries management tool, particularly in developing nations with high fishing pressures.

Education or enforcement – the better deal?

J Alder
Department of Environmental Management, Edith Cowan University, Joondalup WA 6027

ABSTRACT

Education and enforcement are two tools which marine protected area managers have at their disposal to effect legislative requirements and management objectives. The implementation of these two tools, however, is fundamentally different. Enforcement uses the threat of financial costs, loss of access to the resource and public discredit. Education on the other hand attempts to change user behaviours through increased awareness and understanding of the need to comply with management regimes. The cost and effectiveness of these two approaches were investigated for the Cairns Section of the Great Barrier Reef Marine Park between 1986 and 1992.

Both tools were found to be effective. The costs of education and awareness per person contacted were approximately one tenth the cost of enforcement; but the annual overall costs of education programs was often twice that of enforcement. Alone, neither program can meet management objectives, and in fact, these tools interact with the other range of management activities. Together, they do have the potential to be effective tools in marine protected areas.

Aboriginal marine ranger training program

I Kerr
Department of Environment, Port Douglas Qld 4871

ABSTRACT

Development of program
Developed by the Department of Environment, Low Isles Preservation Society, Bamanga Bubu Ngadimunku Corporation and Mona Mona Aboriginal Corporation, the Program was designed to train Aboriginal people to work as Marine Park Rangers in their sea country.

The trainees obtain their position through an interview process and the two successful applicants are employed by their communities as Community Rangers on the Community Development Employment Program (CDEP) with additional funding provided by the Australian Nature Conservation Agency. The trainees wear Departmental uniforms and work on Departmental programs in day to day management of the Marine Park.

The major strategy of the program is for the trainees to learn from an experienced Marine Park Ranger under a mentor system. Assessment is based on a skills matrix which has been designed for training of marine rangers within the Department of Environment. Trainees are required to complete specialised licences and are encouraged to enrol in tertiary education.

Daily work program
Day-to-day management duties are used as on-the-job work experience as they learn skills in areas such as:

- natural and cultural resource management
- weather recording
- public contact and enforcement
- interpretation
- infrastructure maintenance/construction
- vessel operation
- workplace health and safety
- administration
- communication and education.

These skills may be passed on to the communities and in return cross-cultural relations are increased and Marine Parks can keep in touch with the cultural and spiritual beliefs of the area in making management decisions.

Past and present trainees
The 1995–96 financial year saw the first two trainees of the program compete for and successfully obtain full-time positions within the Department after completing one year of training. Brandon Walker and Brian Singelton secured Marine Ranger positions at Northern Beaches and Green Island respectively. The two new trainees are Clayton Enoch with the Djabugay Ranger Agency and Line Walker with the Bamanga Bubu Ngadimunku Corporation. These trainees began in March of 1996 and to date have successfully completed formal training in the Reef Naturalists Course, Radio Operators Course, Mooring Maintenance Course, Certificate in Shipboard Safety and Coxswains Ticket. Both also represented the Department and their Communities by attending the Coastal Management Conference which was held in Adelaide in April.

Too much planning and research: not enough action? The role of community groups in coastal conservation in north Queensland

A Reynolds
Marine and Coastal Community Network, PO Box 364, Townsville Qld 4810

ABSTRACT

The rapid population growth and associated development in north Queensland has resulted in a plethora of coastal plans, policies, laws, education programs, voluntary codes of practice and the like. Despite the development and implementation of some of these coastal management initiatives, degradation of the coastal zone continues. There are over 200 proposed large-scale coastal developments in north Queensland.

Consequently, community groups increasingly demand to be involved in coastal planning and research. The more they become involved, the more they see planning and research as resulting in managers being kept busy and not making decisions to protect the environment. The more they become involved, the more they realise that communities are essentially powerless and used to ratify decisions taken at a management level. There are numerous cases to support this view; reflecting management and legal frameworks that favour developers and developments over community concerns and environmental protection.

Questions raised by the community in their quest to protect the coast include: How much research is enough research? Is there ever enough? Are the research results useful for management and do they enable agencies to take direct action? What are the triggers for action? When will management agencies adopt a precautionary approach to management? How useful is planning when coastal developments are approved regardless of planning processes? How useful is community involvement in the process? How can the cumulative impacts of rapid development be ecologically sustainable? How and when can a representative system of protected areas by established alongside the rapid development?

The community have a valuable role to play in coastal management through highlighting problems, advocating solutions and steering social change.

APPENDIX

Delegates to The Great Barrier Reef: Science, Use and Management Conference

Name	Affiliation
Ms Melanie Abela	Pure Pleasure Cruises, Townsville, Qld
Dr Achmed Abdullah	PHPA, Indonesia
Ms Tania Adami	GBRMPA, Townsville, Qld
Ms Robin Aiello	Great Adventures, Cairns, Qld
Dr Al Susanto	Bakosurtanal, Indonesia
Ir Alam Syah Mapparessa	BAPEDAL, Indonesia
Mr Don Alcock	CRC Reef Research Centre, Townsville, Qld
Dr Jackie Alder	Dept of Environmental Management, Edith Cowan University WA
Dr Dan Alongi	AIMS, Townsville, Qld
Mr Ken Anthony	Dept of Marine Biology, James Cook University, Qld
Mr Naniel Aragones	TESAG, James Cook University, Qld
Dr Aris Poniman	Bakosurtanal, Indonesia
Dr Peter Arnold	Museum of Tropical Queensland,Townsville, Qld
Ir Augustenno Siburian	BAPPEDA Tk. I. NTB, Indonesia
Ms Jenny Baer	GBRMPA, Townsville, Qld
Mr Andrew Baird	Dept of Marine Biology, James Cook University, Qld
Ms Briony Barnett	Queensland Dept of Environment, Townsville, Qld
Mr Keith Bashford	CSIRO Marine Labs., Hobart
Ms Dominique Benzaken	GBRMPA, Townsville, Qld
Dr John Benzie	AIMS, Townsville, Qld
Dr Penny Berents	Australian Museum, Sydney
Ms Mikaela Bergenuis	James Cook University, Qld 4811
Mr Ray Berkelmans	GBRMPA, Townsville, Qld
Beny Bestawan	BAPEDAL, Indonesia
Dr Alistair Birtles	Dept of Tourism, James Cook University, Qld
Mr Steve Blake	ERIN, Dept of Environment Sport and Territories, Canberra, ACT
Dr Lance Bode	Dept of Maths, James Cook University, Qld
Dr Rob Bramley	CSIRO Soils, Davies Laboratory, Townsville, Qld
Mr Andrew Broadbent	Dept of Chemistry, James Cook University, Qld
Mr Jon Brodie	GBRMPA, Townsville, Qld
Mr Danny Brooks	GBRMPA, Townsville, Qld
Mr Ross Brown	Queensland Dept of Environment, Cairns, Qld
Mr Ron Brown	Lane Cove, NSW
Dr Gregg Brunskill	AIMS, Townsville, Qld
Ir Budi Emawan	DG BANGDA, Indonesia
Cr Ann Bunnell	Townsville City Council, Townsville, Qld
Mr Mark Burnham	Qld Dept of Environment Northern Region, Townsville, Qld
Mr Butarbutar	DG BANGDA, Indonesia
Ms Tamsen Byfield	Dept of Marine Biology, James Cook University, Qld
Ms Patricia Carvalho	Mawson Graduate Centre, Adelaide University SA
Mr Colin Chalmers	Fisheries Dept of WA, Perth, WA
Mr Andrew Chin	University of Central Queensland, Rockhampton, Qld
Ms Sandy Clague	Queensland Dept of Environment, Cairns, Qld
Mr Grant Clifford	Capricorn Barge Co., Fortitude Valley, Qld
Mr Malcolm Cole	AAP, Brisbane, Qld
Dr Rob Coles	Qld DPI, Northern Fisheries Centre, Cairns, Qld
Mr Tro Collie	Qld Dept of Environment Northern Region, Townsville, Qld
Mr Phillip Cosser	Queensland Dept of Environment, Brisbane, Qld
Ms Elizabeth Cotterell	Dept of Zoology, University of Queensland, Brisbane,Qld
Ms Linda Craig	Queensland Dept of Environment, Cairns, Qld
Mr Nick Crosbie	AIMS, Townsville, Qld
Prof. Chris Crossland	CRC Reef Research Centre, Townsville, Qld

Prof. Peter Cullen	CRC Freshwater Ecology, Canberra ACT
Mr Rob Curtis	Qld Dept of Environment Northern Region, Townsville, Qld
Ir Dadang Kadarisman	PPGL/MGI, Indonesia
Mr Andy Darbyshire	Ningaloo Marine Park, Dept of Conservation & Land Management,WA
Mr Johnston Davidson	TESAG, James Cook University, Qld
Dr Campbell Davies	CRC Reef Research Centre,Townsville, Qld
Mr Jon Day	Qld Dept of Environment,Townsville, Qld
Dr Lyndon De Vantier	AIMS, Townsville, Qld
Mr Deddy Koespramoendyo	BAPPENAS, Indonesia
Dr Deddy Setiapermana	P30-LIPI, Indonesia
Cmdr Jon Delaney	Australian Defence Force Academy, Canberra, ACT
Dr Bill Dennison	Dept of Botany, University of Queensland, St Lucia Qld
Ir Denny Irawan Saardi	BAPPEDA Tk. I. SULSEL, Indonesia
Dr Zena Dinesen	GBRMPA, Townsville, Qld
Dr Peter Doherty	AIMS, Townsville, Qld
Ms Michaela Dommisse	AIMS, Townsville, Qld
Dr Terry Done	AIMS, Townsville, Qld
Ms Sally Driml	Kinhill Economics, Brisbane, Qld
Mr Peter Driscoll	Abrolhos Islands Management Advisory Committee, Dept of Fisheries, WA
Mr Andy Dunstan	Undersea Explorer, Port Douglas, Qld
Ir Edison Siaglan	DG BANGDA, Indonesia
Ms Melinda Edwards	Reef Tourism 2005, Cairns, Qld
Dr Joanna Ellison	AIMS, Townsville, Qld
Mr Mark Elmer	QFMA, Fortitude Valley, Qld
Mr Udo Engelhardt	GBRMPA, Townsville, Qld
Dr Katharina Fabricius	AIMS, Townsville, Qld
Mrs Ida Fellegara	Dept of Zoology, University of Queensland, Brisbane, Qld
Dr Leanne Fernandes	TESAG/CRC Reef, James Cook University, Qld
Mr David Fisk	Reef Research & Information Services, Lismore, NSW
Dr MilesFurnas	AIMS, Townsville, Qld
Dr Mike Gagan	Research School of Earth Sciences, ANU, Canberra, ACT
Ms Sue Gardiner	Qld Dept of Environment Northern Region, Townsville, Qld
Mr Gert Jan Gast	Netherlands Institute of Sea Research, The Netherlands
Ms Siriol Giffney	CRC Reef Research Centre, Townsville, Qld
Ms Maree Gilbert	GBRMPA, Townsville, Qld
Ms Stephanie Golden	Queensland Dept of Environment, Cairns, Qld
Dr Michael Gourlay	Dept of Engineering, University of Queensland, Brisbane, Qld
Mr Ed Green	Reef Tourism 2005, Cairns, Qld
Mrs Joan Greenwood	Dept of Zoology, University of Queensland, St Lucia, Qld
Mr Eric Gustavson	Qld Dept of Environment Northern Region, Townsville, Qld
Ms Meredith Hall	Qld Dept of Environment Northern Region, Townsville, Qld
Miss Vicki Hall	Dept of Marine Biology, James Cook University, Qld
Dr Hari Nur Cahehe Murni	DG BANGDA, Indonesia
Dr Vicki Harriott	Southern Cross University, Lismore, NSW
Mr Mick Hartcher	GBRMPA, Townsville, Qld
Mr David Haynes	GBRMPA, Townsville, Qld
Ir Hendrian	BAPPEDA Tk. I. SUMSEL, Indonesia
Mr John Hicks	Qld Dept of Environment Northern Region, Townsville, Qld
Ir Heri Sadmono	BPPT, Indonesia
Dr Robert Hilliard	Le Provost Dames and Moore, Spring Hill, Qld
Dr Bruce Hodgson	Ecologist, Centre for Marine Studies, UNSW, Sydney
Mrs Tamiko Hodgson	Wahroonga, NSW
Dr Ove Hoegh-Guldberg	School of Biological Sciences, University of Sydney, NSW
Miss Edwina Hollander	Dept of Marine Biology, James Cook University, Qld
Prof. David Hopley	Sir George Fisher Centre, James Cook University, Qld
Ms Deirdre Howard	Dept of Environment, Sport & Territories, Canberra, ACT
Dr Terry Hughes	Dept of Marine Biology, James Cook University, Qld
Dr Kees Hulsman	Griffith University, Nathan, Qld
Prof Tor Hundloe	University of Queensland, St Lucia, Qld
Mr Rob Hunt	Herbert River Catchment Group, Ingham, Qld
Dr Pat Hutchings	Australian Museum, Sydney NSW
Dr Ir I Gde Sedana Murthe	Balitbang Perikanan, Indonesia

Mr James Innes	GBRMPA, Townsville, Qld
Mr Irwandi Idris	DG BANGDA, Indonesia
Dr Peter Isdale	AIMS, Townsville, Qld
Mr Artie Jacobsen	Qld Dept of Environment Northern Region, Townsville, Qld
Jalaludin SH	BAPPEDA Tk. I JATIM, Indonesia
Dr Maurice James	Dept of Civil & Systems Engineeering, James Cook University, Qld
Ms Olivia Jenkins	Dept of Tourism, Small Business & Industry, Brisbane, Qld
Ms Gayle Jennings	University of Central Qld, Rockhampton Qld
Dr Andrew Johnson	CSIRO Davies Lab, Townsville, Qld
Dr David Johnson	Dept of Earth Sciences, James Cook University, Qld
Mr Brad Jones	Qld Dept of Environment Northern Region, Townsville, Qld
Dr Geoff Jones	Dept of Marine Biology, James Cook University, Qld
Mr Will Jones	International Year of the Reef, University of Sydney, NSW
Ir Julius AN Maskarit	PSL UNPATI, Indonesia
Mr Ross Kapitzke	Dept of Civil & Systems Engineering, James Cook University, Qld
Mr Geoff Kelly	Dept of Environment, Cairns, Qld
Ms Louise Kelly	Dept of Agriculture and Resource Management, University of Melbourne, Vic
Ms Michelle Kelly	Dept of Commerce, James Cook University
Mr Richard Kenchington	GBRMPA, Townsville, Qld
Mr Ian Kerr	Queensland Dept of Environment, Cairns, Qld
Mr Edward Kim	Dept of Tourism, James Cook University, Qld
Dr Brian King	AIMS, Townsville, Qld
Dr Michael Kingsford	School of Biological Sciences, University of Sydney
Ms Selma Klanter	James Cook University, Qld
Mr Gordon La Praik	Queensland Dept of Environment, Cairns, Qld
Mr Norm Land	Qld Dept of Environment Northern Region, Townsville, Qld
Prof Bob Lawn	CRC for Sustainable Sugar Production, Townsville, Qld
Ms Stephanie Lemm	Qld Dept of Environment Northern Region, Townsville, Qld
Mr Warren Lee Long	Queensland DPI, Northern Fisheries Centre, Cairns, Qld
Mr Bill Leggat	Dept of Biochemistry, James Cook University, Qld
Dr Adam Lewis	TESAG, James Cook University, Qld
Dr Charles Lewis	Environment Protection Agency, Barton, ACT
Ms Heather Lloyd	Qld Dept of Environment Northern Region, Townsville, Qld
Mr Kenneth Lim	Dept of Marine Biology, James Cook University, Qld
Mr Brian Long	CSIRO Marine Laboratories, Cleveland, Qld
Dr Janice Lough	AIMS, Townsville, Qld
Prof. Ian Lowe	School of Science, Griffith University, Nathan Qld
Ir Made Sudiarsa	BAPPEDA Tk. I BALI, Indonesia
Mr Hamish Malcolm	Qld Dept of Environment Northern Region, Townsville, Qld
Dr Bruce Mapstone	CRC Reef Research Centre, Townsville, Qld
Prof Helene Marsh	TESAG, James Cook University, Qld
Mr Paul Marshall	CRC Reef Research Centre, Townsville, Qld
Ms Stella Martin	Queensland Dept of Environment, Cairns, Qld
Dr Stan Massel	AIMS, Townsville, Qld
Mr Maurice Mathews	Qld Dept of Environment Northern Region, Townsville, Qld
Mr Neil Mattocks	Qld Dept of Environment Northern Region, Townsville, Qld
Mr Peter Mc Ginnity	GBRMPA, Townsville, Qld
Dr Laurence McCook	AIMS, Townsville, Qld
Dr David McDonald	CSIRO Marine Labs, Hobart, Tas
Mr Bruce McDougall	Currumbin Sand & Gravel, Currumbin, Qld
Dr Ian McPhail	GBRMPA, Townsville, Qld
Dr Mark Meekan	AIMS, Townsville, Qld
Ms Jane Mellors	Hermit Park, Qld
Mr Alan Mitchell	AIMS, Townsville, Qld
Dr Peter Moran	AIMS, Townsville, Qld
Dr Gianna Moscardo	Dept of Tourism, James Cook University, Qld
Mr Andrew Moss	Dept of Environment, Brisbane, Qld
Ir Muchtar Salam Solle	PSL UNHAS, Indonesia
Ir Muhammed Zulfan	BAPPEDA Tk. I. KALTIM, Indonesia
Ms Wendy Murray	Cocos (Keeling) Islands, Indian Ocean
Ms Barbara Musso	TESAG/CRC Reef Research Centre, James Cook University, Qld
Mr David Neil	Dept of Geographical Sciences, University of Queensland, St Lucia,Qld

Dr Vicki Nelson	LeProvost Dames and Moore, Spring Hill, Qld
Mr Tim Norman	The Australian Museum, Sydney, NSW
Ir Nurlian Tomboelu	BAPPEDA Tk. I. SULUT, Indonesia
Mr Paul O'Neill	Queensland Dept of Environment, Rockhampton, Qld
Dr Peter O'Reagain	Qld DPI, Charters Towers, Qld
Ir Oktavianus Ndun	BAPPEDA Tk. I. IRJA, Indonesia
Mr John Olds	Queensland Dept of Environment, Rockhampton, Qld
Dr Jamie Oliver	GBRMPA, Townsville, Qld
Ms Jane Orr	Qld Dept of Environment Northern Region, Townsville, Qld
Mr Will Oxley	AIMS, Townsville, Qld
Cmdr Chris Oyston	Royal Australian Navy, Canberra, ACT
Mr Francis Pantus	GBRMPA, Townsville, Qld
Mr Bruce Parker	AIMS, Townsville, Qld
Mr Alex Peachey	Dept of Economics, James Cook University
Prof. Philip Pearce	Dept of Tourism, James Cook University, Qld
Mr Andrew Petroeschevsky	Herbert River Catchment Group, Ingham, Qld
Ir Petrus Bungaama Kleden	PSL UNDANA, Indonesia
Ms Joan Phillips	GBRMPA, Townsville, Qld
Ms Srisakul Piromvaragoru	Dept of Marine Biology, James Cook University, Qld
Dr Roland Pitcher	CSIRO Division of Marine Research, Cleveland, Qld
Ms Joanna Pitt	Dept of Marine Biology, James Cook University, Qld
Dr Barrie Pittock	CSIRO Atmospheric Research, Aspendale, Vic
Mr Graham Poacher	Qld Dept of Environment Northern Region, Townsville, Qld
Dr Ian Poiner	CSIRO Division of Marine Research, Cleveland, Qld
Dr David Pollard	NSW Fisheries Research Institute, Cronulla NSW
Ms Mary Portefaix	Queensland Dept of Environment, Cairns, Qld
Mr Morgan Pratchett	Dept of Marine Biology, James Cook University, Qld
Dr Tony Preen	TESAG, James Cook University, Qld
Ms Marjetta Puotinen	AIMS, Townsville, Qld
Mr Steven Purcell	Dept of Marine Biology, James Cook University, Qld
Mr Craig Purdon	Qld Dept of Environment Northern Region, Townsville, Qld
Mr Ray Quabba	Canegrowers Herbert River, Ingham, Qld
Mr Steve Raaymakers	Qld Ports Corporation, Brisbane, Qld
Dr Cecily Rasmussen	Sir George Fisher Centre, James Cook University, Qld
Mr George Rayment	DNR & CRC Sustainable Sugar Production, Indooroopilly, Qld
Ir Reflus	BAPPEDA Tk. I. NTT, Indonesia
Dr Russell Reichelt	AIMS, Townsville, Qld
Ms JoAnn Resing	Qld DPI, Townsville, Qld
Ms Anne Reynolds	Marine & Coastal Community Network, Townsville, Qld
Ms Lisa Gay Roberts	Southern Cross University, Lismore, NSW
Mr John Robertson	GBRMPA, Townsville, Qld
Mr Chris Robson	Queensland Dept of Natural Resources, Brisbane, Qld
Ms Michelle Rodrigo	Green Island Resort, Cairns, Qld
Ir Ruddy Suwandi	PSL IPB, Indonesia
Dr Garry Russ	Dept of Marine Biology, James Cook University, Qld
Dr Denise Russell	Dept of General Philosophy, Sydney University, NSW
Mr Martin Russell	GBRMPA, Townsville, Qld
Dr Sajad Daryanto	BMG, Indonesia
Ms Melita Samoilys	DPI,Townsville, Qld
Ir Sapta Putra Ginting	DG BANGDA, Indonesia
Mr David Savage	Qld Dept of Environment Northern Region, Townsville, Qld
Ms Britta Schaffelke	AIMS, Townsville, Qld
Ms Marie-Lisa Schlappy	James Cook University, Qld
Ms Christine Schoenberg	AIMS, Townsville, Qld
Mr Richard Sellers	Fisheries Dept, Geraldton WA
Mr Peter Sesterka	Office of National Tourism, Canberra, ACT
Mr Bob Shepherd	Queensland DPI, Charters Towers, Qld
Ms Tsai Min Sin	Dept of Marine Biology, James Cook University, Qld
Ms Michelle Skuza	AIMS, Townsville, Qld
Ms Janet Slater	GBRMPA, Townsville, Qld
Mr Greg Smith	GBRMPA, Townsville, Qld
Ms Janelle Smith	GBRMPA, Townsville, Qld
Ms Katrina Spinaze	University of New England, Armidale, NSW

Ms Louise Stewart	Southern Cross University, Lismore, NSW
Ms Ilona Stobutzki	Dept of Marine Biology, James Cook University, Qld
Mr Tony Stokes	GBRMPA, Townsville, Qld
Dr Suprajaka	BAKOSURTANAL, Indonesia
Dr Hugh Sweatman	AIMS, Townsville, Qld
Ms Deborah Szekely	Qld Dept of Environment Northern Region, Townsville, Qld
Prof. Frank Talbot	Macquarie University, NSW
Mr John Tanzer	QFMA, Fortitude Valley, Qld
Ms Dianne Tarte	Australian Marine Conservation Society, Yeronga, Qld
Mr Jeremy Taylor	Dept of Molecular Science, James Cook University, Qld
Dr Tina Tentori	University of Central Queensland, Rockhampton, Qld
Mr Lindsay Trott	AIMS, Townsville, Qld
Mr Emre Turak	AIMS, Townsville, Qld
Mr Sven Uthicke	AIMS, Townsville, Qld
Dr Lyle Vail	Lizard Island Research Station, via Cairns, Qld
Mr Jason Vains	University of Central Queensland, Rockhampton, Qld
Mr Peter Valentine	TESAG, James Cook University, Qld
Dr Charlie Veron	AIMS, Townsville, Qld
Dr Paul Vogel	Dept of Environmental Protection, Perth, WA
Dr Daniel Walker	CSIRO Davies Lab, Townsville, Qld
Mr Paul Walker	CSIRO Wildlife & Ecology, Canberra, ACT
Dr Stewart Walker	AIMS, Townsville, Qld
Ms Nicole Walsh	GBRMPA, Townsville, Qld
Ms Margot Warnett	Qld Dept of Environment Northern Region, Townsville, Qld
Ir Wasgeto	BPN, Indonesia
Prof Robert Wasson	Dept of Geography, Australian National University, Canberra, ACT
Mr Trevor Webb	TESAG, James Cook University, Qld
Dr Clive Wilkinson	AIMS, Townsville, Qld
Ms Carolyn Williams	Queensland Dept of Environment, Cairns, Qld
Dr David Williams	AIMS, Townsville, Qld
Mr Glenn Wilson	Dept of Marine Biology, James Cook University, Qld
Ms Paula Wilson	Student, University of Sydney, NSW
Dr Stan Wilson	NOS NOAA, Silver Spring, MD, USA
Dr Eric Wolanski	AIMS, Townsville, Qld
Mr Chris Wood	Qld Dept of Environment, Townsville, Qld
Ms Barbara Woods	Dept of Tourism, James Cook University, Qld
AProf David Yellowlees	Dept of Molecular Science, James Cook University, Qld
Mr HidekiYukihira	Dept of Zoology, James Cook University, Qld
Mr Dirk Zeller	Dept of Marine Biology, James Cook University

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