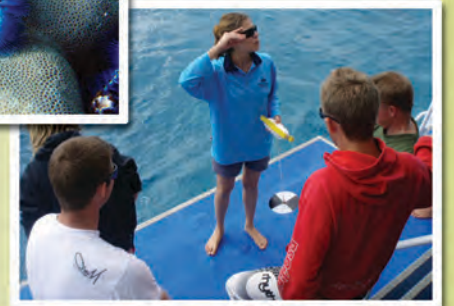
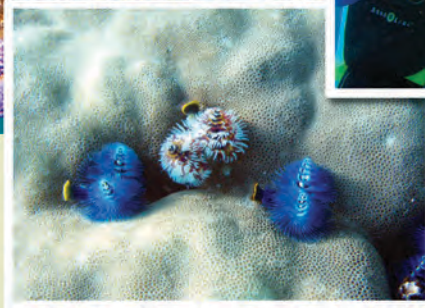




Great Barrier Reef Research: Baseline Synthesis and Year 1 Summary



Great Barrier Reef Research: Baseline Synthesis and Year 1 Summary

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The Marine and Tropical Sciences Research Facility (MTRSF) is part of the Australian Government's Commonwealth Environment Research Facilities programme. The MTRSF is represented in North Queensland by the Reef and Rainforest Research Centre Limited (RRRC). The aim of the MTRSF is to ensure the health of North Queensland's public environmental assets – particularly the Great Barrier Reef and its catchments, tropical rainforests including the Wet Tropics World Heritage Area, and the Torres Strait – through the generation and transfer of world class research and knowledge sharing.

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The information presented in this report was current as of mid 2007. Subsequent advances and publications post mid-2007 are generally not included. Where possible, references to MTRSF literature have been updated and a URL is provided for access to some items online.

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Executive Summary

The Great Barrier Reef (GBR), the world's largest coral reef tract, includes approximately ten percent of the world's coral reefs (by area), globally important inter-reefal areas, tens of thousands of square kilometres of seagrass beds and mangrove forests as well as hundreds of continental islands and sand cays, which collectively support enormous biodiversity. The GBR also holds enormous economic value, as shipping, fishing, boating, diving, aquaculture, research and tourism contribute in the order of \$AUD5.9 billion annually to the Australian economy. The Great Barrier Reef Marine Park (GBRMP), established in 1975, is the world's largest multiple use marine protected area, and was inscribed on the World Heritage Register in 1981 for its outstanding universal value.

Regulatory control of the GBRMP is held by the Great Barrier Reef Marine Park Authority (GBRMPA), with responsibility to the Commonwealth Department of the Environment, Water, Heritage and the Arts (DEWHA). Day to day management is shared with the Queensland Environment Protection Agency (QEPA) and the Queensland Parks and Wildlife Service (QPWS). In 2004, the GBRMP was rezoned, substantially increasing the area of strict protection to 33.4% of the Park. This is recognised internationally as 'state of the art' in marine protected area (MPA) management.

World-leading policy and management initiatives notwithstanding, pressures, risks and threats to the future 'health' of the GBR are multifarious and increasing. These range from the local to the global risks, and include various human uses as well as changes in water quality and climate. In these respects, user- and management-focused research on tourism, shipping and fisheries, coupled with water quality and the effects of climate change, is crucial to ensuring the continued ecological health and socio-economic productivity of the GBR.

The Marine and Tropical Sciences Research Facility (MTSRF), part of the Commonwealth Environmental Research Facilities Program (CERF), an initiative of the Australian Government, is investing \$AUD40 million to develop collaborative, public benefit research among Australia's best tropical environmental researchers to support the conservation and sustainable use of North Queensland's environmental assets – the Wet Tropics rainforests, the GBR, Torres Strait and the connecting coastal regions.

In July 2006, the MTSRF commenced a series of highly collaborative research projects to better understand status and trends, risks and threats and sustainable use of the ecosystems. Some of these projects are continuations of previous Cooperative Research Centre (CRC) supported research and have progressed across the CRC-MTSRF transitional period of 2005/2006; other projects are new, tailored to addressing recently emerging research and management priorities. The research is now producing knowledge across a range of disciplines including biological and physical sciences, economics and social science.

This report synthesises information relevant to the GBR that has been developed in the first operational year of the MTSRF, following a brief introductory review of the geographic, geomorphological, biological, ecological and socio-economic setting, the risks and threats, and the prior research that formed the scientific underpinning for the MTSRF. The report also illustrates the national and international importance of the work being conducted, and future research directions.

The MTSRF research projects are structured under five key themes and the programs they cover. Those of relevance to this report are:

Theme 1 – Status of the Ecosystems: *Understanding the condition, trend and interdependencies of environmental assets of North Queensland*, involving:

- Program 1: Status and trends of species and ecosystems in the Great Barrier Reef; and
- Program 4: Species and communities of conservation concern.

Theme 2 – Risks and Threats to the Ecosystems: *Understanding causes, impacts and mitigation options for specific threats and understanding and measuring the underpinning factors supporting resilience*, involving:

- Program 5(i): Climate Change (Great Barrier Reef); and
- Program 6: Understanding threats and impacts of invasive pests on ecosystems.

Theme 3 – Halting and reversing the decline of water quality, involving:

- Program 7: Halting and reversing the decline of water quality.

Theme 4 – Sustainable use and management, involving:

- Program 8: Sustainable use and management of marine resources of the Great Barrier Reef.

Coincident with the development of these research themes, the rapid application of results in management has improved to the point where the GBR is now widely recognised as both the best-researched and best-managed large reef ecosystem on Earth. In both these respects, the GBR is an important global model. Yet, at the same time, the GBR has also been identified as one of the world's iconic ecosystems most at risk in the coming century from climate change. Management-focused research on the GBR is thus of rapidly increasing national and global significance.

An important cross-cutting aspect in synthesising results for government and industry users is the development of a suite of indicators of ecosystem health and thresholds of concern to environmental conditions and disturbances. Because the response(s) or performance of different indicators will vary, composite indicators based on multi-variable approaches will likely prove most informative, and are a major research focus across both biophysical and socio-economic areas. These will constitute a significant advance on current reporting models and will inform the annual Outlook Reports produced by the GBRMPA, as well as public policy more generally.

Key recent climate change findings indicate that significant warming of GBR waters has already occurred and is projected to continue, with additional effects on circulation patterns, the stability and depth of the surface mixed layer and the depth of the main thermocline. All of these processes can play important roles in regulating heat, connectivity, productivity and exchanges with the atmosphere.

The major reef framework builders, the corals, are at particular risk from climate change and are a major focus of MTSRF research. Coral bleaching is an important indicator of elevated sea temperature, with several major events causing significant coral death on the GBR since the mid-1990s. Recent comparisons of coral bleaching thresholds with mortality thresholds have indicated that thermally sensitive corals die at $<1^{\circ}\text{C}$ (and many at $<0.5^{\circ}\text{C}$) above their bleaching threshold, illustrating the 'fine line' that exists between recovery and death of thermally sensitive corals following a bleaching event. Corals on some reefs have, however, apparently become more tolerant to bleaching after (and possibly because of) the 2002 bleaching event.

Related work has elucidated the first quantitative relationship between bleaching status, photosynthetic capacity and metabolic rate in corals. This has facilitated direct assessment of the energetic consequences of bleaching for coral physiology, with important implications for coral survival during and following a thermal stress event.

Related mathematical modelling of how the processes of thermal bleaching are coupled to coral energy balance, energy stores, and mortality risk is forming a strong basis for developing improved threshold models. Other important findings have shown that variation among corals in thermal tolerance has an underlying genetic component and is not solely due to environmental factors.

An improved understanding of how the impacts of climate change will interact with other stresses, both human-induced and natural, to influence the resilience of GBR ecosystems is being developed. For example, in addition to triggering coral bleaching, high sea temperature is an important factor in outbreaks of coral diseases and initiation of some phytoplankton and other algal blooms.

Other recent findings indicate that the type and severity of response to climate change, terrestrial run-off and other stresses at any particular location depends critically on the physical, hydrodynamic, spatial and biological properties of the location. In these respects, differing levels of gene flow within the GBR will prove crucial to resilience. Loss of biota from poorly-connected areas will be less easily restored through recruitment. Such areas, including reefs and seagrass meadows in the shallow water of poorly-flushed bays that are also likely to be at greater risk from a variety of stresses (e.g. poor water quality, elevated sea temperatures) than their deeper water, well-flushed counterparts, may need particular management focus in the immediate future. New research tracking fish larvae from parental populations via maternal marking with radioactive tracers has important implications for understanding dispersal, levels of connectivity and hence resilience.

With respect to water quality and circulation patterns, recent satellite and field studies indicate that sediment plumes resulting from flood run-off can travel across the continental shelf to the outer reef and into the Coral Sea proper. These plumes have been linked with locally elevated levels of chlorophyll, and have also been correlated with outbreaks of the coral-eating Crown-of-thorns starfish.

The development of abiotic and biotic indicators of water quality is now well advanced. Among the abiotic indicators, chlorophyll and suspended solids / water clarity are relatively well predicted and therefore the most useful, facilitating expression of the data in terms of *relative risk* (high/medium/low) to areas of the GBR. Among biotic indicators, cover, richness and recruitment of hard and soft corals are all inversely correlated with the water quality gradient and simple physiological indicators (e.g. DNA:RNA ratios in corals and fishes) are also promising. Biofilms (Foraminifera, bacteria and diatoms) also exhibit variable, quantifiable effects along water quality gradients. In developing composite indicators, water clarity and light are correlated with reef growth and seagrass abundances. 'Optical depth' (a measure of the transparency of the media through which light is passing) is proving a very useful parameter to quantify water column characteristics relevant for coral reefs, obtained from field measurements and satellite imagery.

Many potential biotic indicators have been surveyed at varying spatial scales on the GBR, with a decadal historical time-series now available. Carefully standardised measures of diversity of key groups (benthic organisms and reef fishes) that are widely used in reporting environmental health are now compiled for many sites along and across the GBR.

The understanding of distributions, status and trends among key biota for both reefal and inter-reefal habitats has improved substantially, with major 'flow-on' benefits for present and

future conservation planning. For example, there have been major shifts in coral cover, including rapid declines and slower increases, in different regions of the GBR during the past fifteen years.

The declines have been driven by predation by Crown-of-thorns starfish, physical impact of cyclones, and most recently, disease such as 'White Syndrome'. Increases in cover have resulted from substantial coral recruitment and growth, which are key aspects of resilience. In respect of another series of Crown-of-thorns starfish outbreaks, no evidence has been found in the northern central GBR of any accumulation in starfish numbers (breeding aggregations) that may signal the start of a new wave of outbreaks. Given that initiation of another outbreak wave is increasingly likely (based on elapsed time), 'early warning' surveys will continue. On the inter-reefal seabed, the overall increase in protection (from *General Use* to higher levels of zoning), has provided demonstrable benefits to seabed habitats, assemblages and biodiversity.

For seagrasses, most of the mapped seagrasses in the GBR are now located in Conservation Park, Marine National Park and Habitat Protection zones and, to a lesser extent, fish habitat area. This is a significant achievement of the 2004 rezoning process. Inshore seagrasses continue to exhibit strong survival rates despite human activities and natural pressures. Large-scale losses have, to date, been mostly associated with catastrophic events including drought, tropical storms and flood run-off. Recovery has typically occurred within several years. Many of the nineteen high-risk areas for seagrasses in the Great Barrier Reef World Heritage Area (GBRWHA) are now well monitored, particularly areas that are in the highest threat category. Data coverage for other seagrass areas is, however, lacking or could be improved. Two major areas have significant information gaps – (1) the coastal area, estuaries and reef platforms of the Cape York NRM region; and (2) the deeper (>15m depth) meadows. These gaps notwithstanding, large-scale spatial patterns of the deep-water seagrasses appear stable over time, with only a 15-25% variation in spatial extent after ten years. Decisions based on spatial needs to protect seagrass were introduced in the 2004 Zoning Plan and are considered likely to remain relevant over long time scales.

Among the many species dependent on seagrasses during at least part of their lifecycle are species of conservation concern, including the dugong (*Dugong dugon*). Three regional groups of dugong populations have now been tentatively distinguished in Queensland from mitochondrial DNA data: Moreton Bay to Shoalwater Bay; Townsville to the Starcke River region; and Torres Strait. Along the urban GBR coastline, long-term decline in dugong numbers has reduced the population to less than ten percent of that present prior to the 1960s. Since the 1980s however, the urban GBR population has stabilised at approximately 3,000 dugong individuals. This suggests that present management is contributing to population maintenance, yet for recovery to pre-1960s levels; non-natural mortality rates will need to be reduced to near-zero. The introduction of Dugong Protection Areas and the 2004 rezoning has improved habitat protection, but dugongs remain at risk during migrations. Similarly, for coastal dolphins such as the 'snub-fins' (*Orcaella heinsohni*), distribution ranges overlap with net fisheries, and non-natural mortality levels need to be reduced to near-zero for recovery. The capacity of acoustic alarms to minimise the bycatch of protected species in commercial gill nets, without alienating the targeted species, is being assessed for three species of coastal dolphins and at least one species of sea turtle.

Populations in the seven major green turtle rookeries of the Northern GBR and Torres Strait are in decline, with smaller sized turtles and poor nesting success, the latter partly related to beach loss due to erosion. Climate change modelling of turtle nest temperature suggests a dramatic change in future sex ratios of hatchlings, with a four or five to one female bias. Given that the GBR supports the largest nesting populations of threatened green turtles

(*Chelonia mydas*) globally, continuing declines in nesting success, and likely shifts in sex ratios of hatchlings, are of increasing national and international concern.

In terms of the socio-economics of the GBR, improved characterisation of the GBR fishery is providing the Queensland Department of Primary Industries and Fisheries (QDPI&F) and the GBRMPA with a better understanding of the present levels of use of resources, towards ensuring that adaptive management strategies provide for ecologically sustainable use. For example, inshore fishery pressures for the East Coast Inshore Finfish Fishery, as measured by fishing boat days, have increased from 1988 to 2003, declining in recent years. Over the past decade, the trend in total catch has corresponded with the number of fishing boat days, particularly since 2002. Differences among the commercial, charter and recreational sectors are much greater than inter-annual differences within sectors, most likely due to fishing behaviour/access, target species and gear and bait types. From 1988 to 2006, sharks dominated overall catch composition of the inshore net fishery, although threadfin, barramundi, mackerel and mullet were also important components, with substantial inter-annual and regional differences within the GBR in both quantity and composition of catch. The shark catch may prove unsustainable, and is another area of conservation concern.

Although results are preliminary, covering a short duration of closure to fishing (~2 years from July 2004), the inner to outer-shelf reefal and inter-reefal studies of the effects of rezoning on fishery resources are demonstrating important direct and indirect (trophic cascade) effects on both target and non-target fish stocks in terms of sizes and abundance.

Biomass of target fish species (coral trout and snapper) has increased in the 'no-take' green zones on reefs, with a slight decrease or stable situation in the fished reef zones. There may be some effect on target fish species of concentration of fishing effort into areas that have remained open to fishing. Earlier studies indicated that after twelve to fourteen years of adequate protection, no-take reserves provided substantial benefits for target species within their boundaries. The strong effects of protection on fish populations were largely due to relatively low levels of fishing infringements (poaching) in the no-take marine reserves of the inshore reefs. On the mid- and outer-shelf coral reefs, initial results are similar to those from the inshore reefs, with consistently more fish in the protected areas (green zones). For example, abundances of coral trout have increased by approximately fifty percent on 'green' mid- and outer-shelf reefs. This suggests relatively rapid benefits from the 2004 Zoning Plan. As longer time-series data accumulate, the results will have profound implications for improved fishery management and the understanding of resilience on the GBR, with important broader application. Very little is known about the quantitative effects of rezoning of MPAs with respect to fisheries enhancement globally. Complementary studies of larval dispersal have the potential to demonstrate significant 'flow-on' effects to areas outside 'green' zones that are open to fishing.

With respect to tourism on the GBR, numbers of visitors have remained above 1.5 million annually since 1994, and approached two million in 2004 and 2005, from what initially was a predominantly Australian market to the present, with large numbers of international tourists. Tourism to the GBR takes many forms, including day trips to reefs or islands, island camping, live-aboard dive trips, longer cruises, live-aboard sailing trips, bareboat charters, independent, non-commercial yacht trips and charter fishing. This growing industry is actively encouraged and well regulated in both the GBR and Wet Tropics World Heritage Areas, and is recognised as relatively benign from an environmental viewpoint.

Recent changes in visitor perceptions and expectations have occurred due to global publicity about the impacts of climate change, with a higher percentage of domestic tourists and local residents using reef cruises than indicated in previous research. Satisfaction remains high across all operators. Most of the tourists who responded to surveys felt that their expectations of the reef and tour had been met. On far northern GBR diving trips, for

example, the overall satisfaction, the wildlife experiences, and the environmental quality or health of the wildlife and reefs were all rated very highly.

Of the total money spent in the region, preliminary estimates indicate that each respondent spent close to AUD\$6,000 (\$5,952 per person), most of which (90%) was directly attributable to the dive-boat trip (i.e. visitors would not have visited the region if they could not go on the trip). It is expected that the GBR will remain an important destination for international tourism in the coming decade.

Future Directions

The GBR, like all the world's ecosystems, is in a state of rapid change at the beginning of the 21st Century. An improved understanding of causality of change and levels of ecological resilience, from local to regional to global levels, with refinement of biophysical targets for the GBR, such as those for sea temperature, ocean acidity and water quality entering the GBR lagoon, will lead to integrated conceptual modelling of 'state of system', with an increasingly refined predictive capacity.

With respect to biodiversity and the socio-economy (e.g. harvest patterns and tourism), the future value of continuing the long-term monitoring datasets (e.g. seagrasses, reefs, dugong and turtles, fisheries and tourism), and the more recent 'baselines' (e.g. inter-reefal shoals and seabed, iconic species) cannot be overemphasised. These are of both national and international significance in providing managers and other stakeholders with relevant, timely information on the 'state of the system' and spatial and temporal trends. Of equal importance, future changes to the ecology, biodiversity and socio-economics of the GBR will be driven/moderated to greater or lesser degree by changes in the physical and biological oceanography of the system. The degree of biological connectivity, of gene flow with other areas of the Indo-west Pacific, and the associated effects on replenishment and resilience in relation to climate change remain critical issues for future research.

Key ecological and biodiversity attributes of certain areas of the GBR, and levels of connectivity with the remainder of the system remain only poorly understood. The far northern area is closest to the Indo-west Pacific diversity centre, and is, as far as is presently known, the most biodiverse region of the GBR. Yet for most invertebrate and some vertebrate groups, the actual levels of diversity are not well known. Similarly, the Pompey and Swain Reef complexes of the central-southern GBR remain relatively poorly understood. Major knowledge gaps also remain for cetaceans. For dwarf minke whales for example, a major and increasing tourism draw-card, basic demographic information such as population size, the purpose(s) of their migration to the GBR (potentially for breeding), and their whereabouts when away from the GBR, all remain uncertain or unknown.

Conferring significant global importance, the GBR forms a key element of the Global Coral Reef Monitoring Network and other international research and management networks (e.g. Seagrass Watch, Reef Check), and knowledge of the system will prove of increasing value in coming years, as the IPCC (Intergovernmental Panel for Climate Change), the United Nations and the world's governments become increasingly focused on the health of coastal ecosystems, coral reefs and inter-reefal areas, as indicators of climate change.

Of particular future importance are emerging synergisms among global and regional factors, such as those between climate change, rainfall and water quality. Levels of resilience to the emerging effects of environmental change remain only poorly understood. A better understanding of resilience and trophic linkages is necessary for setting realistic parameters of scenario models. Understanding of causal relationships and tolerance thresholds of specific indicators and primary, secondary, tertiary effects, cascades and feedbacks among trophic groups and levels (e.g. corals – algae – fish) remains an important area for future

research. Such studies will provide opportunities for further enhancement of integration, both inside the MTSRF and within the broader research community.

The MTSRF is playing a key role in focusing and coordinating bio-physical, ecological and socio-economic research on the GBR. This research spans a broad range of disciplines of high relevance to the sustainable use and adaptive management of the system. The level of research effort, and the linkages across themes, are addressing key aspects of the global 'coral reef crisis', as it applies to the GBR, in a cost-effective manner. Because the MTSRF research platform has a strong foundation in the previous work of the CRC Reef, significant results have already been produced across the four themes. The ongoing synthesis of this information through development of indicators and thresholds of concern will facilitate the timely communication of key results to users, management and government agencies, contributing to rapid development of appropriate management responses.

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Acronyms and Abbreviations

AFZ	Australian Fishing Zone
AIMS	Australian Institute of Marine Science
AIMS LTMP	AIMS Long-term Monitoring Program
AMPTO	Association of Marine Park Tourism Operators
AQIS	Australian Quarantine and Inspection Service
CERF	Commonwealth Environmental Research Facilities Program
CLIVAR	Climate Variability and Predictability
COTS	Crown-of-thorns starfish
CRC	Cooperative Research Centre
CRC Reef	Cooperative Research Centre for the Great Barrier Reef World Heritage Area (also known as CRC Reef Research Centre)
CRC Torres Strait	CRC Torres Strait Ltd
CRFFF	Coral Reef Fin Fish Fishery
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DEH	Commonwealth Department of the Environment and Heritage (now Department of the Environment, Water, Heritage and the Arts at time of report publication)
DEW	Commonwealth Department of the Environment and Water (now Department of the Environment, Water, Heritage and the Arts as at time of report publication)
DEWHA	Commonwealth Department of the Environment, Water, Heritage and the Arts
DHW	Degree heating weeks
DPA	Dugong Protection Area
EAC	East Australian Current
ECIFF	East Coast Inshore Finfish Fishery
ELF	Effects of Line Fishing experiment
EMC	Environmental Management Charge (GBRMPA)
ENSO	El Niño – Southern Oscillation
EPBC Act	Environment Protection and Biodiversity Conservation Act (Commonwealth) 1999
FRDC	Fisheries Research and Development Corporation
GBR	Great Barrier Reef
GBRMP	Great Barrier Reef Marine Park
GBRMPA	Great Barrier Reef Marine Park Authority
GBRWhA	Great Barrier Reef World Heritage Area
GCRMN	Global Coral Reef Monitoring Network
GIS	Geographic Information System
GPS	Global Positioning System
IPCC	Intergovernmental Panel on Climate Change
IRC	Integrated Report Card
ITC	Individual transferable quota
JCU	James Cook University
MODIS	Moderate Resolution Imaging Spectroradiometer

MTSRF	Marine and Tropical Sciences Research Facility
MPA	Marine Protected Area
NAILSMA	North Australia Indigenous Land and Sea Management Alliance
NASA	National Aeronautics and Space Administration (USA)
NOAA	National Oceanic and Atmospheric Administration (USA)
PBFD	Primary boat fishing days
PCQ	Ports Corporation of Queensland
PNG	Papua New Guinea
QDNRW	Queensland Department of Natural Resources and Water
QDoT	Queensland Department of Transport
QDPI&F	Queensland Department of Primary Industries and Fisheries
QEPA	Queensland Environment Protection Agency
QFMA	Queensland Fisheries Management Authority
QPWS	Queensland Parks and Wildlife Service
QSCP	Queensland Shark Control Program
RAP	Representative Areas Program
RAPTS	Regional Activity Plan for Torres Strait
Reef Plan	Great Barrier Reef Water Quality Protection Plan
RTK	Real-Time Kinematic
RRRC	Reef and Rainforest Research Centre Ltd
SEC	South Equatorial Current
SPICE	Southwest Pacific Circulation and Climate Experiment
SST	Sea Surface Temperature
TAC	Total allowable catch
TEDs	Turtle excluder devices
TPC	Threshold of potential concern
TS	Torres Strait
TSRA	Torres Strait Regional Authority
UNESCO	United Nations Educational, Scientific and Cultural Organisation
UQ	The University of Queensland
WPWP	West Pacific Warm Pool
WQ	Water quality

1. Introduction

The Great Barrier Reef (GBR) (Figure 1), the world's largest coral reef tract, is one of the most spectacular and diverse natural wonders of the world. The GBR ecosystem is composed of a diverse array of interconnected habitats including coral reefs, seagrass beds, sponge and soft coral gardens and mangroves that collectively play a critical role in the functioning of this complex system. The habitats also support an enormous diversity of life including more than 400 species of reef-building coral, 1,500 species of fish and 4,000 species of molluscs. In addition to its extraordinary biological and ecological significance, the GBR holds enormous economic value. Shipping, fishing, boating, diving, aquaculture, research and tourism contribute a total of ~\$AUD5.9 billion annually to the Australian economy. The GBR has repeatedly received international recognition for its outstanding natural, cultural and economic values and its world-leading management, and was recently voted the best tourism destination in the world.

To assist in ensuring the protection and preservation of this natural wonder for continued enjoyment and sustainable use in the future, the Australian Government established the Great Barrier Reef Marine Park (GBRMP) in 1975. The GBRMP is recognised as the world's largest multiple use marine protected area (MPA), and in 1981 the GBR was inscribed on the World Heritage Register for its outstanding universal values.

1.1 Management, Legislation and Regulation

Australia has strong national and regional environment policy and management in place to safeguard the GBR, including active surface and air enforcement and monitoring operations. Regulatory control of the GBRMP is held by the Great Barrier Reef Marine Park Authority (GBRMPA), a Commonwealth agency with responsibility to the Federal Minister of the Department of the Environment and Heritage (DEH). Day to day management of the Park is shared with the Queensland Environment Protection Agency (QEPA) and the Queensland Parks and Wildlife Service (QPWS).

Other federal and state agencies with regulatory powers influencing the GBR include the Queensland Departments of Natural Resources and Water; Primary Industries and Fisheries, and Transport (Harbours and Marine). Due to the mix of jurisdictions, state policies and cultures, the socio-economy of the GBR is complex, operating under Australian Commonwealth and State legislation (McGrath 2003). Policy issues and options are thus subject to the interaction between the State of Queensland and the Commonwealth.

Australia is signatory to international conventions and has enacted various national laws and regulations relevant to the GBR, including:

- *Great Barrier Reef Marine Park Act 1975*;
- *Environment Protection and Biodiversity Conservation Act (Commonwealth) 1999*;
- United Nations Convention on the Law of the Sea;
- UNESCO World Heritage Convention;
- United Nations Convention on Biological Diversity;
- Various international maritime organisation conventions (e.g. International Convention for Prevention of Pollution from Ships – MARPOL); and
- The Ramsar Convention on Wetlands (an agreement on the conservation and wise use of wetlands of international importance).

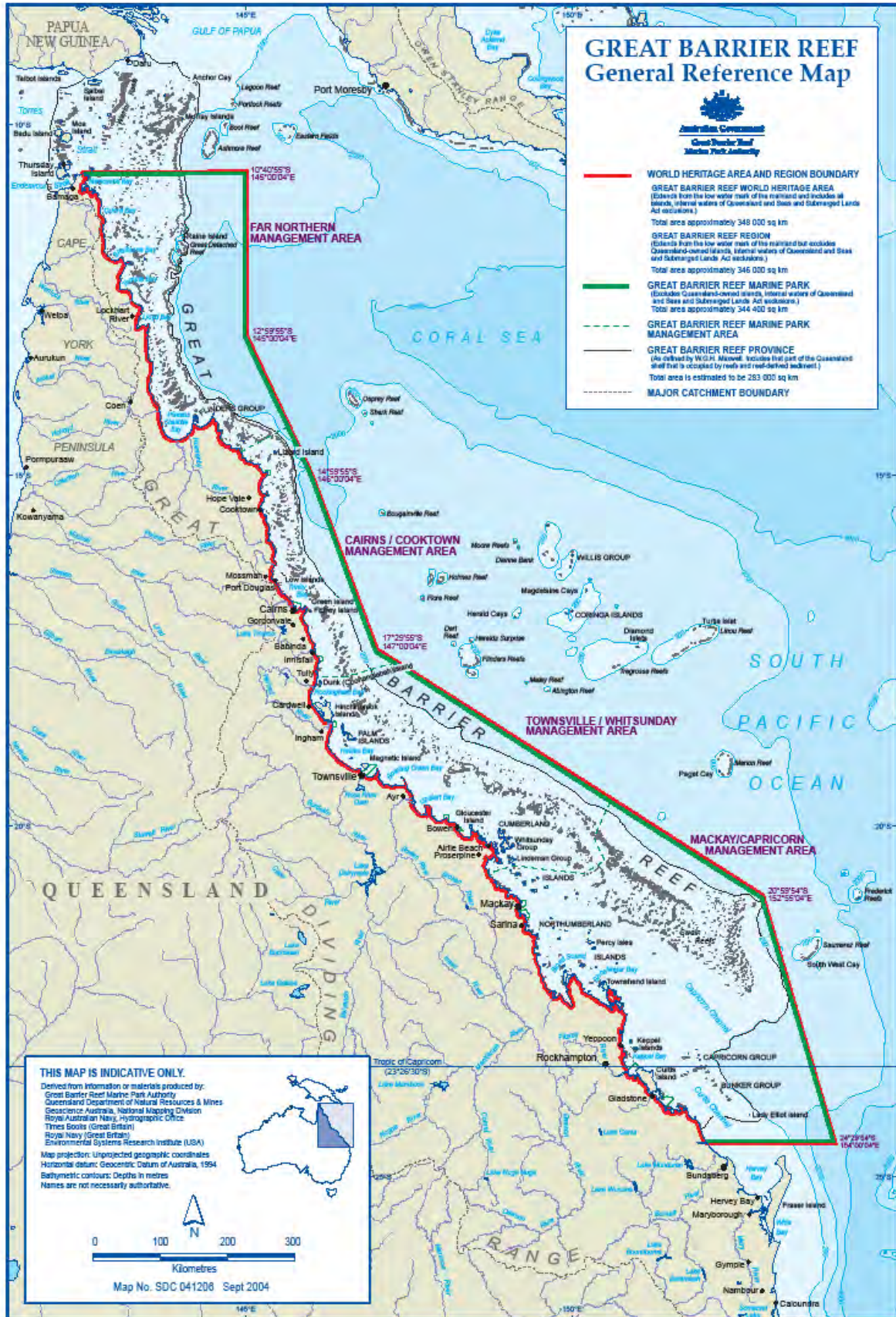


Figure 1: The Great Barrier Reef Marine Park.

An integrated 'Oceans Policy' was released by the Commonwealth Government in 1998, including the concept of regional marine plans advocating an 'ecosystem approach' to natural resource management, in an attempt to balance environmental, economic and social concerns and objectives (Australian State of the Environment Committee 2001). Such ecosystem-based management provides a framework for future policy development, with the focus on recognition that all activities need to be assessed in terms of the linkages and connectivity within the ecosystem – an integrated approach.

The GBRMP was initially zoned from 1981 to 1987. That zoning plan allocated 4.6% of the GBR to highly protected 'no-take' marine reserves, including about 23% of the coral reefs. The remainder of the Park was included in zones with differing levels of protection and use. More recently, in 2004 the GBR underwent a major rezoning process, the result of the Representative Areas Programme (RAP), considered world's best practice. This has increased the area of strict protection to 33.4% of the Park.

The rezoning was targeted at protecting the biodiversity of the GBR within representative habitats of the Park. The process has provided protection of significant inter-reefal, as well as reefal, habitats to ensure the existence of functional corridors among the various habitat types. This seeks to protect biodiversity by protecting the connectivity of the GBR habitats and systems that species may utilise during all phases of their life cycle. The Marine and Tropical Sciences Research Facility (MTSRF) is funding significant research into the influence of the zoning plan, and this is described in detail in Sections 4 and 5 of this report.

These world-leading policy and management initiatives notwithstanding, improved understanding is required to ensure that continued use of the GBR is ecologically and socio-economically sustainable. In particular, research focused on the continued use of GBR resources for tourism, recreation, shipping and fisheries, coupled with development in the river catchments affecting water quality and the global influence of climate change, is crucial for providing greater understanding for management directed at ensuring the GBR retains its ecological resilience and remains in good condition for future generations.

1.2 The Marine and Tropical Sciences Research Facility

The MTSRF is part of the Commonwealth Environmental Research Facilities (CERF) program, an initiative of the Australian Government that will invest \$AUD100 million in world-class public good research over four years from July 2006. Of this \$100 million, \$40 million will be allocated under the MTSRF to develop collaborative, public benefit research among Australia's best tropical environmental researchers to support the conservation and sustainable use of North Queensland's environmental assets – the Wet Tropics rainforests, the Great Barrier Reef and connecting coastal regions, and the Torres Strait.

The MTSRF brings scientific researchers and the users of the scientific results into close partnership. Its purpose is to generate knowledge to inform the Australian people about the condition and trends of North Queensland's environmental assets. The research is answering questions posed by government, industry and the public, and is producing knowledge across a range of disciplines including biological and physical sciences, economics and social science. A critical focus of the MTSRF is to communicate the research findings effectively so as to enhance the adoption of the research results by the public, management and industry. To ensure relevance of the research, the projects are partnered and carried out closely with a wide range of research users. These partnerships will also enhance the delivery and uptake of the research findings. The research, structured in various programs and the projects within them, is clustered into five general themes, which may be broadly defined as *developing an understanding of status and trends, risks and threats* and *sustainable use of the ecosystems*:

- **Theme 1: Status of the ecosystems** – Understanding the condition, trend and interdependencies of environmental assets of the North Queensland region; developing methods to support ongoing regular assessment and reporting; and developing methods to identify priorities for action.
- **Theme 2: Risks and threats to the ecosystems** – Understanding the threats to, and their impacts on the environment and hence the North Queensland region; and developing options to mitigate them.
- **Theme 3: Halting and reversing the decline of water quality** – Understanding the causes and effects of changing water quality and water resource use in North Queensland's coastal catchments; developing options for improving practices, reducing risks and mitigating adverse impacts; and developing ways to measure the effectiveness of regulation, management and other actions to halt and reverse declines. This goal supports the objectives of the Australian and Queensland Government's Reef Water Quality Protection Plan (RWQPP).
- **Theme 4: Sustainable use and management of natural resources** – Understanding the current and potential industry and community uses of biodiversity and natural resources with respect to ecological, social and economic sustainability; and providing information and options to assist North Queensland managers, industries and communities to optimise the use of biodiversity resources and minimise adverse impacts of use where they occur.
- **Theme 5: Enhancing delivery** – Increasing the relevance and adoption of research in policy development, management applications and use practices; supporting effective data exchange and adoption of data standards; funding the delivery of relevant reports in the public interest; providing system-wide overviews through the integration of biophysical studies of the environmental assets of North Queensland and the integration of social and economic research into these; and providing access to data and knowledge for organisations and the public.

A series of highly collaborative research projects began in July 2006 to address the above mentioned critical research themes in accordance with the MTSRF mandate. The knowledge being generated will prove crucial for the conservation and sustainable use of North Queensland's globally significant environmental assets, including the GBRWHA and adjacent ecosystems, the focus of this report.

This report synthesises the key information arising in the first year of the MTSRF programme, following an introductory review of the GBR's biological, ecological, geomorphological and socio-economic setting, pressures and recent management initiatives, and the prior research that formed the scientific underpinning. The report also indicates the national and international importance of the work being conducted, and future research directions, with extensive use of direct quotes from the researchers' recent research publications and updates.

1.3 Geographic Setting and Geomorphology

The GBR is located on the north-east Australian continental shelf, and at its widest point stretches more than 150 km off the Queensland coast. The GBR covers an area of some 348,000 km² adjacent to more than 2,300 km of the Queensland coast. Extending from Lady Elliott Island in the south to beyond the tip of Cape York Peninsula in the north, the GBR is bounded on its eastern seaward extent by the Coral Sea Basin and its southern extent by the Tasman Sea.

The GBR ecosystem is highly connected with adjacent regions by oceanic currents and extends northward across Torres Strait to Bramble Cay and the Australia-Papua New Guinea (PNG) territorial border. The GBRMP, however, in regards to management and heritage listing of the GBR, encompasses approximately 345,000 km², extending from the tip of Cape York in the north to just south of Lady Elliot Island. On its nearshore and landward extent, the GBR is influenced by the catchments, streams and rivers flowing into the GBR lagoon (Figure 2).

On a broader geographic scale, the GBR is a key biogeographic component of the Indo-west Pacific province, forming the major component of the Northeast Australian Large Marine Ecosystem, with characteristic oceanographic, biological and ecological features:

"The Northeast Australian Large Marine Ecosystem owes its unity to the South Equatorial Current (SEC), a part of the Pacific Ocean counter clockwise gyre, and to the Great Barrier Reef system (GBR) ... the largest system of corals and related life forms in the world. The Northeast Australian Large Marine Ecosystem is bounded by the Coral Sea to the East and by the Torres Strait to the North." (http://www.lme.noaa.gov/Portal/jsp/LME_Pages/lme_40.jsp)

A contemporary review of the broader regional aspects of physical oceanography of the Coral Sea and GBR (Steinberg 2007) states:

"The classical view of Coral Sea circulation ... has the broad SEC entering the Coral Sea from the east and bifurcating at the GBR into a northern arm, the North Queensland Current, or Hiri Current, and the poleward flowing East Australian Current (EAC). The location of the bifurcation varies seasonally between 14°S and 20°S and lies at the southern end of this range during the southeast trade wind season (April to November). Underlying the EAC is a permanent undercurrent that flows northwards and eventually joins up with the Hiri Current. (Church and Boland 1983, Church 1987, Hughes 1993, Burrage 1993)

[However, there is] significant complexity and detail in ocean circulation ... the broad westward SEC inflow is broken up into a number of zonal jets by shallow bathymetry associated with island archipelagos. The reef systems effectively impede the flow and force the waters around them ... Once in the Coral Sea, currents deviate around the reef systems on the Bellona (west of New Caledonia), Queensland and Marion Plateaus. This topography produces multiple pathways for the SEC to reach the GBR. Once the jets encounter the Australian continental shelf they form the EAC and Hiri currents flowing along the western boundaries ... A large recirculation of the Hiri Current, known as the Papuan Gyre, provides a pathway from Papua New Guinea waters back to the far northern GBR (Burrage 1993). A smaller recirculation is seen off the southern GBR, south of the Swain Reefs and east of the Capricorn Bunker Group." (Steinberg 2007)

This regional oceanography has profound influences on the GBR's ecology and biodiversity. The GBR contains some 3,000 individual coral reefs, developed on submerged hills and mountains of the northeast Australian continental crust. In total, there are some 600 continental islands, most of which are sparsely populated (e.g. resorts) or uninhabited, and of major importance for biodiversity conservation and cultural heritage. The reefs themselves cover an area of approximately 26,000 km², or ten percent of the global total (Spalding *et al.* 2001) and are of diverse form, including fringing, patch, platform, 'ribbon' and 'deltaic' reefs (Hopley 1982, Hopley *et al.* 1989). The reefs collectively support some 300 coral cays built of reef sands and coral rubble.

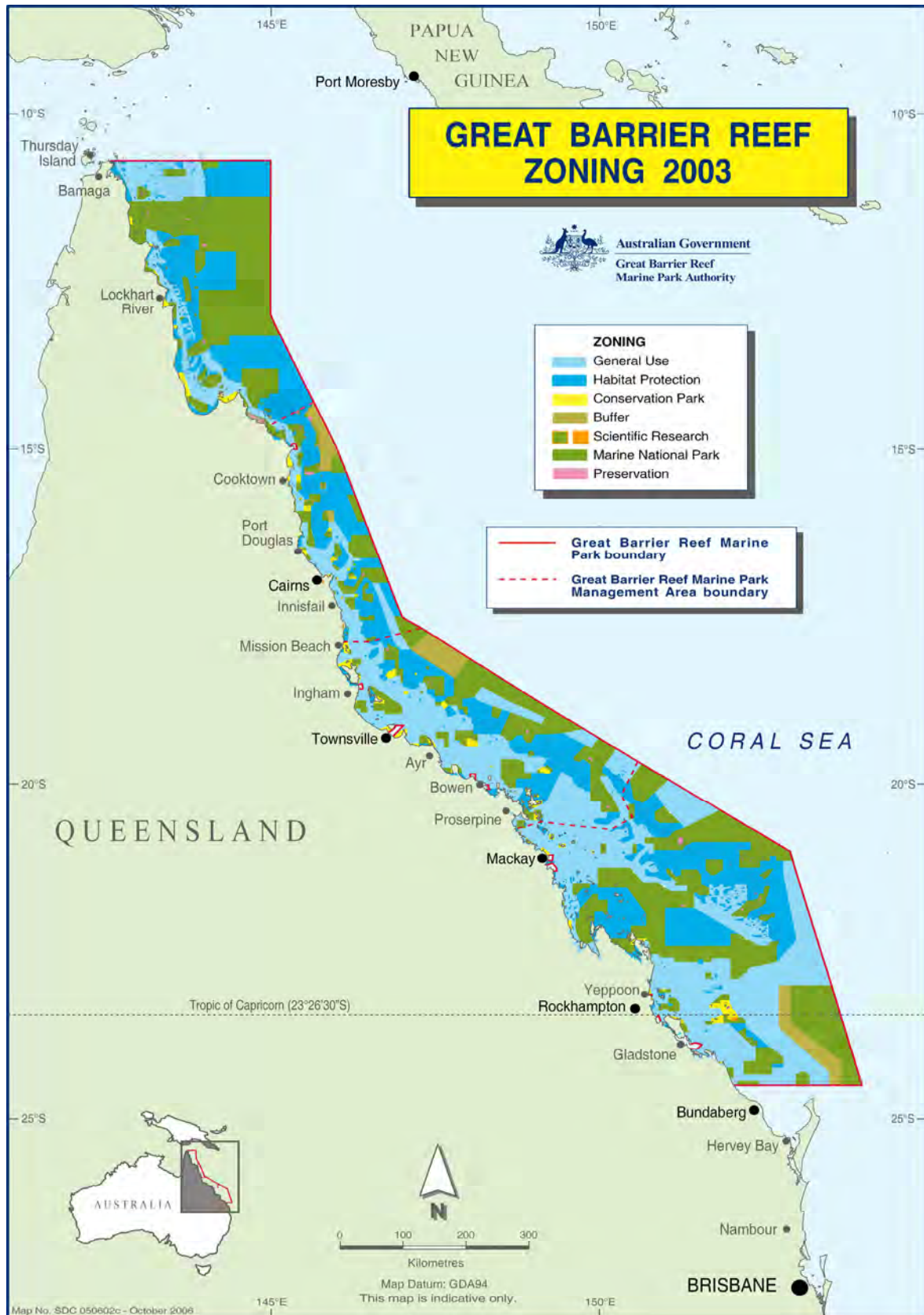


Figure 2: Boundaries of the Great Barrier Reef Marine Park post-rezoning (2004-).

For large sections of the GBR, the reef tract is composed of three more-or-less coherent reef groups oriented long-shore – developed on the inner-continental shelf (mainly fringing reefs), mid-shelf and outer-shelf respectively. The outer barrier reefs are located close to, or at the edge of the continental shelf, adjacent to waters of significant depth (>200m and reaching >1,000m in places) and more or less enclose the GBR against the Queensland coast. The GBR lagoon, located between the coast and the inner reefs of the GBR, is comparatively shallow (mostly <80m depth). Numerous passages of varying width and depth intersect the reef tract, facilitating water exchange (Brinkman *et al.* 2002) and promoting connectivity among the different GBR habitat systems, and biodiversity.

1.4 Patterns in Distribution of Habitats

The GBR lagoon is influenced by both marine and terrestrial inputs; the former as flow-through from the SEC system and the East Australian Current (Church 1987, Wolanski 1994, Steinberg 2007); the latter as run-off from the various river systems and catchments feeding the GBR Lagoon (Brodie 1995, Furnas 2003). The coastal catchments under the immediate influence of these river systems typically support mangroves and seagrasses and are mostly devoid of fringing coral reefs that are better developed further offshore, fringing the continental islands and forming the extensive reef tracts of the mid-shelf and outer barriers.

Significant broad-scale cross-continental shelf and latitudinal variability exists among GBR habitats and the benthic and pelagic communities they support. Cross-shelf variability is reflected in the physico-chemical, geomorphological and ecological characteristics of the outer, mid and inner reefs. Near-shore reefs are most influenced by coastal processes of run-off, terrestrial nutrient and sediment input and re-suspension, and associated biological activity. Mid-continental shelf reefs are developed in clearer waters with less terrestrial influence, but with greater oceanic inputs and wave energy, and reefs of the outer shelf are most strongly under the influence of oceanic waters, waves, currents and upwelling from the Coral Sea.

The varying effects of these cross-shelf influences on the different reef groups and their biodiversity are being measured, monitored and mapped to develop an understanding of the effects of terrestrial run-off, changing climate and influences on water circulation patterns.

The reefs, however, comprise just six percent of the total area of the GBRMP, with the remaining area of the continental shelf supporting a diverse range of non-reefal habitats and benthic and pelagic communities. These habitats include large areas of inter-reefal and continental slope soft bottom areas, smaller areas of hardgrounds (shoals), seagrass beds, sponge and soft coral 'gardens' and mangrove forests, the latter fringing the mainland coast and continental islands. The shallow inter-reef and lagoon areas collectively comprise about 58% of the area of the GBR, with the remainder occupied by slope areas of the continental shelf and deeper ocean (Wachenfeld *et al.* 1998).

The sand cays are important habitats, although more ephemeral, providing nesting sites for the GBR's seabird and marine turtle populations, and also supporting more-or-less diverse vegetation, other vertebrate and invertebrate communities. In total, the GBR has approximately 55 significant seabird islands supporting around two million seabirds of 22 species (H. Marsh, pers. comm.). The bays, estuaries, rivers, reef platforms and inshore lagoon of the GBR provide a high diversity of seagrass habitats. The seagrasses exhibit complex spatial and temporal patterns in their distributions:

“Adding to this complexity is the range of habitat types seagrasses have colonised in the GBRWHA. They can be found on reef edges exposed to waves, on reef platforms, at sixty metres deep on coralline sands in the reef lagoon, on

sandy coastlines both inter-tidal and sub-tidal, and in estuaries colonising muddy banks and the edges of mangrove creeks. They are found from the tip of Cape York more or less continuously to the southern boundary of the GBRWHA, a distance along the coast of some 2000 kilometres.” (Coles *et al.* 2007)

In all, the GBR region has about 36% of the total recorded area of seagrass in Australia (Coles *et al.* 2007). More than 5,000 km² of coastal seagrass meadows occur in shallow waters (<15m depth), while some 40,000 km² of the deeper seafloor (to ~60m depth) has some seagrass present (Coles *et al.* 2003, 2007). These benthic habitats in turn support more mobile fauna, including species of conservation concern such as dugong and turtles, and commercially important species of crustaceans, molluscs and fish.

Inter-reefal waters provide the developmental and dispersal medium for the larval stages of most invertebrates and fishes, and also provide migration corridors for cetaceans, dugong and pelagic fishes. The pelagic communities, based on phytoplankton, support more-or-less complex food webs of zooplankton, cephalopods (squid and allies), a diverse array of fishes and cetaceans. Although the degree of dispersal, and hence level, of genetic connectivity varies among species in respect of their life histories, many GBR species are widely dispersed. For a variety of reef fishes for example, recent work has demonstrated that dispersal is much more under the control of the larvae themselves than previously realised (Leis 2004). For many invertebrate larvae however, dispersal is more strongly influenced by the ocean currents.

Multi-phase life histories and migration patterns mean that many species, including commercially important fishes, rely on multiple habitats within and adjacent to the GBR to successfully complete their life cycles – from the estuarine mangrove systems, to nearshore seagrass beds, to inter-reefal hardgrounds to the reefs themselves (Figure 3). The high degree of biological connectivity within the GBR, both along and across the reef system, is a key element in its ecological resilience, biological and economic productivity. Developing a better understanding of this connectivity and resilience of various systems within the GBR is an important component of MTSRF research (Sections 4 and 5 and Appendix 1).



Figure 3: Catchment to Reef – representing connectivity of reefal environments with landscapes and coastal waterways (Source: Catchment to Reef, <http://www.catchmenttoreef.com.au/>).

1.5 Biodiversity

The uniqueness and importance of the biodiversity that forms the GBR cannot be overstated. As the world's largest coral reef ecosystem, the GBR is home to approximately 400 species of reef-building corals (half the global tally), 4,000 species of molluscs, 800 species of echinoderms, 1,500 species of sponges, 1,500 species of fish, 215 species of birds, six species of sea snake, six species of sea turtle, some 30 species of cetacean (including residents and migrants) and one of the largest remaining populations of dugong in the world (<http://www.gbrmpa.gov.au/>). A new species of dolphin was recently discovered, and there may also be a new species of Dwarf Minke whale within the GBRMP (H. Marsh pers. comm.). There are 39 species of mangroves (including hybrids), around 500 species of seaweed and 15 species of seagrass in and adjacent to the GBR. For many invertebrate groups, species tallies are not complete, and considerable taxonomic work remains to be undertaken.

Importantly, while a proportion of the species present are endemic, only being found within the GBR region, many also occur elsewhere in the Indo-Pacific biogeographic realm (see, for example, <http://www.reefbase.org/> and <http://www.fishbase.org/>). For these species, the GBR forms an important part of their global distribution range and meta-population. The enormous geographic scale of the GBR means that for many of these species, the local populations comprise significant proportions of their global populations, as for example with turtles and dugong.

“The green turtle population in the northern Great Barrier Reef and Torres Strait ... is the largest in the world. Based on turtle nesting data collected by Queensland Parks and Wildlife Service since 1976, it is estimated that an average of 50,000 females breed each year in this population (Limpus *et al.* 2003). Approximately 90% of this occurs on two small sand cays in the northern GBR: Raine Island and Moulter Cay. Other main nesting sites are Bramble Cay and Murray Islands (Mer, Dowar and Waer) in Torres Strait and Milman Island and Sandbanks 7 and 8 in the northern GBR.” (Hamann and Fuentes 2007)

And

“Dugongs occur along much of the tropical and sub-tropical coast of Australia from Shark Bay in Western Australia to Moreton Bay in Queensland. The northern Great Barrier Reef and Torres Strait support globally significant populations of dugongs (Marsh *et al.* 2002).” (Marsh *et al.* 2007)

Furthermore, for many of these species, both terrestrial (e.g. some sea and land birds) and marine (e.g. turtles and some cetaceans), the GBR is an important migration corridor and/or breeding site. For many groups, a net decline in species richness occurs with increasing latitude from north to south along the GBR, consistent with global patterns, with some species replacement in southern areas. Many species exist all the way across the continental shelf, but there are major differences in richness and relative abundance of species across the shelf.

The species present among the different taxonomic groups, such as corals and fishes, form more-or-less discrete assemblages, nested in community hierarchies of increasing spatial scale. For example, well-defined coral communities in small areas within the GBR, such as the Whitsunday Islands, form part of larger communities (in the far north, north and south), which in turn form part of the whole-GBR community and larger communities of the Coral Sea Basin. At each level, the communities are comprised of characteristic species, albeit sharing a high proportion of their total species complement. For example, recent studies

have confirmed that the majority of the approximately 400 species of reef-building corals on the GBR are broadly, if sparsely, distributed along and across the reef tract (DeVantier *et al.* 2006). The best-differentiated communities for corals are those of the far north, characterised by species rare or absent from more southerly reefs, and those of the more exposed outer barrier reefs. Importantly, species diversity of corals, as indeed most taxonomic groups, for the far northern GBR is not yet well known, with the likelihood of additional species records raising total diversity of the GBR closer to that of the Indo-Philippines global centre of marine diversity, 'the Coral Triangle' (Green and Mous 2004). Fish communities also exhibit a degree of cross-continental shelf and latitudinal differentiation, and, like the corals, a high proportion of fish species, including many commercially important species, are widely distributed in the GBR and greater Indo-Pacific (<http://www.fishbase.org/>).

The processes governing these patterns of species richness and community structure are complex and scale-dependent, attributable to different life histories of the organisms themselves, dispersal, contrasting habitat diversity, local disturbance histories, gradients in wave energy and water clarity, depth, and terrestrial influences affecting water quality. Importantly, detailed GBR-scale assessments of richness and community structure have yet to be made for most (non-coral) invertebrate groups, particularly those of inter-reefal habitats – an important focus of the MTSRF (Sections 4-6 and Appendix 1).

1.6 External Influences

Habitats and biodiversity of the GBR are affected by many factors external to the system itself, both point source and diffuse. Far northern waters, for example, are under the influence of the major river systems of southern PNG, while the SEC brings water from further east to the system. Other external influences include human use through fishing and shipping, land-based activities affecting the quality of water entering the GBR catchments and lagoon, seasonal regional weather patterns of the monsoon and episodic tropical cyclones, and inter-annual global effects of changing climate, notably the El Niño-Southern Oscillation (ENSO).

The GBR, particularly the nearshore area, is profoundly influenced by the adjacent landmass, most notably via run-off from the river systems carrying freshwater, sediments of various size, nutrients, pesticides and other chemicals. Water quality is a major influence on, and hence concern for, the GBR for many reasons. This is covered in a separate synthesis report by the Reef and Rainforest Research Centre (RRRC), and briefly summarised here.

The entire GBR catchment encompasses some 424,000 km², which represents about six percent of the Australian continental landmass. This catchment area includes 35 drainage basins (Furnas and Mitchell 2001, Mitchell *et al.* 1996, Williams 2001, Furnas 2003b). These catchments, which reflect major differences in rainfall, can be sub-divided into three major catchment groups:

- Cape York – eight catchments – 43,000 km² – 10% of the total catchment;
- Wet Tropics – eight catchments – 13,000 km² – 3% of the total catchment; and
- Dry Catchments – 17 catchments – 370,000 km² – 87% of the total catchment.

The Cape York catchments have low levels of development compared to those further south, and are considered closest to pristine. The Wet Tropics catchments are relatively small, although rainfall is concentrated there. As the name implies, the area receives some of the heaviest rainfall on Earth – exceeding 8,000 mm annually in some places. Much of the steeper parts of the Wet Tropics catchments, which remain undeveloped, form part of the Australian Wet Tropics World Heritage Area. In comparison, parts of the lowlands and inland

areas receive far less rain (<1,000 mm yr⁻¹), which is more comparable to that received by the Dry Tropics regions (dry catchments), such as along the coast in the vicinity of Townsville and Bowen. Within the dry catchments the climate is hot with a marked dry season and average annual rainfall of approximately 1,000 mm. The Townsville-Bowen region, including much of the Burdekin River catchment, is one of the driest parts of tropical coastal Australia. These dry catchment areas can experience severe water shortages during drought, in part related to episodic onset of ENSO.

Adding to the patchy influence of rainfall into the GBR Lagoon, substantial inter-seasonal and inter-annual climate variability is related to the onset and intensity of the summer monsoon, ENSO and cyclonic storm activity. Tropical cyclones are common and exert pronounced effects on the continental shelf and on coastal marine ecosystems, as well as the adjacent land and human settlements. Rain from cyclones can be a major source of fresh water and can cause widespread damage through episodic flooding, influencing run-off to the GBR Lagoon from the river systems.

Thus, despite its great size, the GBR is not an isolated system. On its western margin it is the receiving area for a large proportion of Queensland's river run-off, while also falling under the influence of the oceanographic processes of the larger Coral Sea and western Pacific, all of which have important implications for biodiversity and ecological resilience and the related socio-economy.

1.7 Socio-Economic Characteristics

Because of its huge size, exceptional diversity and good ecological condition, the GBR provides enormous value in 'ecosystem services' to Australia and the world (see, for example, Costanza *et al.* 1997, Access Economics 2005). The GBR falls within Australia's Exclusive Economic Zone. Presently, there are approximately one million Australians living in close proximity to the GBR, distributed mostly in towns and cities spread along the coast and across the lowlands. The larger urban settlements include the industrial cities and ports of Townsville and Gladstone, the agricultural centres of Bundaberg, Rockhampton, Mackay and Bowen and tourist centres of Cairns and the Whitsundays coast. The economy of the region is a mix of primary industry, mostly agriculture, grazing, fisheries, and mining, various forms of secondary industry and, increasingly, tourism. There are very few permanent residents on the GBR itself, a major point of difference with most reef tracts worldwide, where large, local island-based populations rely directly upon, and can cause significant impact on, the adjacent reefs.

The GBR alone is estimated to return almost \$AUD6 billion to the Australian economy annually. Much of this (\$5.1 billion) results from tourism that has grown substantially over the past several decades to be by far the most important single industry on the GBR. Tourism is currently estimated to provide employment for some 63,000 people, making it the largest employer in many coastal towns and an increasingly important contributor to the Queensland and broader Australian economies.

Numbers of visitors have remained above 1.5 million annually since 1994, and approached 2 million in 2004 and 2005 (Sutton 2007), from what initially was a predominantly Australian market to the present, with large numbers of international tourists. Tourism to the GBR takes many forms, including day trips to reefs or islands, island camping, live-aboard dive trips, longer cruises, live-aboard sailing trips, bareboat charters, independent, non-commercial yacht trips and charter fishing (Prideaux and Coghlan 2007). This growing industry is actively encouraged and well regulated in both the GBR and Wet Tropics World Heritage Areas, and is recognised as relatively benign from an environmental viewpoint.

In addition to tourism, fisheries are an important export earner and are conducted by commercial, recreational and Indigenous users. The major forms of commercial fishing include benthic trawling, line fishing and trolling, and netting. The GBR is a multi-species fishery where approximately 125 species are targeted by commercial, recreational and charter fishermen. These include prawns, coral trout and other serranids, red throat emperor and other lethrinids, red emperor and other lutjanids, and Spanish mackerel. Coral trout account for approximately half the total commercial harvest, with red throat emperor and Spanish mackerel each accounting for a further 15-20%. Indigenous hunters primarily take dugong and turtle, for which current rates of harvest may be unsustainable in the longer term (H. Marsh, MTSRF Conference 2007, see <http://www.rrrc.org.au/news/2007conf.html>), and to a much lesser extent than other sectors also target fishes, primarily in inshore waters.

The Queensland commercial fishing industry, with some 2,400 licences in all, generates about \$AUD220 million annually in gross value of production (QDPI&F 2006). Trawling (mostly for prawns and to a lesser extent scallops) accounts for around \$120 million (Williams 1997, 2002) from the 24,000 tonnes harvested, a relatively poor return by comparison with recreational and charter fishing, which takes much less catch (approximately 4,000 tonnes; <http://www.gbrmpa.gov.au/>). The net fishery and inshore finfish fishery account for a further \$40 million and \$20-30 million respectively. The inshore finfish fishery, comprised of four sectors – commercial, recreational, charter and indigenous – supports a large number of users, including more than 750,000 recreational fishers and approximately 500 commercial operators (QDPI&F 2006, Simpfendorfer *et al.* 2007b).

With growth of commercial fishing on the GBR since the 1940s, there has been increasing research into fishing effort. Today, daily reporting of catch and effort is compulsory for all commercial line fishers. Considerable effort has been devoted to developing ecologically sustainable fisheries in the GBRMP, through dedicated management-focused research into the effects of trawling, the reef line fishery, commercial netting, recreational and charter fisheries, in which the CRC Reef (previously) and the MTSRF play important roles. This work has facilitated policy review, revision of zoning and regulation by the GBRMPA and revision of management plans by the QDPI&F. Within the GBRMP, fisheries are regulated in terms of location, gear, catch and effort, and management practices are adapting in response to ongoing research and policy advances.

Agriculture in the adjacent lowlands and hinterland produces a wide range of food-stuffs for local consumption and export markets, using considerable quantities of fresh water, provided in part by numerous weirs and dams on several of the major rivers (e.g. Burdekin Falls Dam). Beef production is another major industry in the drier areas of the hinterland, and has disturbed fragile soils in some riparian areas, contributing to erosion. Large areas in the wetter parts of the coastal lowlands have been extensively planted with sugar cane, mostly for export markets.

Agricultural practices have traditionally used significant quantities of chemicals in fertilisers and pesticides, with significant export in run-off to rivers and coastal waters of the GBR Lagoon. With increasing recognition of the 'downstream' risks, this is changing, with improved 'adaptive' management of the GBR and adjacent areas. Research being conducted under the MTSRF addressing these concerns is described in Section 4 of this report and in Brodie *et al.* 2008.

1.8 Recent Research

Biophysical, ecological and socio-economic research on the GBR has expanded rapidly, particularly during the last two decades, from comparatively modest beginnings in the early-mid 20th Century. Over the past decade, the GBR has become widely recognised as one of the best-researched tropical marine ecosystems globally (Figure 4).

Of particular relevance to the present report, the CRC Reef coordinated and undertook collaborative research on the major issues facing GBR managers and industry from 1999 to 2006 (<http://www.reef.crc.org.au/>). This included seminal studies of the effects of global warming, over-fishing and water quality, biodiversity conservation, emerging tourism and recreation pressures. These were conducted under six broad programs: Conserving World Heritage Values; Sustainable Industries; Maintaining Ecosystem Quality; Healthy Country, Healthy Reef; Reef Futures and Torres Strait. Results from these programs informed the GBRMPA and other government and industry bodies, alerting reef managers to emerging issues in a period of rapid change. This recent research work is summarised in the latest 'State of the Reef Report', a review of status, trends and risks to the GBR (<http://www.gbrmpa.gov.au/>). The CRC Reef research and other work provided a solid foundation on which to design the MTSRF research platform.

Results of this research are well evidenced by the current understanding of the region's geomorphology, oceanographic processes, biodiversity and endemism, impacts, risks and threats, and by the descriptions, mapping and monitoring of the distribution of resources through time, the latter particularly important for effective management. The timely assessment and reporting of trends in the ecological condition or 'health' of the GBR has received increasing attention in recent years. Monitoring, notably of the reefs and seagrass beds and some commercially-important fish species, has now occurred consistently for more than a decade, conducted and supported by agencies including the Australian Institute of Marine Science (AIMS), QDPI&F, James Cook University (JCU), the CRC Reef and the GBRMPA.

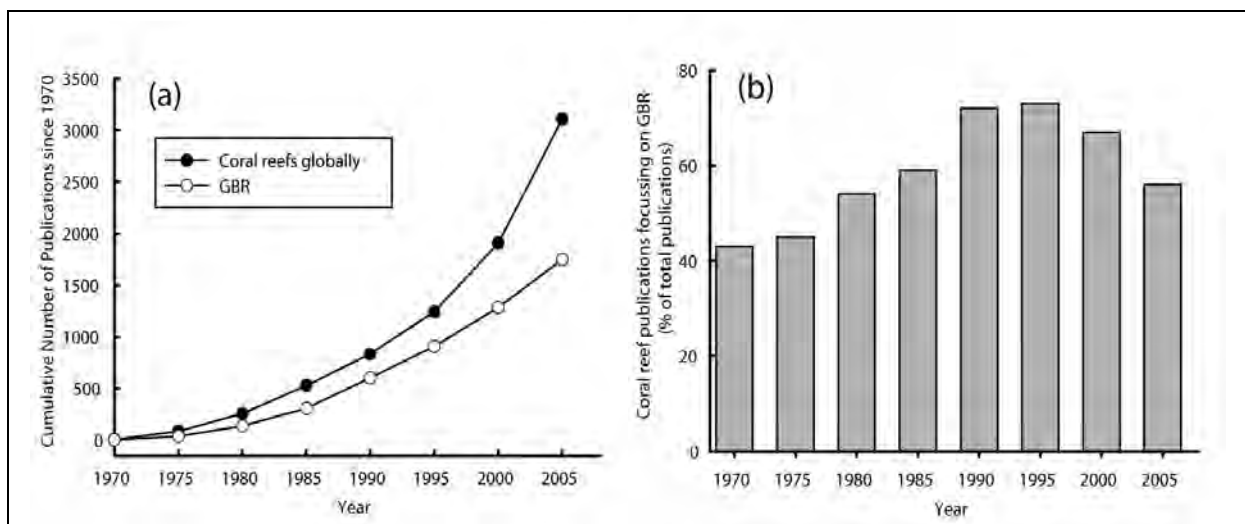


Figure 4: Share of global research on coral reefs devoted to the GBR. (a) Comparison of cumulative totals of publications in the world and the GBR region respectively (figures obtained from searches on Biological Abstracts database). (b) Research publications based on the GBR as a proportion of total publications (from Cvitanovic *et al.* 2007).

These studies have assessed and compared the selected taxa and attributes (coral cover, seagrass biomass, fish sizes and abundances, etc.) within closed and open zones of the GBRMP (the majority of the work was conducted prior to rezoning in 2004) at geographic locations considered representative of the GBR more generally. The distribution of seagrass meadows has also been well mapped in coastal locations, and community monitoring groups (such as Seagrass Watch) have also monitored biodiversity and distribution of benthic assemblages that utilise seagrass meadows as a key habitat. For coral reefs, the Reef Check organisation supports an increasing community-based monitoring network of recreational dive operators and others.

With respect to fisheries, major studies of the effects of trawling and line fishing (ELF) were undertaken by CSIRO and JCU with support from the CRC Reef. The ELF study (see, for example, Mapstone *et al.* 2001, 2004) included a large-scale manipulative experiment of fishing effort on four clusters of six reefs, investigating changes in abundances of target species resulting from line fishing. Other ELF research examined catch statistics and the biology of the major target species. These results were used in developing recent management initiatives for the line fishery (Section 2.6).

The ELF experiment demonstrated that the protection offered by closure of reefs has the potential to sustain high biomass of reproductively mature populations of target species, assuming sufficient compliance with the closures (Mapstone *et al.* 2004). As the ELF program was focused on coral trout, the primary target species of the reef line fishery, the direct and indirect effects of fishing on other species were less clear. Fishery logbook data has demonstrated that a number of other species and species groups are increasingly being targeted by fishers or are being affected as bycatch. Further research to support management actions for the other species is a focus of the MTSRF (Sections 4 and 5 and Appendix 1).

The trawling study revealed major patterns in seabed biodiversity and habitats at spatial scales relevant to regional conservation and management needs (Pitcher *et al.* 2007a). Integration of biological, habitat, physical and bottom-water data, with analysis of bio-physical relationships, allowed identification of important environmental variables and stratification of the GBR seabed. The study also revealed major differences in benthic community structure between trawled and untrawled areas, with important flow-on effects for biodiversity conservation and replenishment. Predictive maps of biodiversity, assemblages and habitats formed the basis of seabed spatial characterisation and ecological risk assessments for the trawl fishery in the region (Pitcher *et al.* 2007a). This information is also informing development of indicators of protection following the 2004 rezoning.

Effects of the new zoning plan on the biomass and abundance of the key fisheries target and other species is currently under investigation. The relative influences of factors such as climate change and water quality on these attributes, in addition to fishing pressures, are not well understood. These are being addressed through the MTSRF via synthesis of information from long-term monitoring programs, and the alignment of this information with research to understand the processes affecting the biodiversity, abundance and persistence of key species and habitats of the GBR through time (Sections 4 and 5 and Appendix 1).

Although the GBR is one of the best-studied ecosystems globally, its enormous size and complexity mean that much remains unknown, particularly with respect to resilience to present and future disturbance and use. Recent reports regarding the likely effects of climate change suggest that the health of the GBR is already in decline, and at increasing risk from global warming and changes in ocean chemistry.

“Even the Great Barrier Reef, widely regarded as one of the most ‘pristine’ coral reefs in the world, shows system-wide decline ... terrestrial run-off, over-harvesting and climate change are changing the dynamics and stability of the region ... Inputs of sediment and nutrients from land have increased fourfold since European settlement, while the numbers of turtles, dugongs and other macrofauna have greatly decreased ... Comparisons of adjacent reefs open and closed to fishing today indicate that the biomass of targeted reef fishes has been reduced by up to 60%, causing substantial changes in the abundance of their prey. Coral cover has significantly declined over the last forty years, reflecting the impacts of three successive major outbreaks of crown-of-thorns starfish since the 1960s and two large-scale bleaching events in 1998 and 2000. In 2003, more than half the reefs sampled had <10% cover. The low coral cover is likely to reflect marked demographic changes, reduced reproductive output of brood stocks, lower rates of recruitment, impaired connectivity, and species-level changes in coral composition.” (Bellwood *et al.* 2004)

However, other recent studies suggest that the high degree of spatial and temporal variability across and along the GBR preclude such definitive conclusions. For example:

“It is debatable whether the GBR complex has declined over the last forty years. The reef is in a continuous state of flux and diverse historical datasets are particularly difficult to compare with modern ones ... the reefs are highly dynamic and generally resilient, with short periods of decline due to disturbance, followed by longer periods of recovery.” (Miller and Sweatman 2004; also see Halford *et al.* 2004)

Thus, aspects of Bellwood and others’ analysis (2004) remain controversial, particularly the validity of the comparisons between historical (1960s) and recent (post-1990s) reefs. Nevertheless, their report does reflect the rapidly growing concerns among scientists and managers alike for the future of the GBR, with increasing recognition of the risks posed by water quality, over-fishing and climate change, among others. These concerns have been brought into sharp focus by the recent Inter-governmental Panel on Climate Change (IPCC) reports, which identified the GBR as an ecosystem particularly at risk (IPCC 2007) (see also Section 2.5).

In summary, in less than four decades, and with a dedicated, world’s best practice management regime in place, the prevailing view is shifting from one of a near-pristine GBR ecosystem to one already suffering significant impact and facing growing pressures.

2. Risk and Threats to Habitats and Biodiversity

The coastal and marine habitats and biota of the GBR have developed since the return of higher sea levels during the Holocene transgression (last 6,000 years), with a disturbance regime that has been dominated by tropical storms and river floods. This has been augmented in recent times by human changes to the river systems, increasing fishing pressure, major population outbreaks of crown-of-thorns starfish, and mass coral bleaching, among other impacts (DeVantier *et al.* 2006). As with reef systems globally, risks and threats to the GBR are multifarious and increasing. Unlike most other reef systems, however, the GBR tract itself is not heavily populated, greatly reducing many of the local impacts that affect reefs in Asia and meso-America.

With respect to pressures facing the GBR, the recent *State of the Great Barrier Reef Report 2007* (<http://www.gbrmpa.gov.au/>) identified the following:

- Since the European settlement of Australia, the annual flow of nutrients and sediments from the land into the GBR has increased approximately four times;
- Since 1998, the GBR has suffered its two worst ever recorded coral bleaching events, caused by unusually hot sea water;
- The third series of crown-of-thorns starfish outbreaks since the 1960s;
- The commercial harvest of sharks and rays has increased fourfold since 1993;
- Over the last 40 years, numbers of nesting loggerhead turtles have declined by between fifty and eighty percent; and
- Estimates of dugong populations adjacent to the urban coast of Queensland indicate a major decline, with the populations currently only about three percent of what they were in the early 1960s.

Additional risks arise from introductions of alien species, particularly by ship ballast water discharge.

With respect to cumulative impacts, the *State of the Great Barrier Reef Report* noted that:

“Declining water quality and overfishing may be contributing to increasing outbreaks of crown-of-thorns starfish ... The cumulative pressure from climate change and coral bleaching events, declining water quality and other localised pressures on top of natural disturbance events poses a significant risk to the long-term health of the Great Barrier Reef.” (<http://www.gbrmpa.gov.au/>)

The different pressures can be broadly categorised as terrestrial, fisheries, population outbreaks, species introductions and climate change. The GBRMPA considers these priority issues, and interventions have and continue to be implemented to address the more manageable issues, such as sediment, nutrient and pesticide inputs in river run-off and fisheries (Section 3).

2.1 Terrestrial Pressures

Terrestrial pressures are chiefly related to the transport of sediments, nutrients, pesticides and other chemicals in the river systems flowing into the GBR Lagoon. As introduced above, terrestrial inputs to rivers and coastal waters of the GBR have increased dramatically since European settlement of the catchments in the mid 1800s (see, for example, Pulseford 1996, Neil *et al.* 2002, Furnas 2003b, McCulloch *et al.* 2003, Brodie and Mitchell 2005, among others). A clear signal of changes to catchments following European settlement (since the

1860s) has been discovered in barium isotopes stored in coral cores taken from massive *Porites* coral heads. This signal was not well correlated with Burdekin River floods, suggesting a potentially important role for local run-off.

With the increasing use of fertilisers over the past century, there has been a strong increasing trend in nutrient flux to the GBR Lagoon, with approximately fifty percent of applied fertilisers lost to streams, groundwater and the atmosphere, and a clear signal of catchment fertiliser use in nutrient export to the river systems (see Brodie *et al.* 2008).

Computer modelling suggests a two- to five-fold increase in total sediment input to the GBR Lagoon, with a two-fold increase in nitrogen (60% particulate) and four-fold increase in phosphorous (80% particulate). Nutrient input is directly correlated with sediments, with the majority discharged from the large dry catchment rivers and to a lesser degree from the Wet Tropics rivers, in eroded soils and following extensive fertiliser application for agriculture (Pulseford 1996, Neil *et al.* 2002). Overall, the three broad catchment areas of the GBR discharge on average approximately 20 million tonnes of sediment to the GBR Lagoon annually (Furnas and Mitchell 2001 and pers. comm.), with the Cape York catchment contributing <2 million tonnes (10% of total), the Wet Tropics >2 million tonnes (11%) and the Dry Tropics catchment some 14 million tonnes (79%).

In total, the GBR lagoon receives some 50,000 tonnes of nitrogen annually, with about half as particulate and half as dissolved forms (Mitchell *et al.* 1996, Furnas and Mitchell 2001, Furnas 2003b, Brodie and Mitchell 2005). Of this, the Dry Tropics catchment rivers deliver some 34,000 tonnes (69% of total), the Wet Tropics some 8,000 tonnes (17%) and Cape York some 7,000 tonnes (14%). Phosphorous export follows a similar pattern, with Dry Tropics catchment rivers discharging some 8,000 tonnes (82% of total), Wet Tropics some 860 tonnes (10%) and Cape York some 750 tonnes (8%) of the total of ~10,000 tonnes annually (Furnas and Mitchell 2001). Most phosphorous is delivered from eroded soils and through extensive fertiliser application for agriculture in the central to southern part of the Queensland catchments. By contrast, the northern Australian Cape York rivers are close to pristine, and the northern GBR receives little additional nutrient compared with pre-European settlement.

Most sediment and nutrient discharge to the GBR Lagoon is event-based, through floods that produce plumes with sediment and nutrient concentrations of 10–100 times ambient levels. Although most of the coarse sediments settle out close to the river mouths, fine sediments transported in the plumes can reduce water clarity over considerable areas, including near-shore and even mid- and outer-shelf coral reefs. The suspended solids in these plumes are usually of the order of only a few milligrams per litre (Taylor 1996, Larcombe and Woolf 1999), yet this muddy, nutrient-enriched sediment fraction may remain in the GBR ecosystem for months after discharge. The fine sediments pass through cycles of deposition and resuspension before being metabolised or trapped in bays (Fabricius and De'ath 2000).

Most plumes are generated from Wet Tropics rivers (six to seven plumes every ten years), whereas the major Dry Tropics catchment rivers, the Burdekin and Fitzroy, produce just one plume every ten years on average. Most plumes tend to hug the coast, moving in a northerly direction under the influence of prevailing near-shore currents and southeast winds. The main reef areas at risk from these plumes are the approximately 440 inshore reefs of the GBR system within 20 km of the coast, although northerly winds tend to push the plumes further offshore. There is a well-defined gradient in water quality across and along the GBR in relation to the major river discharges (Fabricius 2005, Fabricius *et al.* 2005).

There is also evidence of declining water clarity on inshore coral reefs during the 20th Century. For example, average underwater visibility at the Low Isles to the east of Port Douglas has declined from ~11 m in 1927-1928, to ~6 m today (Wolanski and Spagnol

2001). There is increasing evidence of changes in benthic biodiversity on fringing reefs due to sediment (and possibly nutrient) effects. Release of nutrients from sediments can enhance phytoplankton production, further contributing to increased turbidity. Recent CRC Reef-funded studies of corals, algae and fishes have identified strong regional trends along the water quality gradient, and a 400 km long region of low local-scale coral diversity adjacent to the Wet Tropics coast. This was attributed to the disturbance regime, with both natural and anthropogenic components, the latter including run-off (Fabricius and De'ath 2000, Fabricius *et al.* 2005, DeVantier *et al.* 2006).

Fabricius (2005) identified four fundamentally different processes that have to be distinguished when assessing the effects of terrestrial run-off on coral reefs, arising from:

- Dissolved inorganic nutrients;
- Enrichment with particulate organic matter;
- Turbidity-related light limitation; and
- Sedimentation.

“Responses to terrestrial run-off therefore depend on whether changes occurred predominantly in sedimentation, turbidity, particulate organic matter or dissolved inorganic nutrients. In most places, reduced recruitment success in corals, together with the promotion of macroalgae and *A. planci*, arguably represent the most significant direct effect of terrestrial run-off on coral reefs. In severe conditions, the overall outcome is reduced reef calcification, shallower photosynthetic compensation points, changed coral community structure, and greatly reduced species richness. Hence reef ecosystems increasingly simplify with increasing exposure to terrestrial run-off, compromising their ability to maintain essential ecosystem functions at the presently increasing frequencies of human-induced disturbances.” (Fabricius *et al.* 2007)

For seagrasses, six categories of (mainly) terrestrial threats have been identified (Rasheed *et al.* 2007c) for high risk areas of the GBRWHA: coastal development (e.g. marinas, boat ramps, reclamations, aquaculture); port activities (e.g. dredging); urban and industrial run-off; agricultural run-off (includes river/flood inputs); oil/chemical spills (proximity to high risk areas of shipping lanes); and localised physical disturbances (e.g. anchoring, bait worming). The impacts of these vary among locations. For example:

“Sediment and nutrient loads associated with agricultural land use may have exacerbated the impact on seagrass of a flooding event in Hervey Bay leading to the loss of 1,000 km² of seagrass (Preen *et al.* 1995). However it is difficult to know whether catchment impacts in Queensland have led to overall increases in seagrass growth, or amplified natural losses through increased soil erosion, caused sub-lethal stresses, and slowed the recovery of seagrasses after loss (Lee Long *et al.* 2000).” (Coles *et al.* 2007)

Globally, seagrass beds are an increasingly threatened ecosystem (Orth *et al.* 2006), and like the adjacent coral reefs, are considered as “the coal mine canaries of coastal ecosystems” (Dr. William Dennison of the University of Maryland Center for Environmental Science): “The fate of seagrasses can provide resource managers advance signs of deteriorating ecological conditions caused by poor water quality and pollution.” Another recent international study proposed that indirect consumer effects, rather than eutrophication *per se*, are the primary drivers of coastal benthic ecosystem structure and function, including in seagrass beds and coral reefs (Heck and Valentine 2007):

“Most studies of eutrophication have been conducted long after the numbers and diversity of larger marine consumers were dramatically reduced by centuries of intense harvesting. It is now understood that these once abundant predators played pivotal roles in regulating ecosystem structure and function, and that the widespread overharvesting of large consumers can trigger indirect effects that alter species compositions in ways that are very similar to those reported to result from eutrophication. All of this suggests that we should re-evaluate whether the many negative effects attributed to eutrophication are actually a result of nutrient additions or whether they may be the result of the indirect effects of dramatically altered coastal food webs”.

2.2 Fisheries Pressures

The present level of fishing in the GBRMP of ‘biologically sensitive’ groups such as sharks (with slow rates of reproduction), from the more accessible areas such as nearshore reefs and shoals, may be unsustainable in the long term. From 1990 to 2001, fishing effort increased from some 23,000 primary boat-fishing days (Pbfd) to more than 41,000 Pbfd, for total landings of some 4,400 tonnes of fish (Williams 2002, Goggin *et al.* 2003).

Since 1991, commercial fishing licenses to operate in Queensland waters have been capped in an attempt to reduce potential for over-fishing. Approximately forty percent of the total 2,679 licenses that were registered on the Queensland Fisheries Service database were engaged in hook-and-line fishing, with a significant number of these also conducting trawling (24%), crabbing (28%) and/or netting (32%) (Fenton and Marshall 2001). Line fishing, most actively undertaken between June and November, is concentrated along much of the GBR in numerous coastal and offshore areas. As noted above, the ELF study found that the closure of reefs to fishing had a significant positive effect on local stocks of some species (<http://www.reef.crc.org.au/>). This finding was incorporated in the recent rezoning of the GBR, and is the subject of continuing MTSRF-supported research. Since the 2004 rezoning, there has been significant ‘buy-back’ of licences and other management measures (Section 3).

There have also been significant shifts in effort and focus among fisheries over the past decade, notably the emergence of the live food fish trade. Until 1993, there was no live fish trade in GBR waters – all fish were marketed locally or internationally as chilled whole fish, frozen fillets or gilled and gutted fish. By 2000 almost half of the coral trout (*Plectropomus* spp.) catch was exported live to international markets, mostly in East Asia. Under Queensland legislation, live fish must be transported back to port by the fisher and sold to a licensed fish buyer. Prices for live fish are up to three times those for dead fish, providing a lucrative incentive to develop the live fish export industry. Fishing effort for the live fish market increased rapidly (e.g. from some 100 days in 1993 to 19,200 days in 2001; Williams 2002, Goggin *et al.* 2003). This raised concerns among fisheries managers of unsustainable levels of fishing effort, with reactivation of previously unused licenses, also addressed in recent management initiatives (Section 3). In 2004, the annual total allowable catch (TAC) of coral trout, the main target of the GBR live fish trade, was set at 1,350 tonnes, the level of catch taken by the commercial fishing sector in 1996, thought to represent full exploitation of stocks across the GBR (Russell 2006). The increased focus on live fish has helped to reduce bycatch and may prove ecologically less damaging than traditional fishing, in that non-target species are regularly caught but are returned live to the sea.

Various recent management initiatives notwithstanding (Section 3), significant issues remain, not least with respect to long-term ecological sustainability and potential for cascading impacts on other non-fished species groups, as well as the need for compliance and

enforcement of regulations. For the inshore GBR, most exploited by the net fishery and recreational fishing sector, it has been noted that:

“The vast area of the GBRMP and the remoteness of many reefs mean that surveillance and enforcement of the marine park is problematic. It is evident that the inshore reefs are the most adequately patrolled and protected areas of the GBRMP. However it has been shown that there is a low level of poaching in green zones of these inshore reefs by recreational fishers (Davis *et al.* 2004). There is documented and much anecdotal evidence that poaching of reserves occurs more extensively within the GBRMP, particularly in remote areas where surveillance levels are low (Gribble and Robertson 1998). Furthermore, fish stocks on the near shore fringing reefs have been exposed to significant levels of fishing mortality for decades. The data presented in Williamson *et al.* (2004) suggests that stocks of coral trout were locally depleted on these fringing reefs as early as 1983/1984 and have remained in that state on reefs which have remained open to fishing.” (Russ *et al.* 2007a)

The commercial trawl fishery that targets prawns (mostly *Penaeus* spp.), was, until the recent effort-capping and rezoning, conducted by just under half of the total commercial fishing businesses in Queensland waters (47% of fishers, with approximately 9% of licenses unused) (Fenton and Marshall 2001). Trawling occurs throughout the year, although recent introduction of seasonal closures has affected this pattern. Within the GBR, the most common areas for trawl fishing were Princess Charlotte Bay in the far northern area, and coastal areas between Port Douglas and Cairns, Innisfail and Bowen, and Yeppoon and Hervey Bay. The trawl fishery produced far more bycatch than product (6-10 times), by far the largest tonnage of bycatch in the GBRMP (GBRMPA Fisheries Group), and also caused significant disturbance to seabed habitats and biodiversity.

The net fishery also takes significant bycatch, including threatened species of turtle and dugong, the latter particularly in nearshore waters. With respect to dugong, a key species of conservation concern, Marsh *et al.* (2007) note the following:

“The main threats in the northern GBR and Torres Strait are:

1. The bycatch of dugongs in commercial gill net fisheries (northern GBR);
2. Unknown levels of harvest by Indigenous Australians (both regions);
3. Unknown levels of harvest by neighbouring countries of the Asia/Pacific region, especially PNG (Torres Strait);
4. Illegal poaching by Australians and foreign fishers (both regions but especially Torres Strait); and
5. Marine debris (unquantified but likely in both areas).

In our opinion the major threats to the dugong in this region are [points] 2, 3 and 4 above.”

The effects of the 2004 rezoning, the largest designation of ‘no-take’ zones globally, on both reefal and inter-reefal fish stocks, and other recent management initiatives (Section 3) are key topics of MTSRF-supported research (Sections 4 and 5 and Appendix 1).

2.3 Population Outbreaks and Diseases

The first reported outbreak of the Crown-of-thorns starfish (COTS) on the GBR occurred at Green Island Reef in 1962, subsequently spreading to many reefs of the central third of the system by the mid-1970s. A second series of outbreaks occurred from 1979 to the late 1980s. A third series of outbreaks began in the early 1990s. The three outbreak series have repeatedly affected many of the same reefs, particularly on the mid- and outer-continental shelf between Cooktown and Proserpine (<http://www.aims.gov.au/reef-monitoring>). Some reefs of the Swains complex of the southern GBR have also sustained outbreaks throughout much of this period. The outbreaks have recurred on individual reefs after ~15-17 years, causing repeated loss of up to 90% of living cover of the reef-building corals and major short-term reductions in coral diversity, although there has been considerable variability in intensity of predation, both within and among reefs (Done 1987, 1988). Recovery of the coral cover has taken a decade or more, with some evidence of a slowing in its rate (Seymour and Bradbury 1999), and increasing concern for the overall status of GBR reefs (Pandolfi *et al.* 2003, Bellwood *et al.* 2004).

With respect to the historical pattern of outbreaks prior to the 1960s, work supported by the CRC Reef on the dating of old, dead 'scarred' surfaces on long-lived massive corals concluded that while it is likely there have been past sporadic outbreaks on the GBR and elsewhere, the frequency and geographic spread of outbreaks has increased during the 20th Century, coincident with increasing human use of the GBR for fisheries and changing run-off following modifications of the catchments. The old coral scar patterns provided inferential evidence of outbreaks prior to the 1960s, most notably in the 1930-1940s, increasing in frequency and geographic spread in recent decades.

"The evidence suggests that outbreaks are neither completely natural nor entirely human-induced. Rather, what appear to have been isolated and sporadic events in the past are now more widespread and frequent. In retrospect, the earlier polarization of the controversy into the natural versus anthropogenic dichotomy, with their respective corollaries of 'do-nothing' versus 'intervention' or control, now appears simplistic. The seastar is apparently adapted to major population fluctuations, yet the initiation, propagation and ecological effect of outbreaks may all be linked with human activities." (DeVantier and Done 2007)

COTS population dynamics, and the development of 'early warning' systems are current areas of MTSRF research (Section 4 and Appendix 1).

Disease outbreaks for key faunal groups on the GBR, such as the reef-building corals, appear to be increasing in recent years, coincident with warming of the sea. There is, for example, a highly significant positive relationship between the frequency of warm temperature anomalies and the frequency of 'White Syndrome', a common disease of Indo-Pacific reef-building corals (Selig *et al.* 2006). These authors also reported a highly significant, 'nearly exponential' relationship between total coral cover and the number of disease cases.

"Both high coral cover (>50%) and anomalously warm water appear to be necessary for white syndrome outbreaks to occur ... These results suggest that rising ocean temperatures could exacerbate the effects of infectious diseases on coral reef ecosystems." (Selig *et al.* 2006)

2.4 Introduced Species

Foreign marine species have been accidentally brought into Australian ports on ships' hulls or in ballast water. Such introductions have caused major ecological damage and economic losses elsewhere in Australia, although fortunately no such major impacts have become apparent to date on the GBR.

"A 1997 risk assessment examining introductions to twelve tropical ports in Queensland (Australia) concluded that far fewer marine species appeared to have been introduced, even at major bulk export ports where the number of ship visits and volume of discharged ballast water are more than at most of Australia's cooler water ports. Results from recent surveys looking for introduced species in tropical ports across northern Australia are beginning to support this conclusion, although the lack of historic baseline surveys and the poor taxonomic status of many tropical groups are preventing a precise picture." (Hutchings *et al.* 2002)

The biological, ecological and economic effects of such introductions are potentially a major issue for the GBR and are a continuing focus of management (Section 3).

2.5 Climate Change

Climate change has become a major over-arching threat, highlighted in the IPCC (2007) reports, on which MTSRF researchers Professors O. Hoegh-Guldberg and T. Hughes (UQ and JCU, respectively) provided advice. The summary report of Working Group 2 on impacts, adaptation and vulnerability (<http://www.ipcc.ch/>) specifically acknowledged the GBR:

"Significant loss of biodiversity is projected to occur by 2020 in some ecologically-rich sites including the Great Barrier Reef and Queensland Wet Tropics."

Details of the physical science underpinning the reports, and the most recent predictions, are available via the IPCC website (<http://www.ipcc.ch/>).

The GBR is threatened by climate change through a number of direct and indirect mechanisms (Veron, in press), including temperature rise, changes in ocean chemistry and physical oceanography, effects on large-scale weather systems such as ENSO, and effects on local tropical storm frequency and intensity.

As introduced above, anomalously high sea surface temperatures have already caused major mortality of reef corals (Marshall and Baird 2000), particularly during the 1998 and 2002 bleaching events (Berkelmans *et al.* 2004). In 1998, more than forty percent of the GBR was affected by varying levels of bleaching. In 2002, more than fifty percent was affected, with resultant changes in the structure of coral reef communities, mostly on near-shore reefs of the central and southern GBR. Surveys of the entire length of the GBR, of over 600 reefs during the 2002 bleaching event, indicated that damage was not uniform but confined to the coastal areas except in the Townsville region where bleaching extended to the outer reefs (Berkelmans *et al.* 2004). This pattern differed from the 1998 bleaching event where damage was confined to the inner reefs.

Since 1970, water temperatures of the GBR region have increased between 0.2-1°C, and the warming trend is predicted to continue (Steinberg 2007). This is of particular concern for the GBR, which is likely to be highly prone to future temperature increases and episodic heatwaves, developed as it is on a continental shelf highly enclosed by the outer barrier

reefs, and with the vast majority of reefs bathed by shallow (mostly <80 m depth) GBR Lagoon waters.

Even under a moderate warming scenario of 2°C by 2100, mass coral bleaching may be an annual event on at least parts of the GBR. This could be the case within the next 25 years, and almost certainly by 2050, as corals on the GBR are likely to be exposed to summer temperatures that regularly exceed their current thermal thresholds (Hoegh-Guldberg 1999, Guinotte *et al.* 2003). Because recovery times for coral cover of a decade or more typically follow severe bleaching events that cause high coral mortality, corals on large portions of the GBR could be replaced by seaweeds, unless acclimation and/or adaptation occurs at a very rapid rate (T. Hughes and O. Hoegh-Guldberg pers. comm.). Rates of acclimation and/or adaptation are a major focus of MTSRF research (Sections 4-6 and Appendix 1).

“Reef organisms have evolved adaptations over hundreds of millions of years to cope with recurring disturbances: damage or destruction, followed by recovery or regrowth. These are natural features of coral reef history. However, recent global increases in reef ecosystem degradation and mortality (the ‘coral reef crisis’) appear to be sending a clear message that the rate and nature of recent environmental changes are frequently exceeding the adaptive capacity of coral reef organisms and communities ... leaving few, if any, parts of the ocean truly hospitable for healthy coral reef communities.” (Buddemeier *et al.* 2004; also see Guinotte *et al.* 2003)

Increasing thermal stress may also be linked with recent increases in the severity and frequency of disease epidemics (Selig *et al.* 2006). Diseases and mass bleaching can also affect coral recovery following other disturbances, synergistically reducing resilience. For example, GBR coral communities exhibited strong recovery following repeated disturbances during the 1960s-1980s (e.g. Done 1992a, 1999). Following cyclones and crown-of-thorns starfish outbreaks that caused high levels of coral death, corals exhibited rapid, high recruitment from ‘upstream’ reefs, facilitating return of cover and diversity in approximately 10-15 years.

This resilience is now threatened, as the previous key refugia and sources of larval supply following starfish outbreaks in very shallow waters were most severely impacted by the bleaching events of 1998 and 2002. Long-term losses of coral cover and diversity can produce cascading impacts for associated biota, as with reef fishes (e.g. Jones *et al.* 2004).

For the GBR’s seagrasses:

“It is likely that global climate change will lead to an alteration of seagrass habitats. Increased temperatures can alter seagrass growth rates and other physiological functions. The distribution of seagrasses is likely to shift as a result of increased temperature stress to existing plant populations and changes in the patterns of sexual reproduction (Short *et al.* 2001). Global climate change affects sea level, increasing water depths, changing tidal variation, altering water movement, and increasing seawater intrusion into estuaries and rivers. Climate change will result in greater storm frequency and intensity. A major impact of all these changes on seagrasses will be a redistribution of existing habitats. The impact of increases in CO₂ will vary between species and environmental circumstances, but could affect seagrasses by altering the competition among species as well as between seagrass and algal populations. Increases in UV-B radiation resulting from climate change may inhibit photosynthetic activity, and add to the increased metabolic cost of producing UV-B blocking compounds within plant tissue. The effects of UV-B radiation will likely be strongest in the tropics and in southern oceans (Short *et al.* 2001).” (Coles *et al.* 2007)

Change in ocean chemistry – the increasing acidity from increasing CO₂ dissolving in the ocean – is another serious, and perhaps more insidious, threat (Kleypas *et al.* 1999, Veron in press). Average pH of ocean surface water has fallen by 0.1 units in the last two centuries. A continuing increase in acidity is predicted to reduce the capacity for corals and other calcifying organisms to extract aragonite from seawater to build their skeletons, with major ramifications for the GBR, as indeed for reefs and other marine systems globally.

The effects of climate change may also be manifested through changes in the frequency and intensity of ENSO events, with flow-on effects on temperature, rainfall and run-off. Other potentially important effects include increases in intensity and/or frequency of severe tropical storms and changes in ocean currents. As introduced above, a key element of ecological resilience on the GBR is the oceanographic connectivity imposed on the system by the bifurcation of the SEC and long-shore flow of the East Australian and Hiri Currents (Church 1987, Steinberg 2007). The GBR is predicted to experience significant climate change-related impacts on physical oceanography and circulation (Steinberg 2007), with ramifications for habitats and biodiversity.

At present, there is only small seasonal variation in the SEC, the main driver of circulation in the Coral Sea. Future variations in the strength and breadth of the SEC are critical to circulation in the GBR. The relative contributions of the various zonal jets entering the Coral Sea are predicted to vary the location of the bifurcation in the SEC and hence the relative strengths of the south-flowing EAC and north-flowing Hiri Current (Steinberg 2007). The EAC and Hiri Current are expected to increase in strength through direct forcing from the SEC, although whether one current strengthens at the expense of the other remains uncertain (Steinberg 2007). If the SEC bifurcation moves south, central GBR currents may weaken and reverse and the Hiri Current may deepen the thermocline, resulting in central and southern GBR reefs experiencing a reduction in nutrients and warmer waters (Steinberg 2007).

The EAC will likely exhibit more pulsing due to stronger southeast winds in the Coral Sea, impeding the poleward flow (Steinberg 2007), although modulations from the Asian monsoon and ENSO will likely dominate variability. If local atmospheric perturbations in the wind and pressure fields increase, waves are likely to increase in strength. However tidal currents are not expected to increase significantly, although the tidal range will increase as sea levels rise, according to local shelf and coastal topography (Steinberg 2007). Tides centred on Broad Sound, north of Rockhampton, are likely to show the largest increase along the GBR. Upwelling is projected to be highly variable and episodic (Steinberg 2007).

It is fair to say that climate change took most, if not all, of the world's marine scientists and managers by surprise in the 1990s. Since then, research and management agencies have been increasingly focused on understanding and addressing the issue (e.g. Schuttenberg and Marshall 2006). Yet major gaps remain in our understanding. For example, in 2006 the Australian Greenhouse Office reported (<http://www.climatechange.gov.au/impacts/publications/>):

“Evidence from Australian waters is sparse, mainly due to a lack of historical long-term data collection. Importantly, little modelling has been conducted to predict future changes in Australian marine ecosystems and this remains a critical gap. This report identified six key questions that need to be addressed by future modelling and monitoring programmes:

1. How will the distribution and abundance of marine species and communities alter with climate change?
2. Which species are candidate indicators for climate change impacts?

3. Within large marine domains, where are sensitive areas or hotspots of change?
4. How will ocean productivity alter with climate change?
5. How would reduction in non-climate related stressors increase ecosystem resilience to climate change?
6. To what extent will marine climate change impacts affect socially and economically important uses of Australian marine ecosystems?"

These questions are major research areas for the MTSRF (Sections 4-6 and Appendix 1).

3. Recent Management Initiatives

Coincident with development of the various research themes over the past decade, the rapid application of results in management has improved to the point where the GBR is now widely recognised as both the best-researched and best-managed large reef ecosystem on Earth. In both these respects, the GBR is an important global model. Yet at the same time, the GBR has also been identified as one of the world's iconic ecosystems most at risk in the coming century from climate change. Management-focused research on the GBR is thus of rapidly increasing national and global significance.

Several new management initiatives have recently been introduced (<http://www.gbrmpa.gov.au/>). A Climate Change Response Programme developed by the GBRMPA receives scientific advice from the MTSRF and partners. This was designed to improve understanding of the ecological and socio-economic risks and impacts of climate change, and to explore mechanisms to increase resilience of the ecosystem, communities and industries that depend on it.

Terrestrial impacts are being addressed through the Reef Water Quality Protection Plan ('Reef Plan'), involving collaboration between the GBRMPA and State Government agencies, local governments and communities.

Over the coming decade, implementation of the Reef Plan is aimed at halting and reversing the decline of water quality in coastal catchments, and is expected to improve land management practices in the catchment area. Various research and monitoring studies assessing water quality and ecosystem health with respect to the Reef Plan's effectiveness in reducing pollutant loads to the GBR are occurring under the MTSRF.

Recent increased support for improving water quality has been provided in the federal budget of 2007-08:

"This Budget commits a further \$14.2 million over four years from the Natural Heritage Trust to comprehensive monitoring and reporting of water quality and ecosystem health of the Great Barrier Reef lagoon ... This funding will also help to gauge the success of strategies being implemented to improve water quality. This includes the ongoing implementation of the ten-year Reef Water Quality Plan agreed to by the Australian and Queensland Governments in 2003 to halt and reverse the decline in water quality from land based sources, with about 26 rivers flowing into reef waters." (Minister, DEW).

To address exotic pest introductions in a coordinated manner, the Consultative Committee on Introduced Marine Pests Emergencies was established in 2000. Port surveys have been conducted through the Australian Association of Ports and Marine Authorities and the CSIRO Centre for Research on Introduced Marine Pests (Australian State of the Environment Committee 2001). In providing better management support, the surveys form part of Australia's Decision Support System, administered by the Australian Quarantine and Inspection Service (AQIS), which will incorporate results from surveys nationwide. The Decision Support System will help to estimate the risk of a particular vessel that could be a carrier of alien species, and thus will act as a risk assessment tool. On the GBR and in Torres Strait, surveys for introduced species were conducted by CRC Reef researchers in the ports of Weipa, Karumba, Cairns, Lucinda and Townsville.

Addressing these risks, particularly risks associated with transport via ship ballast water, has recently received additional Federal support. The Australian Government has allocated \$AUD14.8 million over four years to implement the 'National System for the Prevention and

Management of Marine Pest Incursions'. This will establish national legislation for ballast water with regulations to ensure vessels entering Australia, including the GBR, are not fouled with marine pests:

"This decision will ensure that Australia meets its obligations as a signatory to the International Convention for the Control and Management of Ships' Ballast Water and Sediments." (Minister DEW)

To minimise fishery impacts, recent management initiatives have included negotiation of improved regulation of the East Coast Trawl Fishery, the Coral Reef Finfish Fishery and the Tropical Rock Lobster Fishery. New regulatory interventions on fishing gear and area restrictions have been introduced. The removal of commercial netting latent effort in the Queensland East Coast Finfish Fishery by the QDPI&F began in mid 2004 (<http://www.gbrmpa.gov.au/>). The Coral Reef Finfish Fishery Management Plan (2003) established a Total Allowable Catch (TAC) and Individual Transferable Quota (ITQ) system for the commercial sector from 2004. New fish-size and bag limits were introduced for the commercial, charter and recreational sectors. Fish spawning season closures were also introduced (Russell 2006).

Three nine-day spawning season closures occur over the new moons in October, November and December each year, covering all fishes in the coral reef finfish fishery (Russell 2006). Enhanced protection of fish spawning aggregation sites (Samoilys 1997, Russell 2001) is also proving effective. For example:

"Preliminary site assessments one year after the rezoning of Scott Reef as a green zone have shown that the numbers of leopard coral grouper visiting the spawning aggregation site have increased. In contrast, the numbers of leopard coral grouper visiting the Elford Reef spawning aggregation site [open to limited fishing] have remained relatively constant ... However, it is too soon after the rezoning to conclusively determine if the rezoning has affected the number of fish visiting these spawning aggregation sites ... The management measures on the GBR are exceptional in that a precautionary approach has been taken, to a certain extent, to ensure the long-term sustainability of the reef fish resources. This is preferable to the many situations around the world in which management measures, such as spawning season closures, were introduced only after it was found that spawning aggregations were in decline." (Russell 2006)

Export fisheries are, since November 2004, strategically assessed against the Australian Government guidelines for ecologically sustainable management under the *Environment Protection and Biodiversity Conservation Act 1999*. Several fisheries have now been given provisional export approval, subject to their meeting recommendations imposed by the Australian Government (<http://www.gbrmpa.gov.au/>). Vessel monitoring systems (satellite tracking devices) are mandatory on some five hundred commercial fishing vessels operating in the GBRMP, including trawlers and fishing vessels that target sea cucumbers and trochus (<http://www.gbrmpa.gov.au/>).

A restructuring package linked with the 2004 rezoning resulted in some commercial operators leaving the fishery. In summary, recent restructuring and effort-capping in the trawl and reef line fisheries have likely improved sustainability, while causing some job losses and social disruption among fisher families (Section 4 and Appendix 1).

Destructive aspects of fisheries are also being addressed, particularly those that impact on species of conservation concern such as dugong and turtles, for example, through effort-capping and implementation of aerial and seasonal closures in the trawl fishery. In 2001 a revised East Coast Trawl Management Plan capped fishing effort at the 1996 level,

introduced a tradeable effort quota system, and closed an additional 96,000 km² of the GBRMP to the fishery (<http://www.gbrmpa.gov.au/>). Additionally, since 2002, by-catch reduction devices and turtle excluder devices have been mandatory in trawl nets within the Park. A 37% reduction in trawl effort has occurred from the 1996 level, the number of vessels having declined from 850 in the late 1990s to some 450 at present (<http://www.gbrmpa.gov.au/>), via the combination of structural adjustment schemes, penalty units and licence surrenders.

Closures of areas to net fishing, chiefly to protect dugong, have also been introduced, with establishment of Dugong Protection Areas (DPAs) at sixteen locations along the Queensland coast since 1997. These areas should contribute to the maintenance of dugong populations provided (a) no illegal fishing occurs; (b) that quality seagrass habitat survives; and (c) migrating dugong do not suffer mortality between the DPAs. Management agencies recognise that loss of habitat and habitat quality are crucial issues for maintaining dugong populations, as indeed for maintenance of food webs more generally, with increasing awareness of the risks of trophic cascades. Implementation of the new zoning plan in 2004 resulted in significant expansion in areas within the GBR closed to commercial and recreational fishing.

“The zoning and management arrangements in operation since January 2005 have greatly reduced the risk to dugongs from commercial netting in the Northern Great Barrier Reef region by area closures and effort reduction. Commercial netting is now banned from approximately 64% of the high density dugong habitat, 44% of medium density dugong habitat and 31% of low density habitat. However the actual area where netting is now conducted is much less than these figures indicate: 4% of the high density dugong habitat, 9% of medium density habitat and 7% of low density habitat (Grech *et al.* in review). Grech *et al.* (in review) have identified areas where additional spatial closures would significantly reduce the remaining risk of netting to dugongs.” (Marsh *et al.* 2007)

Following the expansion of green zones, day-to-day management of the GBRMP has recently received increased federal support:

“Another \$15.6 million over four years will support the day-to-day management of the Great Barrier Reef Marine Park. This follows the recent increase in levels of protection within the Marine Park and last year's comprehensive review of the Marine Park legislation.” (Minister, DEW)

As introduced above, the Representative Areas Program (RAP) used a suite of biological, ecological, geomorphological and physico-chemical datasets to identify thirty reefal and forty non-reef bioregions (Fernandes *et al.* 2005). This bioregionalisation was used as the basis for the major revision of the zoning plan (Figure 2).

The RAP built a scientific consensus on the need for increased proportional representation of highly protected areas (‘no-take’ green zones). If of sufficient size and in a dispersed configuration, the zones were considered likely to provide ‘insurance’ towards maintaining the resilience of GBR ecosystems, maintaining biodiversity and replenishment of adjacent areas through ‘spill-over’ and larval recruitment (Fernandes *et al.* 2005). The dispersal of larvae between reefs, modelled mathematically, was used to identify key ‘source’ reefs as well as likely ‘sink’ reefs which may be more easily replenished. It was recognised that green zones do not operate in isolation and external pressures must also be managed. Green zones form important points of reference when assessing status and trends in ecological condition or ‘health’, particularly as a benchmark or ‘baseline’ for comparison with areas where protection levels are lower and human disturbance may be causing changes in the system (Fernandes *et al.* 2005).

“The new Plan introduced a scientifically-based network of protected areas that provides better protection for all the types of habitats and biodiversity found in the Great Barrier Reef Marine Park. This network will also help to ensure that the biodiversity and ecological functions and connections that sustain the Great Barrier Reef are maintained ... The new Zoning Plan came into effect on 1 July 2004 and increased the total percentage of highly protected (‘no-take’) areas from 4.6% to 33.3% of the Great Barrier Reef Marine Park.” (<http://www.gbrmpa.gov.au/>)

In relation to the ‘flow-on’ effects to tourism, for example, it has been suggested (GBRMPA 2003, Hand 2003) that:

“The health of the GBR afforded by the Representative Areas Program will encourage domestic and international visitors to choose the Marine Park over other destinations. Given the increased attractiveness of a well-maintained reef ecosystem when many other reefs around the world are suffering from degradation, visitor numbers to the GBR are likely to increase. Even a minor increase in visitor numbers, such as 5%, would represent a considerable boost to the economic impact of the tourism sector in the region. Overall, GBR catchment tourism is forecast to grow by 15.4% over the period 2001-2010 and 30.5% over the period 2010-2020, giving total forecast growth for 2001-2020 of 50.6%.” (Sutton 2007)

Effectiveness of the rezoning and other recent management initiatives, particularly in relation to biodiversity conservation, ecological resilience, replenishment of fisheries and tourism, are important questions for management. In these respects, the GBRMPA has identified key research directions under 22 research themes encompassing 274 questions, 21 of which were considered of critical importance (Appendix 4) http://www.gbrmpa.gov.au/corp_site/info_services/science_management/research_priorities/database/).

The key research themes include:

- Effects of Zoning;
- Water Quality and Pollution;
- Protection of Threatened Species;
- Ecologically Sustainable Fisheries;
- Impacts and Mitigation of Climate Change;
- Managing Diseases and Introduced Pests;
- Protecting Ecosystem Resilience;
- Understanding and Responding to Community in a Multiple-Use Environment;
- Understanding Biodiversity; and
- Monitoring the Health of Major Habitat Types.

Many of these key themes and questions are current areas of MTSRF research (Appendix 4). The initial results of these projects are discussed below.

4. Role and Outputs of the MTSRF 2006-2007

MTSRF-funded research, in close partnership with agencies and universities including AIMS, CSIRO, JCU, UQ and QDPI&F, is well positioned to provide answers to the key research questions, thereby supporting management of the GBR and providing global leadership in targeted tropical marine science. These goals are being achieved across the themed research areas, each incorporating wide-ranging programs and focused projects. Some of these are continuations of previous research by the CRC Reef and other institutions, and have progressed across the MTSRF transitional period of 2005-2006; others are new and tailored to addressing recently emerging research and management priorities. The programs contain biophysical, ecological and socio-economic projects, developed in light of the key research questions identified by the CRC Reef and GBRMPA. Those of major relevance to the present report are listed below:

Theme 1: Status of Ecosystems

- Program 1: Status and trends of species and ecosystems; and
- Program 4: Species and communities of conservation concern.

Theme 2: Risks and Threats

- Program 5i: Climate change;
- Program 6: Invasive pests.

Theme 3: Water Quality

- Program 7: Halting and reversing the decline in water quality.

Theme 4: Sustainable Use and Management

- Program 8: Sustainable use and management of marine resources of the GBR.

An important cross-cutting aspect in synthesising results for government and industry is the development of a suite of indicators of ecosystem health and thresholds of concern to environmental conditions and disturbances. Because the response(s) or performance of different indicators will vary, composite indicators based on multi-variable approaches will likely prove most informative, and are a major research focus, across both biophysical and socio-economic areas. As the work progresses, the indicators and thresholds will inform the 2009 'Outlook Report' to be prepared by the GBRMPA, and policy more generally.

This and Section 5 of this report synthesise key MTSRF findings to date for the inshore GBR (reefs, shoals and seagrasses) and mid- and outer GBR (reefs, cays and inter-reefal seabed) respectively, across the four themes in relation to the major risks, threats and management issues identified above. A brief summary of the rationale, objectives and progress in each project is included in Appendix 1 (see also <http://www.rrrc.org.au/>).

4.1 Inshore GBR

As introduced above, the inshore region of the GBR is most affected by the adjacent landmass, notably through river run-off and fishing (particularly netting). The generally shallow waters (<50 m depth) and reduced oceanic exchange place the nearshore GBR at significant risk from climate change.

With respect to terrestrial pressures and water quality, a better understanding has been gained of fluxes and flows into GBR waters, and the locations of sediment deposition

(Fabricius *et al.* 2007). Results from flood studies in early 2007 confirm that most suspended sediments do not reach the main reef tracts of the mid- and outer shelf, but rather are deposited inshore and in the lee of continental islands, at rates of $>700 \text{ mg cm}^{-2}$ (recorded over a sixteen-day period in January and February of 2007). High levels of sediment resuspension can cause major reductions in light penetration (e.g. total darkness below 5 m depth). Further, the rapid nearshore deposition of most sediment notwithstanding, major flood plumes pass through and across the entire reef tract, particularly in the area northeast of Cape Grafton, likely resulting from topographic forcing by the Cape (Figure 5). Passage of flood plumes through the area has a major influence on water quality parameters there, including locally elevated levels of chlorophyll that have recently been correlated with outbreaks of crown of thorns starfish (G. De'ath, MTSRF Conference 2007, see <http://www.rrrc.org.au/news/2007conf.html>).

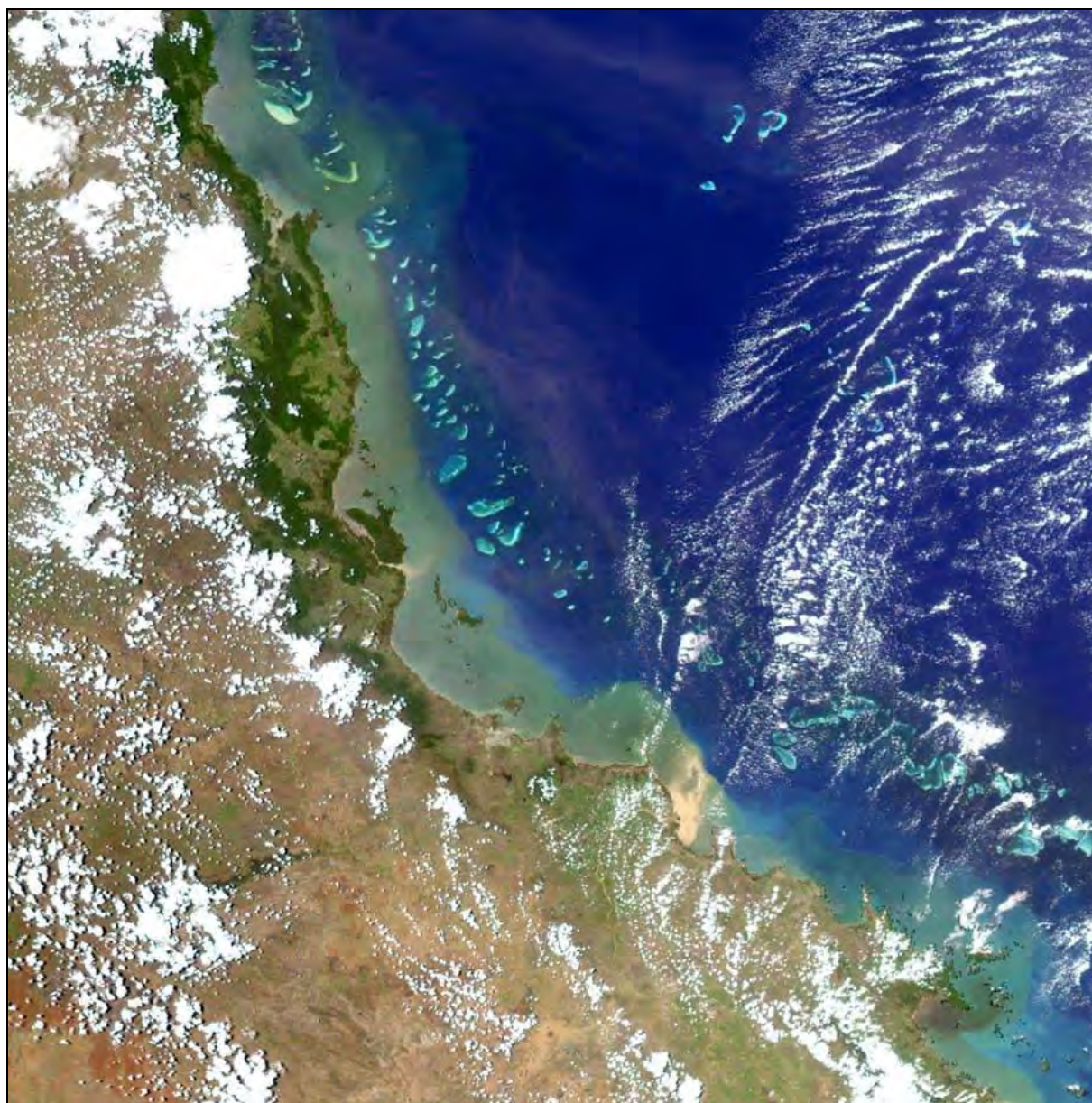


Figure 5: MODIS satellite image of flood plume on the Great Barrier Reef in February 2007.

Although water quality remains something of a 'black box' in terms of identifying the most important components and drivers of ecological change on the GBR, four main components have now been identified (Fabricius *et al.* 2007):

1. Dissolved inorganic nutrients;
2. Sediment;
3. Particulate organic matter and phytoplankton; and
4. Light reduction / attenuation.

An important area of current research is distinguishing the relative importance of these and of any interactions and synergisms among them.

Development of abiotic and biotic indicators of water quality is now well advanced, having progressed through the following series of steps (Fabricius *et al.* 2007):

1. Definition of the function and role of the proposed indicators;
2. Assessment of the many potential indicators in the field;
3. Prioritisation, based on temporal and spatial variability, specificity and ease of measurement through the review of data;
4. For priority indicator candidates, conduct of laboratory tests and field verification, development of dose-response relationships, and identification of threshold concentrations; and
5. Development of a rating system / index, and formation of an indicator system.

Among the abiotic indicators, only 0-40% of the variation in water quality parameters is typically predictable, with chlorophyll and suspended solids being relatively well predicted and derivatives of nitrogen being very poorly predicted (De'ath 2007). There are several relevant spatial and seasonal trends, with a degree of synchrony in seasonal trends among different parameters. Five particulate nutrients have been investigated as an aggregate measure: chlorophyll, phaeophytin, particulate phosphorous, particulate nitrogen and suspended solids. Of these, chlorophyll levels and suspended solids-water clarity (Secchi disk data) are the most useful, minimising problems with sampling, measurement and laboratory analyses (De'ath 2007).

"Concentrations of all water quality parameters decrease by 50-80% from the coast to a distance 15-20% across the Reef. From 20% across the Reef to the outer Reef, they typically decrease by an additional 0-20%. This inner coastal strip should be the focus of future monitoring, with fixed sites and automated logging of a few selected parameters, perhaps water clarity and chlorophyll. This cross-shelf pattern of strong decline in the near-shore varies along the coast for many water quality parameters, and is typically much steeper in the central third of the GBR and much flatter in the far north. Synchronised cyclical seasonal variation occurs for most of the water quality parameters. Nutrients typically peak in March-April and are 10-50% lower in August-September. This seasonal variation must be accounted for in sampling programs." (De'ath 2007)

Thus, taking chlorophyll as an example, highest concentrations occur nearshore and decline rapidly offshore (e.g. twenty percent of the distance across reef, chlorophyll levels are halved (Figure 6). In nearshore waters, higher chlorophyll levels occur in southern areas, with lower levels in the far north. A seasonal peak occurs in March-April, with a decline to the annual low level in July-September. From 1994 to 2006 there has been no significant change in chlorophyll levels in the GBR overall, although with poor predictability (~30%). This, however,

was among the highest level of predictability among the different parameters, facilitating expression of the chlorophyll data in terms of relative risk to areas of the GBR: high / medium / low (De'ath 2007).

Water clarity shows greatest promise as an indicator of water quality on the GBR:

“Water clarity is highly predictable spatially (~75%) and is very high compared to the water quality parameters analysed previously. This statistical property, together with its known links to biotic function and ease of measurement, suggest water clarity could be a very useful indicator of water quality, but additional work is needed to assess temporal variation.” (De'ath 2007)

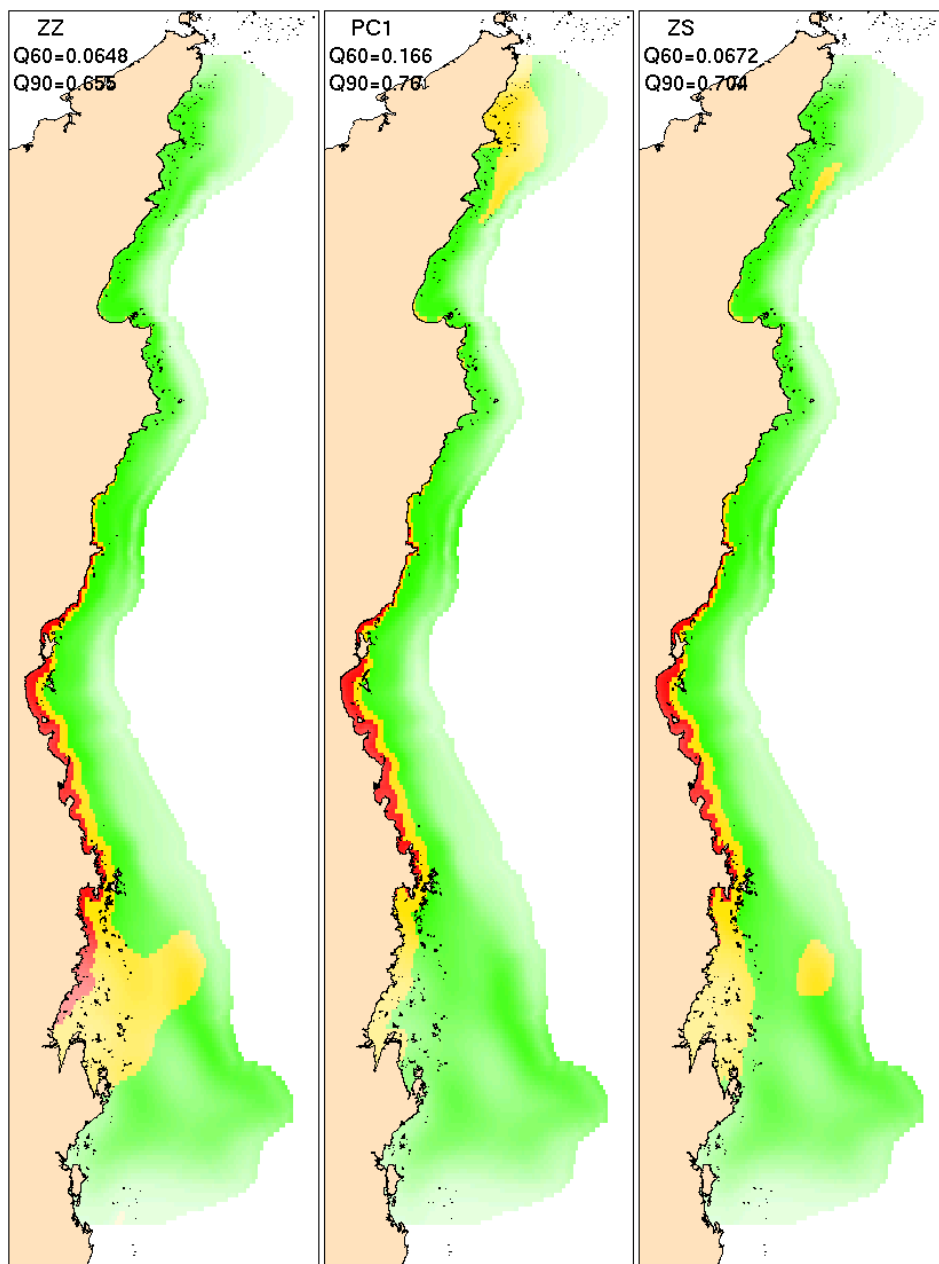


Figure 6: Levels of chlorophyll across and along the GBR (De'ath 2007).

In developing composite indicators, water clarity and light are correlated with seagrass abundances and reef growth. 'Optical depth', a measure of the transparency of the media through which light is passing, is a very useful parameter to quantify water column characteristics relevant for coral reefs, obtained from field measurements and satellite imagery:

"In the Whitsunday Islands, reef development generally extended to a depth of ~5-10% of surface irradiance. This 'irradiance threshold depth' is the water quality-specific critical depth where zooxanthellate corals are so light-limited that photoadaptation and heterotrophy cannot compensate for the lack of light, preventing reef growth. In the Whitsunday Islands, the critical irradiance threshold depth declines along the water quality gradient from a ~22 m on the outer Whitsunday Islands to ~6 m on Repulse Island." (Fabricius *et al.* 2007)

Among biotic indicators, cover, richness and recruitment of hard and soft corals are all inversely correlated with the water quality gradient (Fabricius *et al.* 2005, 2007).

"Hard coral cover declined five-fold (from ~50% to ~10%) along the gradient [in the Whitsunday Islands] from clear to turbid sites, while octocoral cover declined from ~25% to 3%. The taxonomic richness of hard corals and octocoral communities declined towards the most turbid sites to about a third of those of the cleaner-water sites (from 11.5 to 4 hard coral taxa, and from 6.5 to 1.5 octocoral taxa per transect). In contrast, total macroalgal cover, and amongst those especially the cover of brown macroalgae (Phaeophyta) strongly increased along the water quality gradient, from near-absence in clear-water reefs to a coverage of >50% of all substratum on the most turbid reefs ... Juvenile coral densities and taxonomic richness of juveniles also strongly declined along the water quality gradient ... The strength and consistency in response in (1) the abundances of brown and red macroalgae; (2) the taxonomic richness of octocorals; and (3) the density and taxonomic richness of both hard coral and octocoral juveniles all indicate that these basic community measures represent specific, robust and relevant measures of ecosystem status in coral reefs, reflecting prolonged exposure to water quality and other environmental conditions." (Fabricius *et al.* 2007)

Simple physiological water quality indicators for corals are also promising, with a change in the saturation of colony colour along the water quality gradient, measured with a range of different tools, the simplest being a coral colour chart developed for monitoring bleaching events (Fabricius *et al.* 2007). Another promising suite of 'sub-lethal' indicators is the ratio of RNA to DNA in a range of biota including corals and fishes (barramundi). Corals are physiologically more active in clear water, while barramundi RNA:DNA ratios and DNA damage are very sensitive to pollution stress. Although promising as an indicator, the complex interaction between the coral host and algal symbionts, the natural seasonal variation in the RNA:DNA ratio, and changes in the coral-symbiont interactions in response to environmental change, all require further research (Fabricius *et al.* 2007).

Biofilms (Foraminifera, bacteria and diatoms) also exhibit variable, quantifiable effects along water quality gradients. For example, heterotrophic forams are more abundant inshore and the more 'phototrophic' species with symbiont micro-algae more abundant offshore (Fabricius *et al.* 2007).

"An application of the Caribbean FORAM index showed significantly increasing values along the Whitsunday Islands water quality gradient. We conclude that it will be possible to apply the FORAM index to GBR reefs, after adaptations and fine-tuning of the index based on a better understanding of the physiology and

ecology of specific GBR species. Pilot experiments showed that light was an important factor influencing growth and carbonate production in four large symbiont-bearing species, and their specific tolerance ranges agreed with the distribution patterns recorded in situ for these species.” (Fabricius *et al.* 2007)

Of the ~6,000 km² of seagrasses in waters shallower than fifteen metres, and relatively close to the coast, many are in locations potentially influenced by adjacent land use practices. Declines in seagrass in southern Hervey Bay and in the central coast region are an ongoing concern, and data gaps have been identified in the far northern region of the GBR (Section 6). Overall however, inshore seagrasses continue to exhibit strong survival rates in respect of human activities and natural pressures. Large-scale losses have, to date, been mostly associated with catastrophic events including drought, tropical storms and flood run-off.

“Drought’ years of low rainfall and river flows, high temperatures and high solar irradiance cause declines in inter-tidal seagrasses that become exposed to higher temperatures and desiccation during daytime low tides. These same conditions may benefit sub-tidal seagrasses that have more available light due to lower turbid river run-off, but are protected from tidal exposure (see Thomas *et al.* 2006; McKenna *et al.* 2005, 2007). The reverse may be true of ‘wet’ years.” (Coles *et al.* 2007)

Recovery has typically occurred within several years (Lee Long *et al.* 2000, Coles *et al.* 2007):

“Percent cover from the Seagrass-Watch dataset when all sites are combined shows a flat trend since 1998 for inter-tidal coastal seagrass at around twenty percent cover level, a decline in recent years in cover of estuary inter-tidal seagrasses, and an increase in percent cover for reef platform seagrasses. The changes that have occurred are likely to be related to exposure at low tide and temperature and drying effects and are unlikely to be long term effects. Similarly, across locations where fine scale monitoring is conducted there have been decreases in cover of intertidal seagrasses and increases in cover of subtidal seagrasses during dry and hot drought years. The reverse occurred during periods of higher rainfall. Within these overall trends there are some location specific exceptions.” (Coles *et al.* 2007)

In respect of the ~1,800 km² of seagrasses presently mapped in the GBR and adjacent areas, most are coastal, and most of these occur in the Cape York region (Figure 7), which hosts approximately half of the mapped seagrasses of the GBR. Estuarine and reef habitats support comparatively smaller areas of seagrasses throughout the GBRWHA.

“The majority of meadows [in the Cape York region] are in the shallow subtidal waters of large bays sheltered from the prevailing southeast trade winds ... there is little land-based influence with few major rivers. These seagrass meadows are also highly productive and provide important nursery grounds for fisheries (Coles *et al.* 1985). They are also important to the large dugong population within the region (Marsh and Lawler 2002). A dominant influence on coastal habitats, although small, is terrigenous run-off from seasonal rains, similar to the adjacent estuary habitats. Episodic terrigenous run-off events result in pulses of increased turbidity, nutrients and a zone of reduced salinity in nearshore waters. The intertidal upper reaches of the meadows are limited by elevated temperatures and desiccation. The region also has a busy shipping lane immediately adjacent to the coast, where the passage of large ships during low tides can resuspend sediment plumes in their wakes (NRM 2007b) ... Seagrasses in the region also generally face low threat levels from chronic anthropogenic impacts when

compared to other regions in the GBRWHA (Rasheed *et al.* 2007c). While there are high risks associated with shipping accidents and oil spills in the region, none of the ship grounding or collision events in recent times have resulted in major oil spills (QT and GBRMPA 2000).” (Coles *et al.* 2007)

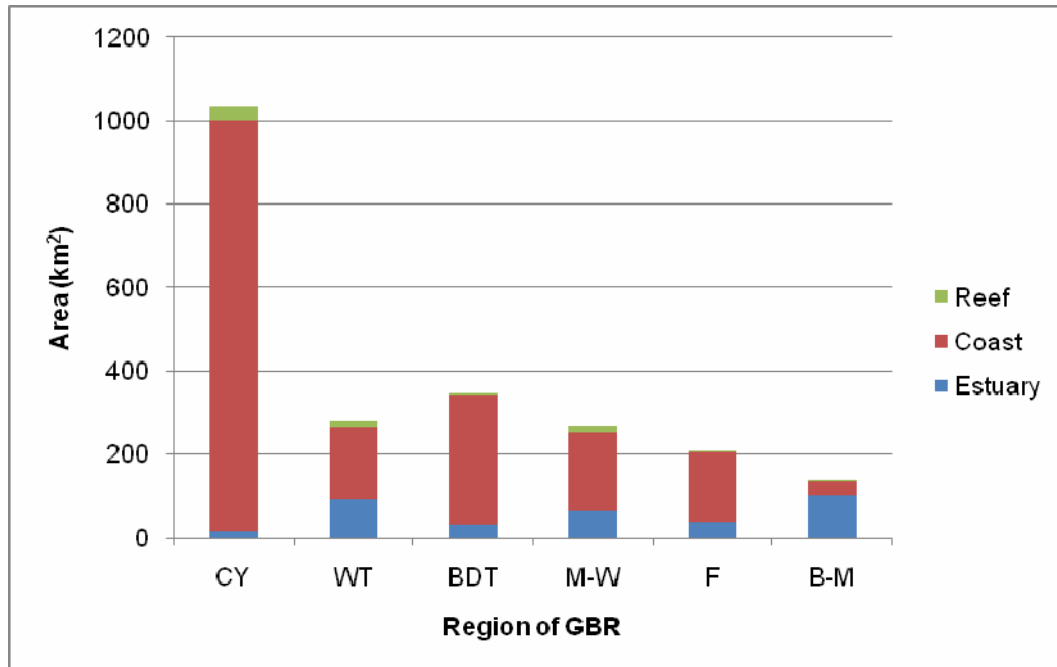


Figure 7: Distribution of seagrasses in three habitat types (Reef, Coast, Estuary) for six regions of the GBR, where CY: Cape York; WT: Wet Tropics; BDT: Burdekin Dry Tropics; M-W: Mackay-Whitsundays, F: Fitzroy; B-M: Burnett-Mary (data from Coles *et al.* 2007).

With respect to the distribution of seagrasses in various GBR zones, most of the mapped seagrasses are now located in Conservation Park, Marine National Park and Habitat Protection zones, and to a lesser extent, Fish Habitat Areas (Figure 8), a significant achievement of the 2004 rezoning process.

Like corals, seagrasses are susceptible to elevated air and sea temperatures, a risk of growing importance as the climate changes. When intertidal temperatures exceed 40°C for several hours, seagrasses die (R. Coles, MTSRF Conference 2007, see <http://www.rrrc.org.au/news/2007conf.html>). Many of the nineteen high-risk areas for seagrasses in the GBRWHA are now well addressed, particularly areas that are in the highest threat category (Rasheed *et al.* 2007d; and see Appendix 1, Project 1.1.3). Data coverage for other areas is however presently lacking or could be improved. Two major areas have significant information gaps – the coastal area, estuaries and reef platforms of the Cape York NRM region, and the deeper (>15 m depth) meadows (Coles *et al.* 2007):

“Apart from the Cooktown area there are no monitoring locations [in the Cape York region], yet this area supports a major fishery and turtle and dugong populations and contains some of the largest reef platform seagrass meadows in the GBRWHA. Management decisions are presently being based on twenty-year-old data ... It is possible that with climate-induced storms and increases in temperature and algae growth, light penetration could be reduced and huge areas of seagrass at the deepest edge (50-60 m) lost. An entire habitat type and all the benthic communities it supports could be lost from a region within the

GBRWHA and it could pass unnoticed for several years. A similar event occurred in 1993 when nearly 1,000 km² of seagrass was lost from meadows around twenty metres deep in Hervey Bay, and this was not recognised until starving dugong were found washed up on the beach.” (Coles *et al.* 2007)

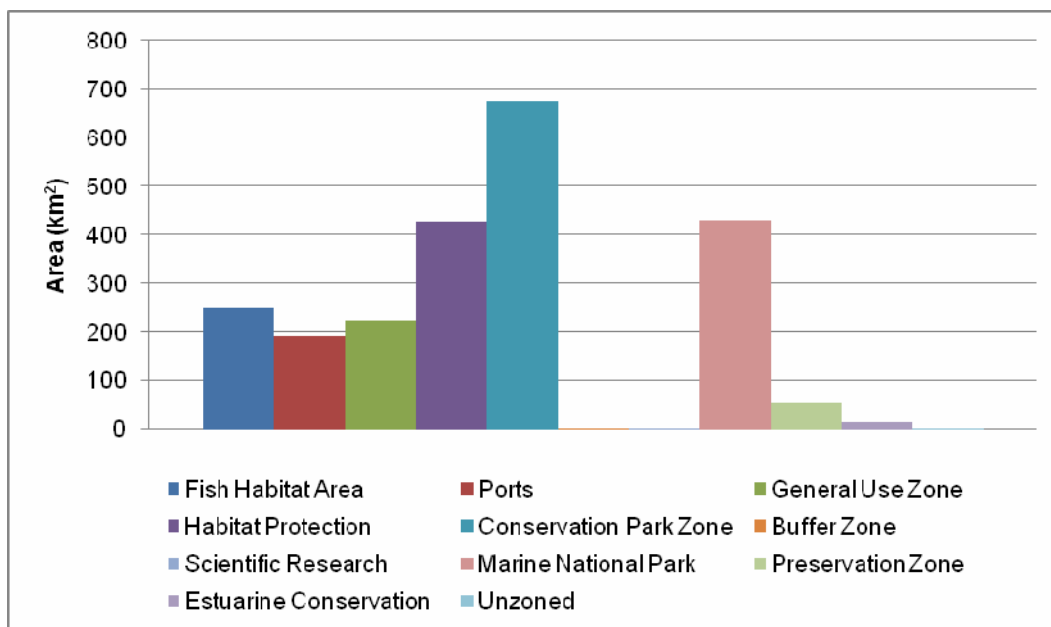


Figure 8: Distribution of seagrasses in various zones and unzoned areas of the GBRWHA and adjacent areas (data from Coles *et al.* 2007).

Losses of seagrasses can have cascading effects on the associated biota, including dugong and other species of conservation concern. Along the urban GBR coastline, long-term decline in dugong numbers has reduced the population to <10% (possibly to as low as 3%) of that present prior to the 1960s. Since the 1980s however, numbers have stabilised at around 3,000 individuals, one of the largest remaining populations globally (Marsh *et al.* 2007). This suggests that present management is contributing to maintenance of the population, yet for population recovery to pre-1960s levels, non-natural mortality rates will need to be reduced to near-zero (<15 deaths yr⁻¹ for the GBR, H. Marsh MTSRF Conference 2007, see <http://www.rrrc.org.au/news/2007conf.html>). The introduction of DPAs and the 2004 rezoning have improved habitat protection, but dugongs remain at risk during migrations. Similarly, for coastal dolphins such as the snubfins, distribution ranges overlap with net fisheries, and here also non-natural mortality levels need to be reduced to near-zero for recovery. In the latter respect, the capacity of acoustic alarms to minimise the bycatch of protected species in commercial gill nets, without alienating the bycatch species, is being assessed for three species of coastal dolphins and at least one species of sea turtle (H. Marsh, MTSRF Milestones Report 2007, see <http://www.rrrc.org.au/news/2007conf.html>).

Inshore fishery pressures for the East Coast Inshore Finfish Fishery (ECIFF), as measured by fishing boat days, increased from 1988 to 2003, declining in recent years:

“Overall harvest in the commercial inshore net fishery in the GBRWHA increased steadily since 1988 to reach a peak of 2,708 tonnes in 2003. Overall harvest has declined rapidly in the three years since 2003 to reach 1,769 tonnes in 2006 [(Figure 9)]. Patterns in boat days of fishing effort closely follow harvest, although catch rates appear to be higher in later years. Since 1996, most of the overall

harvest has been taken from the Townsville region, while overall harvest has always been lowest in the Far North region.” (Simpfendorfer *et al.* 2007b)

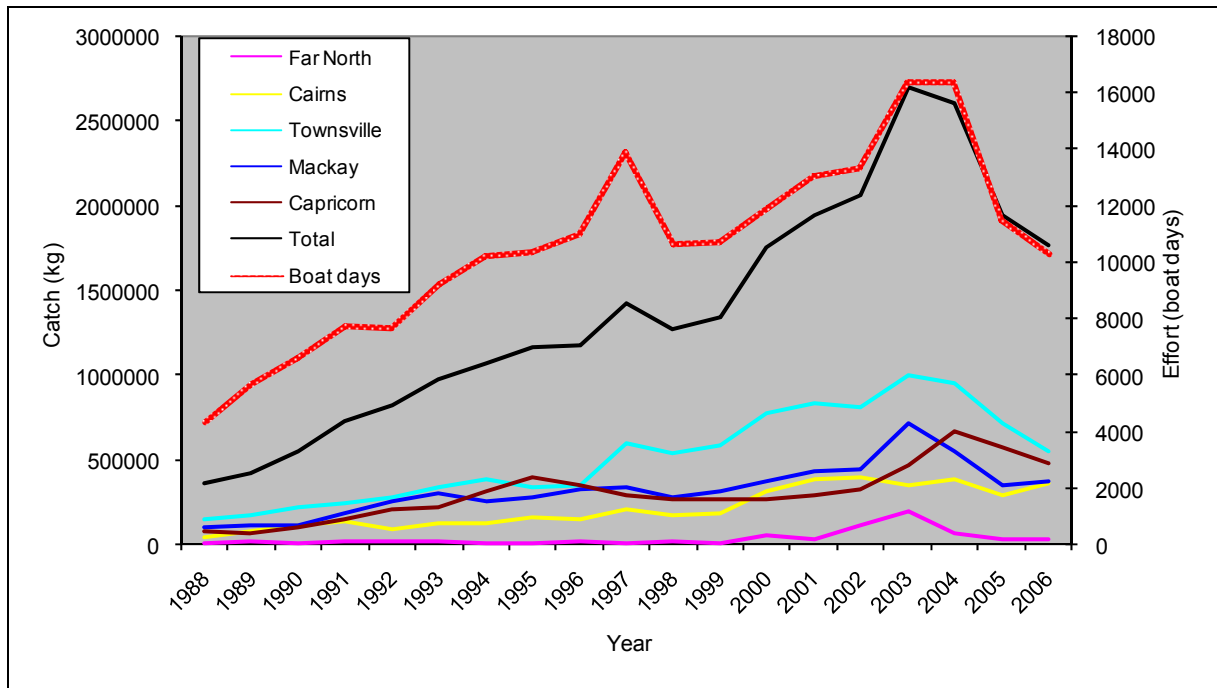


Figure 9: Total commercial harvest (kg) and effort (boat days) reported for the inshore net fishery from the GBRWHA for the years 1988-2006 (from Simpfendorfer *et al.* 2007b, Figure 2).

The most recent QDPI&F estimates of harvest in the ECIFF indicate that the overall commercial harvest of fish (including sharks) in 2005 was 5,437 tonnes, with a value of \$AUD23 million (Simpfendorfer *et al.* 2007b). In 2005, the charter fishery harvested just 150 tonnes, whereas the recreational harvest (in 2002) was 3,826 tonnes (Simpfendorfer *et al.* 2007b). No estimates of Indigenous harvest are available. Over the past decade, the trend in total catch has corresponded with the number of boat days of fishing, particularly since 2002.

The net fishery component, which poses risks to non-target species as noted above, targets five main species or species groups (Williams 2007) including sharks, barramundi, grey mackerel, mixed estuary and baitfish. From 1988-2006, shark dominated overall catch composition, although threadfin, barramundi, mackerel and mullet were also important components (Simpfendorfer *et al.* 2007b; Figure 10). There are substantial inter-annual and regional differences within the GBR in both quantity and composition of catch (Simpfendorfer *et al.* 2007b).

Catch of shark, which comprised 35% of the total inshore commercial fishery harvest, was dominated by Australian blacktip (*Carcharhinus tilstoni* and *C. sorrah*) and scalloped hammerhead (*Sphyrna lewini*). Together these comprised 89% of the shark category (Simpfendorfer *et al.* 2007b). Total shark harvest in the commercial inshore net fishery steadily increased from 1988 to 2003, reaching a peak of 1,168 tonnes, and subsequently decreasing rapidly, to 556 tonnes in 2006 (Simpfendorfer *et al.* 2007b). Substantial gaps in biological knowledge remain for shark, ray and indeed scalefish species caught in the ECIFF, a continuing MTSRF research focus:

“While reproductive data are good for many of the shark species, there are only a few species for which good data exists across the three major data categories.

Age and growth data are limited and demographic parameters are scarce. The rays are particularly lacking in data in all categories, but most have a lower priority because they are only occasionally caught as part of the fishery ... In all, 15 species of shark, 6 species of ray and 10 species of scalefish were identified as having a high priority for data collection. In most cases, these high priorities were assigned due to the lack of data, but for some species high priorities were allocated due to concerns over conservation status (e.g. Family Pristidae) or because they are major target species and there is a need to gather data on a stock-level basis.” (Simpfendorfer *et al.* 2007b)

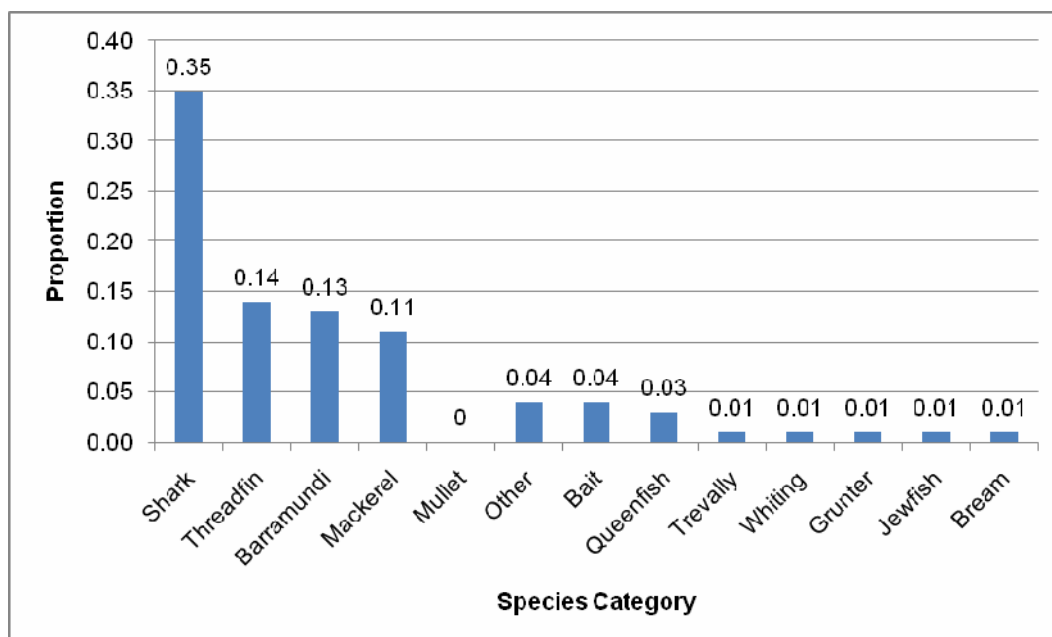


Figure 10: Catch composition of the commercial inshore net fishery from the GBRWHA showing proportions of each species category across the years 1988-2006 (Simpfendorfer *et al.* 2007b, Figure 6).

In the charter sector, overall harvest has been ‘relatively modest’ from 1996-2006 (Simpfendorfer *et al.* 2007b; Figure 11). Species composition was dominated by the ‘other’ species category, mainly reef-associated species such as coral trout, red throat emperor, cod and nannygai (and to a lesser extent tuna), suggesting that much of the effort is directed at inshore reefs (Simpfendorfer *et al.* 2007b). Mackerel were the second most important species category while trevally made up approximately ten percent of the harvest (Simpfendorfer *et al.* 2007b).

Harvest patterns of the inter-reefal fishery, from commercial, charter and recreational sectors indicate that 21 species or species groups are key components of the ‘other species’ catch (Simpfendorfer *et al.* 2007). Substantial differences between the commercial, charter and recreational sectors are evident, being much greater than inter-annual differences within sectors, most likely due to fishing behaviour / access, target species and gear and bait types (Simpfendorfer *et al.* 2007).

Fish stocks on the inshore reefs and inter-reefal shoals have been investigated in relation to the 2004 rezoning. Longer-term data for the inshore reef fishery date to the early 1980s, however there are few ‘historical’ data for the inter-reefal shoals, and MTSRF research is providing the ‘baseline’. The earlier reef studies indicated that after 12-14 years of adequate

protection, no-take reserves provided substantial benefits for target species within their boundaries (Russ *et al.* 2007a, b). The strong effects of protection on fish populations were largely due to relatively low levels of fishing infringements (poaching) in the no-take marine reserves of the inshore reefs (Williamson *et al.* 2004, Evans and Russ 2004, Davis *et al.* 2004).

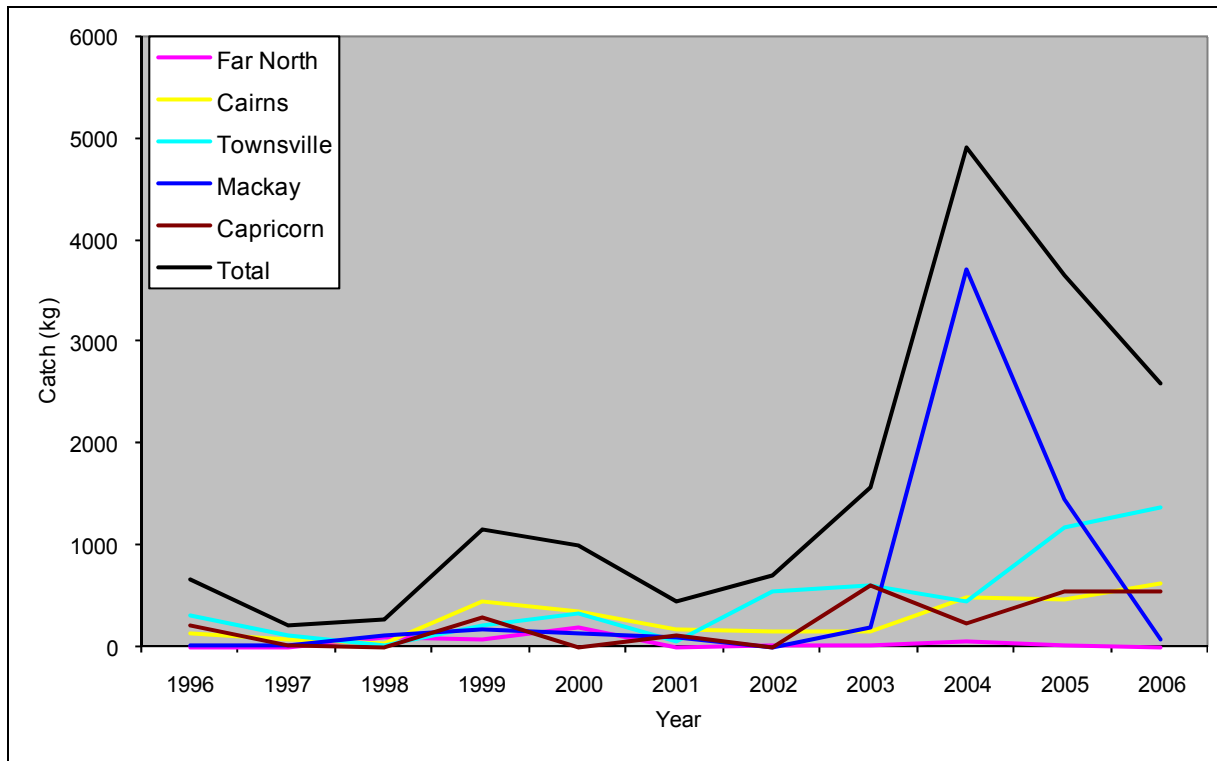


Figure 11: Total and regional charter harvest (kg) reported for the inshore fishery from the GBRWHA for the years 1996-2006 (Simpfendorfer *et al.* 2007b, Figure 4).

To date, the 2004 rezoning has had no statistically significant effects on fish abundances on inshore reefs (Russ *et al.* 2007a, b). However, it is important to note that these are preliminary results, covering a short duration of closure to fishing (~2 years from July 2004). With respect to habitat, coral cover has declined in both fished and protected areas in three island groups in the same period (the Whitsunday Islands, Palm Islands and Keppel Islands). The reductions may have been responsible for coincident declines in abundances of the associated butterflyfish. Structural complexity of the benthos did not change, however, and biomass of target fish species (coral trout and snapper) did increase in the 'no-take' green zones, with a slight decrease or stable situation in the fished zones. These preliminary findings suggest there may be some effect on target fish species of concentration of fishing effort into areas that have remained open to fishing (Russ *et al.* 2007a).

"The consistent pattern of decreased coral cover in all three Island groups, particularly in the Keppel Islands, is cause for concern. Conversely, increases in the biomass of target fish species in newly protected areas of the Palm and Whitsunday Island groups is encouraging, but needs to be interpreted with caution due to the high level of variation within and between island groups. The data are preliminary and continued monitoring of these reefs over the coming years is essential if we are to significantly enhance our understanding of the effects of management zoning and broad-scale environmental impacts on the fish and benthic communities of these high use inshore reefs." (Russ *et al.* 2007a)

These findings have been supported by the most recent results from inshore reefs of Magnetic Island:

“... areas of inshore fringing reefs designated as no-take green zones under the RAP zoning plan are having a positive effect on stocks of targeted fish species. Due to relatively high levels of surveillance and enforcement, and fisher compliance with zoning regulations, these inshore fringing reefs are some of the most adequately protected reefs of the GBRMP (Davis *et al.* 2004). As a result, we would expect that the ecological effects of zoning management would be most apparent on these inshore fringing reefs. The observed increases in mean abundance and biomass of *Plectropomus* spp. and *L. carponotatus* in newly protected zones of Magnetic Island fringing reefs are consistent with results obtained previously by this project for both the Palm and Whitsunday Island groups. Although this project has now demonstrated consistent patterns across regions, it is important to note that low spatial replication of sites within zones, and infrequent temporal replication across years has meant that the results presented here must be viewed as preliminary.” (Russ *et al.* 2007b)

For the inshore inter-reefal shoals, the benthos is composed of a mosaic of rich epibenthic filter feeding communities typically surrounded by low relief algae and seagrasses (Speare and Stowar 2007a, b). The associated fish communities are comprised of a diverse assemblage of taxonomic and trophic groups, including recreationally and commercially important fishes. Approximately thirty percent of all fishes are in groups targeted or otherwise taken by fishers (Speare and Stowar 2007a). Fish communities associated with shoal habitats were typically more diverse than those from the open, low relief areas (Figure 12; Speare and Stowar 2007b); and are using very low relief features, such as sponges, sea whips and gorgonians on low hard grounds. These areas support up to five times the abundance of adjacent (<100 m distant) smooth sand areas (Speare and Stowar 2007a). Overall, 109 species were recorded on the reefal habitats and 71 species on the open sandy bottoms. Fish assemblages on reefal substrates did not vary significantly across green and blue zones but there were dissimilarities between sites (Figure 13; Speare and Stowar 2007b).

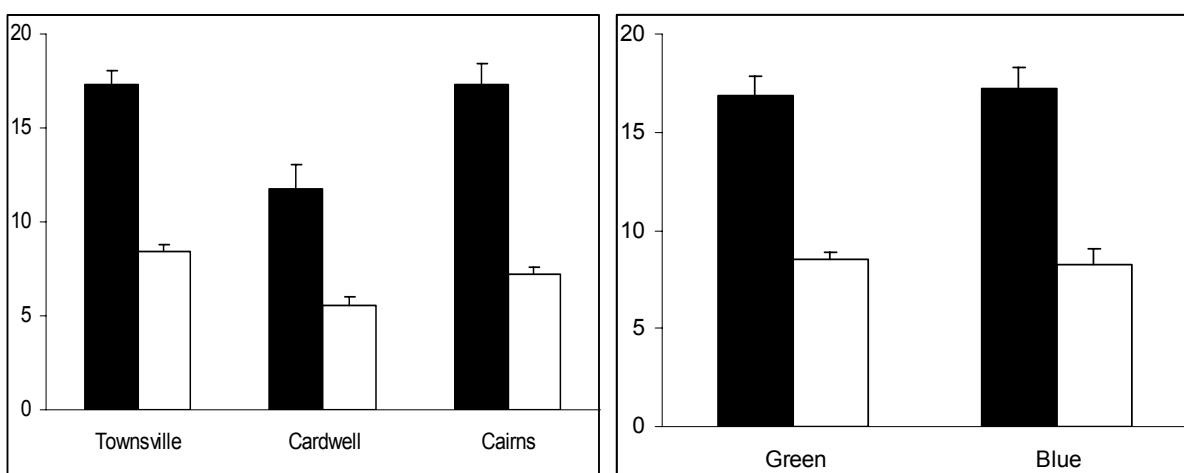


Figure 12: (Left) The mean number of species (± 1 SE) on (closed bars) and off (open bars) the primary habitats recorded from three regional areas. (Right) The mean number of species (± 1 SE) recorded from structurally complex (closed bars) and adjacent rubble sand (open bars) habitats in green and blue zones (closed and open to fishing respectively) off Townsville (extract from Speare and Stowar 2007b).

“The shoals included in this study were each centred on small rocky outcrops ranging in size from tens to hundreds of metres in extent. The species richness associated with this habitat from each of the three study sites tended to reflect their relative sizes. The species richness on the shoal sites in the Cardwell area was relatively low in comparison to that recorded from the other two regional survey areas off Cairns and Townsville.” (Speare and Stowar 2007b)

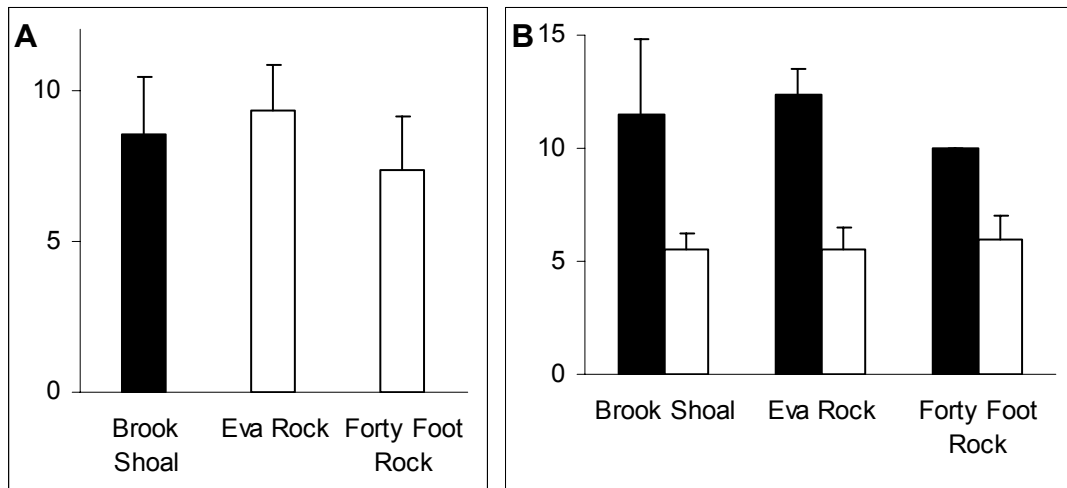


Figure 13(i): The mean number of species ($\pm 1SE$) recorded on Brook Shoal (green zone), Eva Rock and Forty Foot Rock. (A) Muddy sand and rocky habitats combined; (B) closed bars = hard bottom; open bars = soft bottom (extract from Speare and Stowar 2007b).

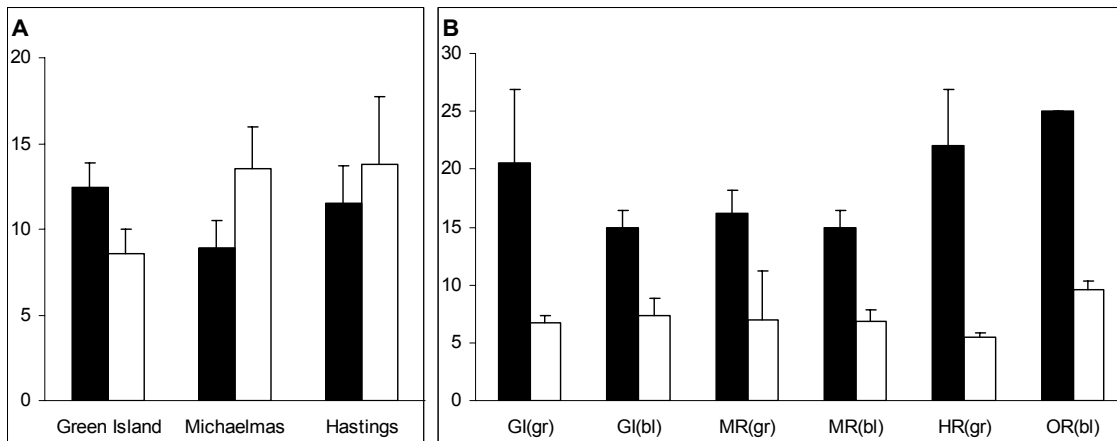


Figure 13(ii): The mean number of species ($\pm 1SE$) recorded on Green Island, Michaelmas and Hastings reefs sites. (A) Green (closed bars) and non-green (open bars) sites; (B) reefal substrates (closed bars), sandy bottom (open bars) (extract from Speare and Stowar 2007b).

4.2 Mid- and Outer Shelf GBR

With respect to status and trends of the reefs, synthesis of the two long-term (decadal) GBR-wide datasets of coral cover (manta-tow and video-transects) has demonstrated that there have been major shifts in coral cover, including rapid declines and slower increases, in different regions of the GBR during the past fifteen years (Sweatman 2007). A comprehensive summary of these results is presented at <http://www.aims.gov.au/docs/research/monitoring/reef/reef-monitoring.html> and thus is not reiterated herein. The declines have been driven by predation by COTS, physical impact by cyclones, and most recently, diseases such as 'White Syndrome', all of which particularly impact on tabular species of *Acropora*, a major component of coral cover on many reefs. Increases in coral cover have resulted from substantial coral recruitment and growth, key aspects of resilience. As to another series of COTS outbreaks, no evidence has been found in the northern GBR of any accumulation in starfish numbers (breeding aggregations) that may signal the start of a new wave of outbreaks (Sweatman 2007).

Regarding fisheries and the 2004 rezoning, results to date are consistent with those from the inshore reefs (Section 4.1), with consistently more fish in the protected areas (green zones), suggesting rapid benefits from the new Zoning Plan. Abundances of coral trout have increased by ~50% on mid- and outer-shelf reefs protected by green zones (P. Doherty MTSRF Conference 2007, <http://www.rrrc.org.au/news/2007conf.html>).

With respect to species of conservation concern, populations in the seven major green turtle rookeries of the Northern GBR and Torres Strait are in decline, with smaller sized turtles and poor nesting success, the latter partly related to beach loss. Climate change modelling of nest temperature suggests a dramatic future change in sex ratios of hatchlings, with a four or five to one female bias (M. Hamann, MTSRF Milestones Report 2007, see <http://www.rrrc.org.au/news/2007conf.html>).

The recently-completed Seabed Biodiversity Project, which mapped seabed habitats, assemblages and biodiversity (Pitcher *et al.* 2007a), provided the basis for estimating indicators of protection under the revised zoning plans developed under the RAP in 2004. Given the overall increase from *General Use* to higher levels of protected zoning of the continental shelf seabed, the expected benefits to seabed habitats, assemblages and biodiversity were apparent in terms of increased levels of protection.

For the nine broad habitat types, four had <20% of their predicted area in zones with higher levels of protection prior to RAP, whereas subsequently all nine had ≥20% in zones with higher levels of protection. The average increase in protection for habitats was 31% (Pitcher *et al.* 2007b). For sixteen seabed species-assemblages, seven had <20% of their predicted area in zones with higher levels of protection prior to RAP, whereas subsequently all of these assemblages had >20% of their area in zones with higher levels of protection. The average increase in protection was 36% (Pitcher *et al.* 2007b). For 38 species-groups, ten had <20% of their predicted biomass in zones with higher levels of protection prior to RAP, and subsequently all had >20% of their biomass in zones with higher levels of protection (Pitcher *et al.* 2007b).

The average increase in protection was 27%. At the level of individual species, prior to the RAP re-zoning, 160 of the approximately 840 species assessed had <20% of their predicted biomass in zones with higher protection, whereas after the re-zoning all species analysed had >20% of their predicted biomass in zones with higher protection (Pitcher *et al.* 2007b). The average increase in protection was 29%.

With respect to GBR tourism, recent changes in visitor perceptions and expectations have occurred in relation to global publicity on the impacts of climate change (Prideaux and Coghlan 2007). Other changes include:

- A higher percentage of domestic tourists and local residents use reef cruises than indicated in previous research (e.g. Moscardo, CRC Reef);
- A low percentage of certified divers and introduction divers. The destination imagery of the Great Barrier Reef as a snorkelling or resort diving destination is supported through content analyses of diving and travel magazines;
- The emergence of helicopter tours and glass-bottom boats as popular means to experience the reef. Both were frequently cited as the best feature of the reef tour; and
- Seasickness, the most commonly cited 'worst' experience mentioned by respondents.

Fifty-five percent of GBR tourism survey respondents indicated they were not aware if their tour operator was eco-certified, and no survey respondents said they had chosen their tour operator based on environmental values. Satisfaction ratings remained high (mean = 8.46/10) across all tourism operators and the majority of survey respondents felt their expectations of the reef and the tour had been met.

For far northern GBR diving trips, the overall satisfaction, wildlife experiences and the quality or health of the wildlife and reefs were all rated very highly by tourists who responded to questionnaire surveys, scoring means of 8.7, 8.8 and 8 out of 10 (representing excellent) respectively (Birtles *et al.* 2007):

“... on average, passengers' expectations of the trip were slightly exceeded by their actual experience ... Fifty-two of the respondents (60%) indicated that they would very likely return, or definitely return to visit the far northern GBR again in the future.” (Birtles *et al.* 2007)

Regarding the iconic wildlife seen during the trips, the far northern GBR represents a wilderness experience of high international calibre. Species encountered included green, loggerhead and hawksbill turtles; silvertip whaler, tiger, wobbegong, epaulette, leopard, hammerhead, grey reef, white tip reef and tawny reef sharks; manta rays; Maori wrasse, barracuda, potato cod, snapper, moray eels, red bass and leafy scorpion fish; brown boobies, night herons and frigate birds; cetaceans, dolphins and dugong (the latter from a single sighting on one trip); and nautilus, nudibranchs, corals and other marine invertebrates. Turtles, sharks and fishes were of highest relative importance to visitors, with each group contributing more than \$AUD1,300 per visitor to regional expenditure (Birtles *et al.* 2007).

Of the total money spent in the region, preliminary estimates indicate that each respondent spent close to \$AUD6,000 (\$5,952) per person, 90% of which was directly attributable to the dive-boat trip (i.e. visitors would not have visited the region if they could not go on the trip; Birtles *et al.* 2007).

5. The Importance of MTSRF Research

The MTSRF is playing a key role in focusing and coordinating bio-physical, ecological and socio-economic research on the GBR. This research spans a broad range of disciplines of high relevance to the sustainable use and adaptive management of the GBR. The level of research effort, and the linkages across themes are addressing key aspects of the global 'coral reef crisis', as it applies to the GBR, in a cost-effective manner. Because the MTSRF research platform has a strong foundation in the previous work of the CRC Reef, significant results have already been produced across the four research themes, despite the MTSRF being in operation for only one year at the time of writing. The ongoing synthesis of this information through the development of indicators and thresholds of concern will facilitate the timely communication of key results to users, management and government agencies, contributing to rapid development of appropriate management responses.

This has been initiated through the first annual research conference held in Townsville in April 2007, numerous other public-speaking engagements by researchers, and various non-technical and technical publications. The following section provides several key examples of the national and global importance of completed and continuing work with respect to the key GBR issues identified in Sections 2 and 3 of this report.

5.1 Terrestrial Issues

Recent results have demonstrated that the type and severity of response to terrestrial run-off at any particular location depends on the physical, hydrodynamic, spatial and biological properties of the location (Fabricius *et al.* 2007).

For coral reefs:

“Reefs that are surrounded by a shallow sea floor, reefs in poorly flushed bays or lagoons, deeper reef slopes, and frequently disturbed reefs are likely to experience changes even at low levels of pollution, in particular when populations of herbivores are low. In contrast, well-flushed shallow reef crests surrounded by deep sea floors or in areas of moderate tides are likely to have the highest level of resistance and resilience, especially when inhabited by healthy populations of herbivores that protect against overgrowth by sediment-trapping macroalgae.” (Fabricius *et al.* 2007)

For shallow water seagrasses, nineteen regions have been identified as being at heightened risk:

“There are considerable pressures on seagrass meadows along the urban coast from river discharge water quality and urban and industrial development ... At small spatial scales – bays, estuaries, meadows – there is considerable variability in meadow biomass and percent cover; but at a GBRWHA scale there is no evidence of sustained losses or gains where monitoring is occurring. Most changes noted are clearly linked to short term environmental events ... seagrass meadows were in a ‘healthy’ state and have been relatively stable over the past twenty years. However within this overall ‘stability’, seagrasses have fluctuated, most often as a response to climate, and at smaller localised scales there have been some acute event-related changes. These fluctuations do not appear to represent long term trends in a particular direction – they are simply fluctuations.” (Coles *et al.* 2007)

For the deepwater seagrasses:

“There is no evidence to suggest seagrasses have been lost from any region in the ten year period [post-1994]. Highest probabilities of finding seagrasses are in the central Wet Tropics from Princess Charlotte Bay to Upstart Bay and in the south offshore from Gladstone. There is a region south of Mackay of high tidal velocities where seagrasses are least likely to be found. These general patterns are present in the data from both surveys suggesting that these large spatial scale patterns are stable over time ... seagrass meadows in the deep water of the GBRWHA have only a 15-25% variation in spatial extent after ten years – a remarkably small change for a biological system. The designers of the new zoning plan can be reassured that spatial decisions to protect seagrass based on the 1994-1999 data set are likely to remain relevant over long time scales.” (De’ath *et al.* 2007)

Another important recent finding relates to the distribution and dispersal of flood plumes from run-off into the GBR during summer 2007. Tracked in a series of satellite images and on-site surveys, it is now clear that sediment plumes can travel to the outer reef and into the Coral Sea proper. Previously, it was thought that the plumes, with their associated sediments, nutrients, pesticides, herbicides and other micro-pollutants, mainly affected only the inner GBR Lagoon and nearshore habitats. However, the NASA MODIS satellite images, taken by GeoScience Australia's Alice Springs site between 9-13 February [2007], showed the plumes more than 120 km offshore, particularly in the area northeast of Cape Grafton (Figure 5) . As noted earlier, passage of flood plumes through the area is linked with locally elevated levels of chlorophyll, which are in turn correlated with outbreaks of COTS (G. De’ath, MTSRF Conference 2007, see <http://www.rrrc.org.au/news/2007conf.html>).

5.2 Population Outbreaks and Diseases

As introduced above, the third wave of COTS outbreaks since the 1960s has passed south through the central GBR over the past decade, with almost fifteen years having now elapsed since the front was discovered on reefs north of Cairns in the early 1990s. As the time interval between apparent initiations of the three successive waves of outbreaks is approximately 15-17 years, the next outbreak wave may be about to start in the region around 16°S latitude. This is consistent with the hypothesis of a primary outbreak population acting as the ‘seed’ of a new wave of outbreaks throughout the GBR. In an attempt to provide an early warning for organising a response before outbreaks become evident in the major tourism centres of the Cairns region and further south, surveys were conducted on 41 reefs in the putative outbreak initiation zone in 2006-2007. No aggregated populations of adult COTS were found. Indeed only four adult starfish were found in total, each on a separate reef. Complementary surveys by Reef Check Australia at 25 tourist dive sites in the Whitsundays found only two COTS, each on different reefs. These results suggest COTS populations are very low at present in the central and northern GBR, consistent with the chronology of past outbreak waves. Given that initiation of another outbreak wave is increasingly likely (based on elapsed time), these ‘early warning’ surveys will be repeated in 2008-2009.

Conferring significant global importance, the GBR forms a key element of the Global Coral Reef Monitoring Network (GCRMN; Wilkinson 2004), and will prove of increasing value in coming years, as the IPCC, the United Nations and the world’s governments become increasingly focused on the health of coral reefs and inter-reefal areas as indicators of climate change.

“In terms of indicators of coral reef health ... many potential indicators ... have been surveyed at varying spatial scales on the GBR. Their usefulness depends on the scale of reporting that evolves; data of many kinds are available, but only for limited areas of the GBR. Carefully standardised measures of diversity of key groups (benthic organisms and reef fishes) are metrics that are widely used in reporting environmental health and are available for many sites. In the absence of clear reference values for interpretation of indicators, the best strategy must be to use the distributions of observed indicator values (appropriately regionalised), in combination with rigorous expert review and, where appropriate, backed by focused research programs.” (Sweetman 2007)

5.3 Climate Change

A recent review of the impacts of climate change on the physical oceanography of the GBR (Steinberg 2007) indicated that significant warming has already occurred and is projected to continue, with additional effects:

“Climate change will affect GBR circulation patterns, the stability and depth of the surface mixed layer and the depth of the main thermocline. All these processes play an important part in regulating heat, connectivity, productivity and exchanges with the atmosphere. The heat content of the ocean is a fundamental environmental variable and influences the health of the GBR ecosystem. The Coral Sea also plays an important role in determining regional climate systems beyond the GBR. Northern Coral Sea waters through the Hiri Current feed the WPWP [West Pacific Warm Pool] and in turn the equatorial current systems that determine ENSO. The southern branch, EAC, sends warm tropical waters poleward affecting the climate along the eastern seaboard of Australia.” (Steinberg 2007)

Several MTSRF-supported projects are providing key information for improved understanding and predictive capacity of climate change impacts. Firstly, validation of the reliability of the remote-sensed MODIS / NOAA hotspots data and other satellite-derived data sets with *in situ* measurements, particularly as hindcast for the intense bleaching years of 1998 and 2002, is a crucial step towards the future use of the remote-sensed data in developing reliable predictive capacity, including scenario models at reef-scale. This also links strongly with development of the Reef Atlas, which will identify areas of major risk and potential refugia, crucial to adaptive management, as for example an iterative zoning process. Of equal importance to the Atlas, studies of organism-response are better defining and refining the understanding of biological acclimation and adaptation, as these relate to ecological resistance and resilience to climate change.

A recent comparison of coral mortality thresholds to bleaching thresholds has indicated that thermally sensitive corals die at $<1^{\circ}\text{C}$ (and many at $<0.5^{\circ}\text{C}$) above their bleaching threshold, illustrating the ‘fine line’ that exists between recovery and death of thermally sensitive corals following bleaching (Berkelmans in press, Hoegh-Guldberg 2007). Time-integrated bleaching thresholds remain appropriate for modelling thermal stress in corals.

“The original bleaching thresholds developed after the 1998 bleaching event accurately predicted the 2002 bleaching event and separated bleaching from non-bleaching years up to that time. However, since 2002 it is clear that a number of reefs have become more resistant to thermal stress. These locations included Myrmidon Reef, Davies Reef, Magnetic Island, Chicken Reef and Daydream Island which experienced warmer conditions in 2004 and/or 2005 than in the bleaching year of 1998, but without bleaching. A number of plausible

explanations have been examined and additional data (UV and light) were obtained and analysed. The strong conclusion remains that these reefs have become more tolerant after (and possibly because of) the 2002 bleaching event.” (Berkelmans in press, Hoegh-Guldberg 2007).

At the coral-zooxanthellae organism (holobiont) level, new findings have indicated that:

“... some host pigments are responsive to changes in external irradiances, and ... the presence of these host pigments is correlated either with changes in photosynthetic efficiency, or with the ability of the holobiont to sustain areal productivity despite experiencing highly significant reduction in the population of photosynthetic endosymbionts. Our study suggests that heavily host pigmented coral operating at elevated temperatures can be severely but not detrimentally ‘bleached’.” (Anthony *et al.* in review reported in Hoegh-Guldberg 2007).

Related work has elucidated the first quantitative relationship between bleaching status, photosynthetic capacity and metabolic rate in corals (Anthony *et al.* reported in Hoegh-Guldberg 2007). This has facilitated direct assessment of the energetic consequences of bleaching for coral physiology, with important implications for coral survival during and following a thermal stress event. Related mathematical modelling of how the processes of thermal bleaching are coupled to coral energy balance, energy stores and mortality risk is forming a strong basis for developing improved threshold models (Anthony *et al.* reported in Hoegh-Guldberg 2007). Other important findings have shown that variation in thermal tolerance in corals has an underlying genetic component and is not solely due to environmental factors (Van Oppen, reported in Hoegh-Guldberg 2007):

“Despite this, our results suggest that, for this one population (Magnetic Island) and trait (maximum quantum yield of fluorescence), the change from one generation to the next due to selection is expected to be relatively small. The expected response to selection of other photophysiological traits, growth and the expression levels of a suite of proteins is currently being analysed” (Van Oppen, reported in Hoegh-Guldberg 2007).

A key aspect with global relevance is the improved understanding of how impacts of climate change will interact with other stresses, both human-induced and natural, to influence the resilience of GBR ecosystems. A multi-disciplinary approach is being implemented for coral reefs, focused in three key research areas: the population genetics of corals and their algal endosymbionts; the population, community and ecosystem ecology of corals and reef fishes; and mechanistic modelling. These studies will provide an integrated, multilevel, assessment of climate change effects at the levels of individuals, populations and communities, and any feedback that the impacts may have on the resilience of coral reef ecosystems (Hughes *et al.* 2007a).

For example, there is growing recognition of the importance of herbivorous fishes in coral recovery following bleaching (Hughes *et al.* 2007b):

“... where fishes were abundant, algal abundance remained low, whereas coral cover almost doubled (to 20%) over a three-year period, primarily because of recruitment of species that had been locally extirpated by bleaching. In contrast, exclusion of large herbivorous fishes caused a dramatic explosion of macroalgae, which suppressed the fecundity, recruitment, and survival of corals. Consequently, management of fish stocks is a key component in preventing phase shifts and managing reef resilience.”

Dispersal is another key aspect of vulnerability, resilience and risk, as it affects the level of connectivity within and between populations:

“Exchange of larvae creates and maintains high levels of genetic diversity and buffers populations against disturbance. Migrants may carry new alleles that may be integrated into populations through reproduction, creating new gene combinations on which selection can potentially act. The spread of selectively advantageous alleles at DNA loci involved in physiological responses such as bleaching resistance is a potentially important consequence of migration. Furthermore, gene flow increases local effective population sizes, thereby enhancing the ability of populations to resist rapid random changes in allele frequencies from one generation to the next through drift. Larval-exporting or source reefs with diverse populations ... are essential to maintain the genetic diversity and resilience of larval-importing or sink reefs.” (Hughes *et al.* 2007a)

Differing levels of gene flow within the GBR have potentially important linkages with climate change, water quality and other stresses, as reefs and seagrass meadows in the shallow water of poorly-flushed bays are likely to be at greater risk from high sea temperatures and poor water quality than their deeper water, well-flushed counterparts. Loss of biota from poorly-connected areas will be less easily restored through recruitment, and such areas may need particular management focus in the immediate future.

For the GBR's seagrasses, high temperatures are an increasing threat, particularly to intertidal meadows:

“Temperature measurements in the shallow intertidal pools formed at low-tide have confirmed that seagrasses in these areas are experiencing temperatures that are known to be detrimental to seagrass photosystems (Campbell *et al.* 2006). Desiccation and ‘burning’ of intertidal seagrasses leaves at low tide was also observed during seagrass monitoring surveys conducted during the drought years [of 2002-2003] ... Extreme temperatures (41°C) were recorded [in the Wet Tropics region] in January and February, 2004 and 2005 respectively.” (Coles *et al.* 2007)

And in the southern GBR:

“The major drivers of seagrass change appear to be strongly linked to climate and tidal exposure. Drought conditions have been prevailing in Gladstone for a number of years, and although they may account for some of the changes, they do not explain all of the fluctuations in seagrass density (Rasheed *et al.* 2006a). Declines in intertidal meadows in past surveys may also be linked to changes in daytime exposure of seagrass banks (Taylor *et al.* 2007). This increased exposure combined with the drought conditions of high solar irradiance and temperature were likely to create conditions of increased thermal stress and desiccation on seagrasses when exposed (Rasheed *et al.* 2005a). In the most recent monitoring in 2006 the number of hours intertidal estuarine meadows were exposed had substantially reduce[d] from the previous two years, and this may explain some of the recent recovery.” (Coles *et al.* 2007)

Temperature also appears to be an important factor in outbreaks of coral diseases (Selig *et al.* 2006) and initiation of some phytoplankton and other algal blooms (Sparrow and Heimann 2008). For example, the colonial microalga *Chrysochloris fragilis* forms blooms on outer reefs of the GBR, growing on dead corals at high temperatures in oligotrophic conditions, where coral has been killed by COTS or bleaching (Schaffelke *et al.* 2004). These are issues of

concern in coral reef dynamics and recovery (see for example Diaz-Pulido and McCook 2003).

Coral bleaching may be considered an indicator of climate change as represented by elevated sea temperatures and/or other triggering parameters. A suite of biophysical indicators of onset of bleaching has already been developed. These include the NOAA remote-sensed coral bleaching products, accessible at <http://coralreefwatch.noaa.gov/satellite/>. These already provide near real-time analyses of sea surface temperature (SST) anomalies, bleaching HotSpot anomalies, Degree Heating Weeks (DHW), and Tropical Ocean Coral Bleaching Indices. However, these products require further development. For example:

“The current ‘Hotspots’ prediction methodology failed to predict the 2006 bleaching conditions [on the southern GBR] despite major impacts observed on coral reefs ... such problems can be ameliorated if seasonal variation in thermal tolerance, likely a result of physiological acclimation, is taken into account. This allows bleaching arising due to abrupt warming in early summer to be forecast by using thermal thresholds that appropriately reflect the long-term mean pattern in seasonal variation.” (Weeks *et al.* in prep, Hoegh-Guldberg 2007)

Related thresholds of concern for the GBR include the thermal thresholds for a suite of GBR coral species (Berkelmans in press).

5.4 Fisheries and Species of Conservation Concern

Several MTSRF-supported projects are providing key information for fisheries management. Regarding impacts of the rezoning on the commercial fishers, effort reduction targets were met for the whole of the marine park, although some variability in the amount of effort purchased at the regional level relative to the impact of the rezoning was evident (Sutton 2007). Some regions had more buy-outs than was targeted, others less than the target (QSIA 2004, Sutton 2007).

And for recreational fishers:

“Preliminary results ... indicate that the majority (70%) ... support the idea of rezoning the GBR and that most (75%) believe the new zoning plan will help maintain the GBR in healthy condition. Approximately 50% of recreational fishers reported experiencing no impacts from the rezoning; 25% reported experiencing negative impacts; and 25% reported experiencing positive impacts. Although support for the rezoning plan was high among recreational fishers, only 40% believed that the concerns of recreational fishers were adequately considered in the rezoning process.” (Sutton 2007)

Improved characterisation of the GBR fishery is providing the QDPI&F and GBRMPA with a better understanding of the present levels of use of resources, towards ensuring that adaptive management strategies provide for ecologically sustainable use. As an example:

“In respect of harvest patterns within all sectors of the [Coral Reef Fin Fish] fishery [CRFFF], the largest take of ‘other species’ is by recreational fishers, with more than 70% in the three years for which comparative data were available. Thus where management of these species is required action must be taken across sectors. All sectors of the fishery showed regional differences in species composition, indicating that management strategies need to recognise these differences. The ELF and charter sector data showed no changes in species

composition over time, while the commercial fishery demonstrated a significant change in harvest pattern with the development of 'live' export practices. This result suggested that harvest patterns can change with changes in the management strategy of the fishery. Further analysis of the data ... will provide for an understanding of changes that may have occurred with the introduction of the quota management system for the CRFFF and also the new zoning plan for the GBR." (Simpfendorfer *et al.* 2007a)

The inner to outer-shelf reefal and inter-reefal studies of the effects of rezoning on fishery resources (G. Russ, P. Doherty, R. Pitcher and colleagues and AIMS LTMP) are demonstrating important direct and indirect (trophic cascade) effects on both target and non-target fish stocks in respect of sizes and abundance, with profound implications for improved fishery management and the understanding of resilience on the GBR. These results have important broader application, as very little is known of the quantitative effects of rezoning of MPAs in respect of fisheries enhancement globally.

For the inter-reefal seabed:

"While there are uncertainties in ... estimates of protection level indicators, the underlying dataset is the most extensive and detailed available and the estimates are likely to be robust at the scale of the entire continental shelf in the GBR region. From these indicators, it appears clear that the 20% protection level target of the RAP re-zoning has been achieved for all aspects of seabed biodiversity analysed: seabed species, seabed assemblages, and seabed habitats..."

"The indicators estimated here have documented the current levels of protection for seabed species, assemblages and habitats in the region and will raise the level of stakeholder knowledge of the nature and protection of the region's ecosystems. These assessments have provided a quantitative regional context that will benefit managers needing to respond effectively to industry and community concerns and achieve an objective balance between human uses and needs for conservation in a multiple-use environment. The community will be informed and benefit from independent information on levels of protection of the seabed. The outputs will facilitate assessment of spatial management in the region and will benefit future planning and regional ecosystem management." (Pitcher *et al.* 2007b)

For the near-shore fringing reefs:

"... areas of inshore fringing reefs designated as no-take green zones under the RAP zoning plan are having a positive effect on stocks of targeted fish species. Due to relatively high levels of surveillance and enforcement, and fisher compliance with zoning regulations, these inshore fringing reefs are some of the most adequately protected reefs of the GBRMP ..." (Russ *et al.* 2007b)

For the seagrasses:

"Pressures on seagrass other than from events such as cyclones can be influenced by management approaches, protected areas and changes in land use practice. This has been recognised in the GBRWHA with recent representative area zoning dramatically increasing the areas of seagrass meadow protected from direct damage, and an ongoing Reef Plan initiative to improve land use practices and the quality of run off water entering the reef lagoon. Reclamation remains only a small total effect and routine dredging for

shipping occurs with tightly controlled restrictions and monitoring.” (Coles *et al.* 2007)

For species of conservation concern, dugong populations along the urban GBR coastline appear to have stabilised, and the GBR in total supports one of the largest remaining populations globally (Marsh *et al.* 2007). Along the Queensland coast, three regional groups of dugong populations have been tentatively distinguished from mitochondrial DNA data (Blair *et al.* in review): Moreton Bay to Shoalwater Bay; Townsville to the Starcke River region; and Torres Strait, with important management implications (Marsh *et al.* 2007). The remote coast of north Queensland (Cooktown north including Torres Strait), an area of almost 56,000 km², supports an estimated total population of approximately 24,000 dugongs, (Marsh *et al.* 2007). The area to the south of Cooktown is estimated to support a further 4,500 dugong (Marsh *et al.* 2005, 2006), such that the Queensland coast, including the GBR to Torres Strait, may host some 25-30,000 dugongs in total. Since the 1980s, numbers in the northern region do not appear to have declined significantly (Marsh *et al.* 2007). However, Marsh *et al.* (2007) caution against using this result as a reason for postponing management actions, as detection of declines in marine mammal stocks is generally poor. Reductions in levels of non-natural mortality are necessary to restore the population to pre-1960s level. The development of culturally acceptable and scientifically robust mechanisms to manage Indigenous hunting is a major priority for effective management (Marsh *et al.* 2007).

“The 'National Partnership Approach' to the management of Indigenous hunting of turtles and dugongs is being implemented by the Commonwealth Department of the Environment and Heritage in cooperation with the relevant states and Northern Territory governments (Anon 2005) ... Within the Great Barrier Reef region, the intention is to regulate the dugong and turtle harvest through the development of Traditional Resource Use Management Agreements (Havemann *et al.* 2005). The priorities of Indigenous peoples and government agencies are likely to be different ... Nursey-Bray showed that Indigenous people prioritised social justice community and culture whereas management agencies prioritised biodiversity conservation and species viability. Consequently, a process needs to be developed to promote the development of solutions that satisfy the needs of both groups with an associated increase in mutual understanding and trust ... effective dugong management requires initiatives to be co-ordinated across jurisdictions ... the genetic and movement data both indicate that the appropriate ecological scale for management is some hundreds of kilometres (Blair *et al.* 2005; Sheppard *et al.* 2006).” (Marsh *et al.* 2007)

In respect of the risk to species of conservation concern from fisheries by-catch, Soto (2007) concluded:

“Given the conditions in the Great Barrier Reef World Heritage Area, spatial risk assessment approaches using geographic information systems [GIS] should be encouraged. This approach could be applied in several ways to identify: (1) potential sites for further area closures, especially locations in which commercial fishing activities which cause bycatch are still allowed in habitat of high or medium conservation value to species of conservation concern, as suggested by Grech *et al.* (in review); (2) areas where compliance activities should be focused, such as areas of high risk for turtles being caught in trawls when fishers fail to use TEDs (Robins 2002); [and] (3) areas where efforts to determine the causes of death of marine wildlife should be focused, such as areas close to major sites where stranded wildlife are likely to be found and reported by the general public and where the capacity exists to conduct necropsies. The long-term recording of wildlife mortality by the Queensland Shark Protection Program provides an invaluable data set and should be continued.”

Given that the GBR supports the largest nesting populations of threatened green turtles globally, continuing declines in nesting success, and likely shifts in sex ratios of hatchlings, are of increasing concern.

“... since 1996 several biological indicators have been suggested as early warning signs that the population is in early stages of decline; for example declining size of nesting turtles. In addition, in the last ten years both the proportion of females ashore on any night that successfully lay eggs, and hatchling production has been very low and approaching zero. Several factors have been identified as likely or probable causes: gradual net sand loss from the island, changes to the beach rock profiles, flooding of nests, very dry sand that does not allow nest digging, or combinations of the above. Factors underlying these causes could be both natural and anthropogenic (as a result of island or reef crest alteration during mining operations).

Given that it is generally accepted that successful sea turtle populations require in order of 75% hatchling production to maintain recruitment, it is clear that the low nesting success and poor hatchling production is not sustainable at current levels ... A consequence of poor hatchling production will be reduced juvenile recruitment into the foraging areas five to ten years later. Given that the poor hatchling production was first recorded in 1996, surveys in the coming years will be crucial to assess rates of recruitment.” (Hamann and Fuentes 2007)

6. Future Research Directions

The GBR, as indeed all the world's ecosystems, is in a state of rapid change at the beginning of the 21st Century. With respect to biodiversity and the socio-economy (e.g. harvest patterns and tourism), the future value of continuing long-term monitoring datasets (e.g. seagrasses, reefs, dugong and turtles, fisheries and tourism), and the more recent 'baselines' (e.g. inter-reefal shoals and seabed, iconic species) cannot be overemphasised. These are of both national and international significance in providing managers and other stakeholders with relevant, timely information on the 'state-of-the system' and spatial and temporal trends, and researchers with accurate time-series data for predictive modeling.

For the seagrasses, for example:

"[Q]DPI&F hold extensive datasets on seagrass change over ten years and more formal correlative analysis on how these changes are related to climate is to be undertaken in the future ... While resilience factors are complex – they may include the previous history of the meadow, species mix, genome types, availability of viable seed banks, reproductive ability, nutrient availability, sediment type and a variety of location specific factors – they are essential in understanding the 'performance' of a meadow under stressful conditions. There are long term data sets that show the range of fluctuations that can occur but the limits to successful recovery and the processes that support recovery are poorly understood. Without this information it is difficult to model scenarios such as the effect of climate change in a meaningful way." (Coles *et al.* 2007)

Of equal importance, future changes to the GBR will be related, to greater or lesser degree, to changes in the physical and biological oceanography of the system.

"Given the sparse number of observations of the GBR and Coral Sea, it is therefore important to encourage initiatives such as CLIVAR's Southwest Pacific Circulation and Climate Experiment (SPICE) and dedicated regional array on the GBR that can monitor the EAC variability and structure over the longer term. The recent Australian Integrated Marine Observing System initiative goes some way toward achieving these goals for the GBR. Without these dedicated systems for long term accurate measurements, detection of climate related change oceanographic processes will remain unresolved or uncertain. Further modelling studies are needed to provide hypothesis testing on local affects of climate change through downscaling from global predictions." (Steinberg 2007)

The degree of biological connectivity – gene flow with other areas of the Indo-west Pacific, and the associated effects on resilience / replenishment in relation to climate change – remain critical issues for future research. Within the GBR, the key biodiversity attributes of certain areas, and levels of connectivity with the remainder of the system, remain only poorly understood. The far northern area is closest to the Indo-west Pacific diversity centre, and is, as far as is presently known, the most biodiverse region of the GBR (e.g. see DeVantier *et al.* 2006 for reef-building corals). Yet for most invertebrate groups, the actual levels of diversity are not well known. Similarly the Pompey and Swain Reef complexes of the central-southern GBR remain relatively poorly understood. Major knowledge gaps also remain for cetaceans. For dwarf minke whales for example, a major and increasing tourism draw-card, basic demographic information such as population size, the purpose(s) of their migration to the GBR (potentially for breeding), and their whereabouts when away from the GBR, all remain uncertain or unknown (Birtles *et al.* 2007).

Of particular future importance are emerging synergisms among global and regional factors, such as those between climate change, rainfall and water quality. Levels of resilience to the emerging effects of environmental change remain only poorly understood. A better understanding of resilience and trophic linkages is necessary for setting realistic parameters of scenario models. Understanding of causal relationships and tolerance thresholds of specific indicators and primary, secondary, tertiary effects, cascades and feedbacks among trophic groups and levels (e.g. corals – algae – fish) remains an important area for future research. These will prove important research areas for the future 'health' of the GBR and will provide developing opportunities for further enhancement of integration both inside MTSRF and with the broader research community. For example:

“Climate change, potential sea level rise, and increased intensity and frequency of tropical storms will all impact on coastal and estuarine seagrass meadows [and other habitats] although opportunities for intervention within the GBRWHA are limited. Events associated with climate change combined with the effects of local catchment use may explain some of the seagrass changes observed in coastal waters (Thomas *et al.* 2006) ... These processes are complex and poorly understood and will require collection of long term data from a range of sites before a reliable model could be developed.” (Coles *et al.* 2007)

With respect to the continuing development and refinement of indicators and thresholds of concern for water quality, various biological and ecological indicators are being developed (Fabricius *et al.* 2007), and risk maps using chlorophyll and water clarity also show promise (De'ath 2007; Figure 14). Future work will explore the possibilities of establishing functional relationships between pollutants and biotic responses.

“By establishing such environmental-biotic relationships, the effectiveness of risk maps to management could be greatly improved. For example, it would provide us with the possibility of predicting biotic responses to environmental change.” (De'ath 2007)

Biotic effects of very low concentrations of pesticides and heavy metals are increasingly being discovered (see, for example, Environmental Science and Technology, DOI: 10.1021/eso62287r). Pollution levels far below those considered dangerous for aquatic life can dramatically alter animal behaviour in other ecosystems, with potentially important food-web effects. The degree to which this has occurred or is occurring on the GBR is little understood.

“Pesticides can be found in seagrass meadows in the GBRWHA, but not at levels that appear to have had any major effect, although at levels where there is potential for a reduction in photosynthetic activity (Haynes *et al.* 2000; Schafelke *et al.* 2005; McKenzie *et al.* 2006b).” (Coles *et al.* 2007)

And:

“In some cases experimental work may provide a basis for setting thresholds for the lower bounds of ecosystem condition. For instance, Markey *et al.* (2007) tested five insecticides for their effects on larvae of one species of coral, *Acropora millepora*, and found that concentrations as low as $1\mu\text{g.l}^{-1}$ caused decreases in settlement and metamorphosis of 50-100%. Experimentally determined values need to be evaluated critically and confirmed for local species and conditions.” (Sweatman 2007)

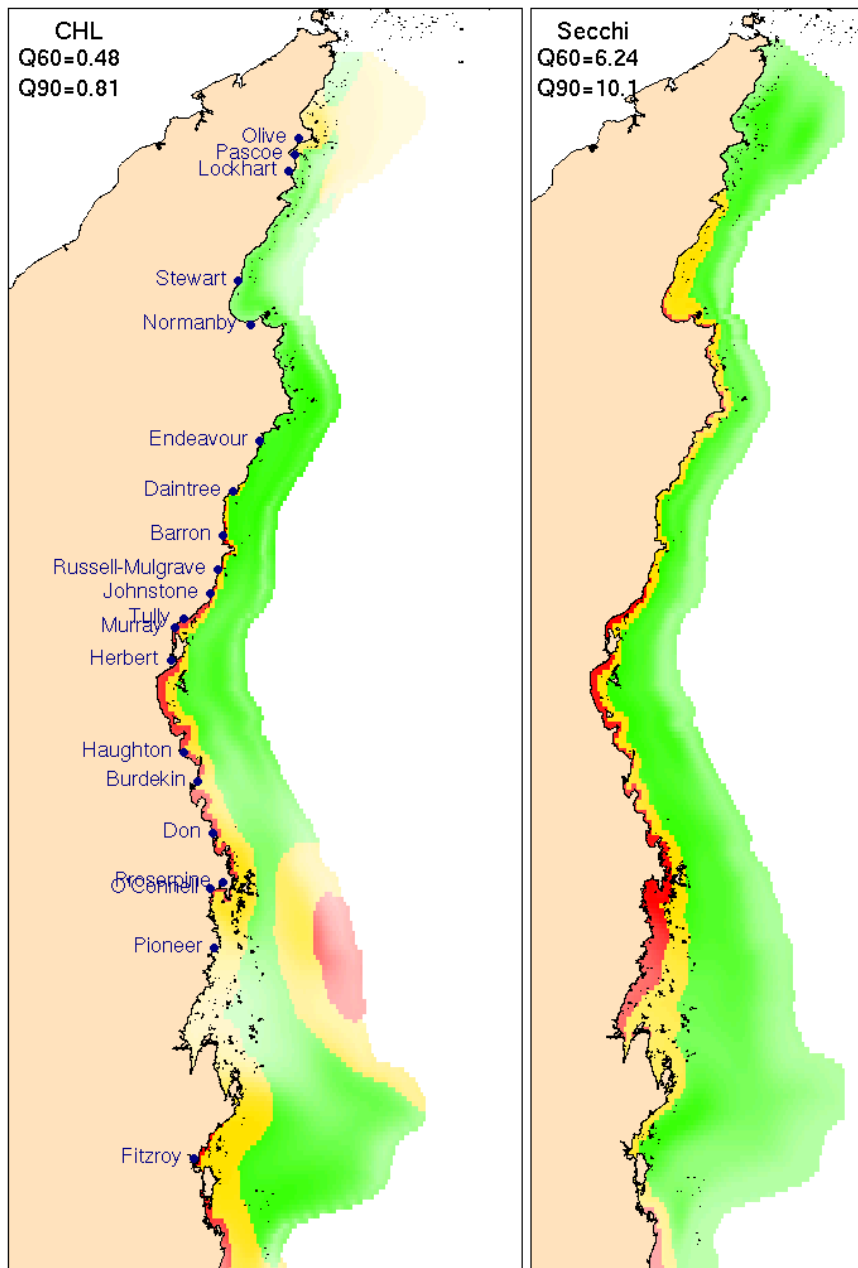


Figure 14: An example of risk maps with associated uncertainty. (*Left*) Risk map for chlorophyll; and (*Right*) the risk for water clarity as measured by Secchi disk. Regions of relative risk are mapped using the '60-30-10 rule'. This rule is a tentative suggestion for defining levels of relative risk that may be suitable for ecosystem management in the absence of known critical exposure levels. Predicted values lower than the 60th percentile of the *observed* data are declared 'low risk', the 60th-90th percentile are 'moderate', and higher than 90th percentile are high risk. Having a small 'high risk' band is attractive since (a) this focuses attention exclusively on the highest risk areas, and (b) the relatively small size may make risk-reduction through action more feasible. For simplicity and ease of interpretation, red, orange and green coloring is used to indicate high, moderate and low risk regions respectively. Additionally, the certainty of the predictions are estimated and represented by colour saturation with strong shades indicating low uncertainty, and pale shades indicating high uncertainty. Although classification of relative risk into these three categories can be a useful summary for non-technical presentation, it does constitute a substantial loss of information, and is not recommended for all purposes. In particular, small areas of extreme risk may be missed, and for management to be effective we require systems that can quantitatively combine and display multiple sources of risk at high spatial and temporal resolution, for example through contour and trend plots (Source: De'ath 2007).

Organism-response studies to water quality and climate change include physiological and genetic studies and modelling. For the physiological studies, careful selection of future experimental species will be crucial in assessing the likelihood of differential survival and associated shifts in populations and communities (e.g. in relation to trophic mode of corals – phototrophic and heterotrophic models for species with restricted / broad distribution ranges). Other emerging research areas include the secondary and tertiary effects of such population and community shifts, including trophic cascades, with important implications for both the ecology and socio-economy of the GBR. There is a clear parallel need to incorporate multiple synergistic and cumulative aspects, including SST, changing ocean chemistry (increasing acidification), diseases and other factors in the modelling.

An improved understanding of causality and levels of ecological resilience, from local to regional to global levels, with refinement of biophysical targets for the GBR, such as those for sea temperature, ocean alkalinity and water quality entering the GBR lagoon, will lead to integrated conceptual modeling of 'state of system', with an increasingly refined predictive capacity.

7. Relevant MTSRF-Related Publications 2006-2007

The information presented in this report was current as of mid 2007. Subsequent advances and publications post mid-2007 are generally not included. Where possible, references to MTSRF literature have been updated and a URL is provided for access to some items online.

Reports and Journal Articles

Berkelmans, R. In press. Bleaching and mortality thresholds: How much is too much? In: *Coral Bleaching: Patterns, Processes, Causes and Consequences* (van Oppen, M. J. H. and Lough, J. M., Eds), Springer.

Birtles, A., Valentine, P., Stoeckl, N., Mangott, A., Brown, V. and Curnock, M. (2007) *Understanding the social and economic values of key marine species in the Great Barrier Reef*. Marine and Tropical Sciences Research Facility Task 4.8.6 (a), (c). Preliminary Report to the Reef and Rainforest Research Centre, Cairns.

Brodie, J., De'ath, G., Devlin, M., Furnas, M. and Wright, M. (2007) Spatial and temporal patterns of near-surface chlorophyll *a* in the Great Barrier Reef lagoon. *Marine and Freshwater Research* 58: 342-353.

Church, J. A. and Boland, F. M. (1983) A permanent under current adjacent to the Great Barrier Reef. *Journal of Physical Geography* 13: 1747-1749.

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Cvitanovic, C., Fox, R. J. and Bellwood, D. R. (2007) *Herbivory by fishes on the Great Barrier Reef: A review of knowledge and understanding*. Marine and Tropical Sciences Research Facility. Preliminary Status and Trends Report, June 2007 (<http://www.rrrc.org.au/publications/downloads/Project-25i3-Herbivory-Status--Trend-Report-June-2007.pdf>)

De'ath, G. (2007) *The spatial, temporal and structural composition of water quality of the Great Barrier Reef, and indicators of water quality and mapping risk*. Report to Marine and Tropical Sciences Research Facility. Australian Institute of Marine Science, Townsville (<http://www.rrrc.org.au/publications/downloads/115-AIMS-Death-2007-WQ-on-GBR.pdf>)

De'ath, G., Coles, R., McKenzie, L. and Pitcher, R. (2007) *Spatial distributions and temporal change in distributions of deep water seagrasses in the Great Barrier Reef region*. Report to Marine and Tropical Sciences Research Facility. Australian Institute of Marine Science, Townsville, and Queensland Department of Primary Industries and Fisheries, Cairns, June 2007 (23pp.) (<http://www.rrrc.org.au/publications/downloads/113-AIMS-DPI-Death-et-al-2008-Deep-water-seagrasses.pdf>)

Fabricius, K., Uthicke, S., Cooper, T., Humphrey, C., De'ath, G. and Mellors, J. (2007) *Candidate bioindicator measures to monitor exposure to changing water quality on the Great Barrier Reef*. Final Report to the Catchment to Reef Joint Research Programme. Marine and Tropical Sciences Research Facility Research Report Series. Reef and Rainforest Research Centre Ltd, Cairns (253pp.) (<http://www.rrrc.org.au/publications/downloads/Final-C2R-Report.pdf>)

Gordon, I. J. Submitted. Linking land with the ocean: Feedbacks in socio-ecological systems. *Hydrobiologia*.

Grech, A., Marsh, H. and Coles, R. In review. Using spatial risk assessment to evaluate and address the problem of marine mammal bycatch. *Aquatic Conservation*.

- Hamann, M. and Fuentes, M. (2007) *Condition trends and projected futures of marine species of conservation concern*. Milestone Report to Marine and Tropical Sciences Research Facility Project 1.4.1 (Objective b), June 2007 (<http://www.rrrc.org.au/publications/downloads/Project-141-June-2007-Milestone-Report-Objective-B.pdf>)
- Hoegh-Guldberg, O. (2007) Early warning and assessment system for thermal stress on the GBR. Milestone Report to Marine and Tropical Sciences Research Facility Project 2.5i.2, November 2007 (<http://www.rrrc.org.au/publications/downloads/25i2-UQ-Hoegh-Guldberg-2007-November-Milestone-Report.pdf>)
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Appendix 1: Summary of MTSRF Projects 2006-2007

Theme 1: Status of the Ecosystems

Program 1: Status and Trends of Species and Ecosystems in the GBR

Ecosystem status is being assessed for a number of key taxonomic groups, both reefal and inter-reefal, such as corals, seagrasses and fishes. This Program is a mix of continuing and new projects, designed to integrate longer-term (decadal) trends with new discoveries.

Project 1.1.1 Identification of Non-Reefal Species and Potential Indicator Species on a Bioregional Scale

Project Leader and Host Organisation: Dr Roland Pitcher, CSIRO

Rationale and Objectives

The project addresses a hitherto little-studied aspect of the GBR. The Seabed Biodiversity dataset collected as part of CRC Reef is being used to develop indicators of biodiversity protection levels for seabed species, habitats and assemblages, and to investigate seabed habitat/species assemblages to document representation of biological assemblages by GBR zone and bioregions. Indicators of protection levels may be expressed, for example, in terms of: percent biomass by zone for species; percent area by zone for habitats; and percent area by zone for assemblages.

The basic approach to the indicators involved estimating the proportion of area or biomass of an assemblage, species group or species in various zones of the GBRMP. The study area on the continental shelf of the GBRMP (excluding islands, coral reefs and shallow shoals <~12m, coastal shallows <~7m, and slope and abyss deeper than ~80m) was almost 200,000 km², of which 44% is now zoned General Use (down from 75%), 28% is now zoned Habitat Protection (up from 20%), 28% is now zoned Marine National Park (and Conservation Park) (up from 5%), and <1% was Preservation. With respect to change from General Use to higher levels of zoning, the overall increase in protection of the continental shelf seabed has been about 31%.

Progress – Outputs

This project has so far produced: (1) maps of the abundance distribution of about 850 more frequent seabed species from a wide variety of biota such as algae, sponges, echinoderms, ascidians, cnidarians, molluscs, fishes, bryozoans, seagrasses and crustaceans; (2) maps of the abundance distribution of 38 species-groups, where the constituent species had correlated distributions in the GBR region; (3) a map of sixteen seabed species-assemblages in which the mix of biota was as homogeneous as possible and in some way distinct from the mix in other assemblages; and (4) a map of nine broad seabed biological habitat types.

The protection indicators estimated for ~840 seabed species showed that prior to the RAP re-zoning, 160 of the species analysed had <20% of their predicted biomass in zones with higher protection, whereas after the re-zoning all species analysed had >20% of their predicted biomass in zones with higher protection; the average increase in protection over all species analysed was 29%.

An additional ten species not covered by sled and trawl data were provided by the BRUVS and, prior to RAP, five of these ten species had <20% of their predicted occurrence in zones with higher levels of protection, whereas post RAP, all of these species had >20% in zones with higher levels of protection; the average increase in protection was 31%.

The protection indicators estimated for the 38 species-groups showed that prior to RAP, ten of these species-groups had <20% of their predicted biomass in zones with higher levels of protection, whereas post RAP all groups had >20% of their biomass in zones with higher levels of protection; the average increase in protection was 27%. The protection indicators estimated for the sixteen seabed species-assemblages showed that prior to RAP, seven of these assemblages had <20% of their predicted area in zones with higher levels of protection, whereas post RAP, all of these assemblages had >20% of their area in zones with higher levels of protection; the average increase in protection was 36%.

The protection indicators estimated for the nine broad seabed biological habitat types showed that prior to RAP, four habitat types had <20% of their predicted area in zones with higher levels of protection, whereas post RAP one of these habitat types had 20% of area in zones with higher levels of protection and all others had >20%; the average increase in protection was 31%. While there are uncertainties in these estimates of protection level indicators, the underlying dataset is the most extensive and detailed available and the estimates are likely to be robust at the scale of the entire continental shelf in the GBR region. From these indicators, it appears clear that the 20% protection level target of the RAP rezoning has been achieved for all aspects of seabed biodiversity analysed: seabed species, seabed assemblages, and seabed habitats.

Project 1.1.2 Condition and Trend of the GBR Ecosystem: Indicators, Thresholds of Potential Concern, and Ecological Influence of GBR Zoning Plan on Mid and Outer Shelf Reefs

Project Leader and Host Organisation: Dr Peter Doherty, AIMS

Rationale and Objectives

The project builds on past studies monitoring broad-scale status and relative health of coral reefs. The aim is to integrate information on regional and global resilience to disturbance (e.g. cyclones, crown-of-thorns starfish, coral disease and coral bleaching). A major aspect of this work is the AIMS Long Term Monitoring Program (AIMS LTMP), running since 1992. This extensive and growing dataset, the most comprehensive of its kind in the world, will play an increasingly important role in addressing the problem of 'shifting baselines' of ecological status. Details of the rationale, design and regular reports of reef condition and response are available at <http://www.aims.gov.au/docs/research/monitoring/reef/reef-monitoring.html>. The ongoing results of this work will be linked with related research in this program (e.g. Reef Check) and other MTSRF Programs, notably those for water quality and climate change. The AIMS LTMP survey design has recently been modified to address the effects of the 2004 rezoning on benthic and fish diversity and ecological status.

Progress – Outputs

The project has developed a COTS early warning system to allow the tourism industry to prepare tactical responses. Recent surveys of mid- and outer-shelf reefs in the northern part of the putative initiation zone for waves of starfish outbreaks (41 mid-shelf reefs north of Cairns) recorded just three COTS (with another single starfish found on Green Island Reef).

As introduced above, the 2004 GBR Zoning Plan created a large number of new Green (no-take) Zones. In the MTSRF transition year (2005-2006), the abundance and biomass of the

most important target fish, coral trout (*Plectropomus* spp.) were compared on reefs that were protected in 2004 with nearby reefs that remained open to fishing (<http://www.environment.gov.au/programs/cerf/publications/rezone-gbr.html>). Surveys of matched comparisons in five geographic regions are continuing.

With respect to indicators and thresholds of concern, Sweatman (2007) noted:

“There are no agreed thresholds of concern for most of the commonly recorded variables relating to the health of coral reefs. Coral reefs are dynamic systems and reefs that are remote from direct human influence still show cycles of disturbance and recovery that can involve major disturbances from arguably natural causes ... There is an issue of scale that will be important to the MTSRF IRC: coral cover can drop to very low levels on individual reefs, but *Acanthaster planci* outbreaks do not usually affect every reef in a region at the same time. Thus the threshold of concern depends on the scale of the reporting area.

“In the general absence of logical thresholds, thresholds should be based on extreme values (for instance, 90th percentiles) of the distribution of recorded indicator values (suitably regionalised), with scheduled reviews by a panel of reef scientists who should also identify opportunities for experimental work to assist setting thresholds of concern or with interpreting monitoring results in other formats ...

“Most indicators that are more closely related to population and ecosystem processes are only available at a limited number of sites. Measures of diversity of important groups of reef organisms (sessile benthic animals and reef fishes) are commonly used in assessments of environmental health, but data from different monitoring programs will need to be carefully standardised. Development of practical indicators of ecological processes on coral reefs, along the lines of Fairweather’s (1999) eco-assays would be very desirable. Indicators based on population trajectories of key groups of organisms from long-term programs are another possible new development.

“In the absence of easily identified reference sites, values from the distributions of recorded values for indicators (appropriately regionalised) must be used for interpretation. This should be backed up by rigorous expert review and targeted research to refine the *identification of critical values*.”

A large list of potential indicators of aspects of health of coral reefs (rather than the full range of GBR habitats) has been compiled to identify those that could be based on data that are broadly available for the GBR. Those of relevance to water quality that may be sourced from the AIMS LTMP data are listed in Table 1 (from Sweatman 2007).

The project also contains a significant community-based monitoring component to foster local environmental stewardship of tourism intensive sites, being coordinated through Reef Check. Three Reef Check training workshops and secured partnerships with the dive industry have been achieved to date. COTS surveys at 25 dive sites revealed only two starfish (Airlie Beach Region, Whitsundays) and few feeding scars. Baseline mapping of 22 Reef Check sites and integration of information from dive operator site maps are being input to a spatial online database, which will be the major communication channel.

Table 1: List of potential mature indicators for effects of water quality in the marine environment that could be sourced from AIMS LTMP data (selected from Table 3 of Kuhnert *et al.* [2007]).

Marine Indicators	Indicator of	Data sites in GBR (custodian program)	Reference, threshold value or water quality objective
Nearshore and reef ecology			
Hard coral cover	Conditions for reef growth	Yes (AIMS LTMP)	under development
Hard coral richness	Disturbance	Yes (AIMS LTMP)	under development
Hard coral recruits	Sedimentation	Yes (AIMS LTMP)	under development
Herbivorous fish density, biomass, spp. composition	Macroalgal biomass	Yes (AIMS LTMP)	under development
Macroalgal cover	DIN/DIP	Yes (AIMS LTMP)	under development

Project 1.1.3 Condition, Trend and Risk in Coastal Habitats: Seagrass Indicators, Distribution and Thresholds of Potential Concern

Project Leader and Host Organisation: Dr Rob Coles, QDPI&F

Rationale and Objectives

This project also builds on long-term monitoring and assessment work over the past decade supported by the QDPI&F and CRC Reef, and is of increasing regional and global importance in respect of 'shifting baselines' and climate change. The work has strong links to MTSRF Program 4, as seagrass habitats provide a key food resource for threatened species of marine turtles and dugong. The key aim is to detect long-term trends in seagrass abundance, community structure, distribution, reproductive health and nutrient status from representative intertidal and subtidal, including deep-water, seagrass meadows (and their sediments) in coastal and offshore locations.

Research into long-term changes in deep seagrasses and algae will build on prior research and the recent CRC Reef seabed biodiversity project that identified extensive meadows of seagrass and macroalgae in GBR waters deeper than 35 m, and as deep as 60-70 m. Very little is known of the role these presumably slow-growing plant communities play in the GBR ecosystem, and what changes may be taking place. It is nevertheless reasonable to assume that if water quality declines, reducing light penetration, then loss or reduction of these communities will be one of the first signs, because they integrate light availability over long time scales.

Assessment of some of the highest risk areas in the GBR, including ports and shipping lanes, was completed as part of CRC Reef, but there is an identified need for more detailed information on shoal and reef-top habitats along the inner GBR shipping route from the tip of Cape York to Cape Flattery.

The seagrass work has five main components:

1. Seagrass-Watch (a cost-effective community seagrass assessment and monitoring program);
2. GBR WQPP monitoring of seagrass meadows;

3. Fine scale monitoring and mapping in coastal areas at risk;
4. Improved spatial knowledge of key intertidal and shallow subtidal seagrasses; and
5. Long-term changes in deep seagrasses and algae.

Improved spatial knowledge of key intertidal and shallow subtidal seagrasses will result from the remapping of seagrass meadows within the region from Cape York to Cairns, most of which has not been surveyed since 1989 (>15 years). This area was selected because existing data for the region are out of date and of poor spatial resolution. In 2009-2010, the focus will shift more to subtidal seagrasses in areas that have been poorly surveyed: an area including Port Douglas that has been suggested as a new Dugong Protected Area (DPA), and Bowling Green Bay, south of Townsville that includes an existing DPA and a Fish habitat Area. The outputs will include meadow shapes and sizes, species composition and community type, seagrass meadows and algae beds categorized in landscape types, seagrass and algae cover estimates, evidence of dugong feeding trails and preferred dugong feeding sites, evidence of turtle populations and marine debris such as net discards with GPS location.

Continuing expansion of Seagrass-Watch, with an additional fifty sites at fourteen locations (<http://www.seagrasswatch.org/home.html>), complements fifty urban locations and the 22 sites of the GBR Reef Water Quality Plan. This larger geographic spread of sites (currently 122), including those in DPAs and in other areas of community interest will ensure continued development of the present quarterly long-term seagrass monitoring program. Seagrass-Watch monitoring also occurs in twelve other countries in the Asia Pacific, providing an excellent opportunity to evaluate the state of Queensland's seagrasses within a global context.

Using community and industry resources and co-investment to enhance and broaden the scope, and integrating results from the five research components, outputs will have a strong spatial focus. Production of GIS layers for seagrass mapping will contribute to the development of the Reef Atlas. The time series on dynamics and resilience of seagrass meadows at many coastal locations will contribute to determining appropriate performance thresholds based on quantitative indicators like cover and leaf density. As with corals and reefs, very low seagrass cover at a single site will not always be a meaningful indicator of a problem of environmental quality, although there is more potential for local impacts in the coastal zone from point source pollution and other factors (e.g. sedimentation) associated with development. A desktop analysis of long-term changes in seagrasses will be conducted by comparing the results of the two historical broad-scale surveys, generating information about stability and change in these important ecosystems.

Finally, spatial and temporal dynamics of seagrasses will be assessed with simulation models that will then be applied to scenario evaluation and sensitivity analysis to find the limits for resilient seagrass systems.

"The intention in developing a status and trend report for the seagrasses of the GBRWHA was always that it would be a snapshot in time, a document on which to build an evolving picture of the status of seagrasses and the community of species associated with them. It serves a dual role to identify gaps in our knowledge and to assess the performance of our research programs at addressing those gaps." (Coles *et al.* 2007)

Progress – Outputs

At-risk coastal sites have been selected on the basis of likely anthropogenic impacts - ports and sites adjacent to areas of high urbanisation. Fine-scale monitoring and mapping is being conducted to ensure that any change in status is identified. Monitoring sites are associated with river mouths and inshore marine water quality monitoring programs (MTSRF Program 7)

to enable correlation with concurrently collected water quality information. Detailed fine-scale information on changes to seagrass biomass, area and species composition has indicated that there is rapid turnover, of the order of one month, for leaves.

Significant co-investment from industries that may pose risks to coastal seagrasses is offsetting the expense of conducting this fine-scale monitoring. Relationships with industry have been established, with co-investment secured for 2006-2007 and a strong commitment for continued support.

The following is summarised from Coles *et al.* (2007):

“Analysis and discussion of seagrass status and trends to date have been subdivided into the NRM Regions identified in the GBRWHA (Coles *et al.* 2007). These discrete regions have been used for stratifying issues of land- and catchment-based resource management and used to report downstream impacts on the reef environment, such as due to poor water quality. There are 56 NRM regions identified in Australia, fifteen are in Queensland and six are part of the coastal processes of the GBRWHA. These regions are mostly based on catchments or bioregions using assessments from the National Land and Water Resources Audit. Regional plans have been developed for each of these, setting out the means for identifying and achieving natural resource management targets and detailing catchment-wide activities addressing natural resource management issues, including land and water management, biodiversity and agricultural practices. Seagrass habitat data forms part of these targets and activities. Within each region Coles *et al.* (2007) also report separately on estuaries/inlets, coasts, reef platform and deepwater seagrasses. The climate, associated macro-fauna, fisheries and information gaps are also discussed.”

Cape York – Regional Summary

The only regular monitoring of seagrasses in the area comes from Archer Point, where seagrass cover has remained relatively constant since 2004. Due to the lack of monitoring in the region it is difficult to determine how seagrasses are trending. Of the few sites that have been revisited since broadscale mapping in the 1980s (e.g. Margaret and Shelbourne Bays) most appear to have maintained at least a similar distribution, indicating that seagrasses in the region may be relatively healthy (Rasheed *et al.* 2005, 2006). Seagrasses in the region also generally face low threat levels from chronic anthropogenic impacts when compared to other regions in the GBRWHA (Rasheed *et al.* 2007c). While there are high risks associated with shipping accidents and oil spills in the region, none of the ship grounding or collision events in recent times has resulted in major oil-spills (QT & GBRMPA 2000).

Information Gaps

Very little seagrass monitoring information is collected in this region, with the majority of seagrass habitat types unrepresented in the current program. The large reef-top seagrass areas of Corbett and Clack Reefs have not been mapped in any detail and no monitoring is currently conducted. These meadows are highly important for dugong. No subtidal coastal or estuary seagrass habitats are monitored in this region.

Wet Tropics – Regional Summary

Seagrasses in the Wet Tropics NRM region appeared to be in a relatively healthy state. In 2006 coastal intertidal meadows had generally expanded with *Zostera* meadows at their largest aerial extent and evidence of expansion of intertidal *Halodule uninervis* meadows. Subtidal seagrasses in coastal areas had also expanded in area and biomass in 2006. The major drivers of seagrass changes were likely to be linked to changes in regional and local climate, especially temperature, rainfall and associated turbid catchment run-off and tidal exposure.

Differences in seagrass changes were apparent between coastal and estuarine habitats and between intertidal and subtidal seagrasses, with the majority of changes explained by the differing effects of the major climate forcing factors in the different habitat types. The seagrass at Yule Point and Lugger Bay appears to have changed relatively little since 1967, when den Hartog (1970) photographed the area and described the species present and sediment condition. At Lugger Bay, however, seagrass cover was generally low (<10%), which is similar to observations in the early 1990s at this location (Mellors *et al.* 2005). The decline of seagrass at Lugger Bay in 2006 appears to have been a consequence of severe Tropical Cyclone *Larry* that crossed the coast fifty kilometres north of the location on 20 March 2006. No significant changes in species composition were observed at either of the locations (McKenzie *et al.* 2006b).

Despite the severe cyclone in March 2006, seagrasses in Mourilyan Harbour were able to recover to some extent by December 2006. Even a small *Zostera capricorni* meadow that was close to being completely lost had shown the first signs of recovery (McKenna *et al.* 2007). Should climate conditions remain favourable for seagrass growth, these meadows should continue to recover. However, the resilience of meadows to additional stresses in the near future is likely to be low, with intertidal seagrasses particularly vulnerable.

Information Gaps

There is a need for collection of baseline data for seagrasses in the northern section the Wet Tropics region, north of Yule Point. Good baseline information has been collected for seagrasses in the southern section of the region between Hinchinbrook and Lucinda in 2007 but at this stage ongoing long-term monitoring is unfunded. There is a need for further research and detailed analysis of the links between climate and seagrass change. While it appears that the key factors of rainfall, temperature, solar irradiance and exposure may be driving the observed seagrass changes, formal analysis of these links is required.

Burdekin Dry Tropics – Regional Summary

Information Gaps

No regular monitoring information is collected in the region on the status of subtidal seagrasses or changes to area of representative seagrass meadows. A fine scale monitoring program for meadows in the high risk Townsville/Cleveland Bay area (Rasheed *et al.* 2007b) would add significantly to our understanding of the status of seagrasses in the region.

Mackay-Whitsunday – Regional Summary

Information Gaps

The majority of information for the region comes from intertidal Seagrass Watch sites. No regular monitoring information has been collected in the region (since 2004) on the status of sub-tidal seagrasses. Changes to area of representative seagrass meadows are also not regularly monitored. A monitoring program for sub-tidal meadows in the high risk Whitsunday area (Rasheed *et al.* 2007a) would add significantly to our understanding of the status of seagrasses in the region.

Fitzroy – Regional Summary

Seagrasses in the Fitzroy NRM region appeared to be in a relatively healthy state. In 2006 coastal and estuarine meadows had generally shown increasing trends, with subtidal *Halodule* and *Halophila* meadows at their highest recorded biomass. The major drivers of seagrass changes were likely to be linked to changes in regional and local climate, and tidal exposure (Taylor *et al.* 2007). Seagrasses within the Port Curtis area also face a high level of anthropogenic threat, with major port expansions including reclamations, new facilities and capital dredging planned or underway. The recent collision and fuel oil spill from the 'Global

Peace' in Port Curtis also highlighted the potential risks to the marine environment from shipping activity in the GBRWHA (Taylor *et al.* 2006). A major industry-funded seagrass assessment and monitoring program is conducted in the Port Curtis area with the goal of minimising potential impacts of these activities on seagrasses. The program will come under the umbrella of the Port Curtis Integrated Monitoring Program in 2007 and is set to expand with direct physical and chemical measurements at seagrass monitoring meadows (including temperature, light and contaminants) to assist in determining and formalising the links to drivers of seagrass change.

Information Gaps

Seagrass status and trends are well addressed for the seagrass habitat types found in the Fitzroy NRM region.

Burnett/Mary – Regional Summary

Seagrass habitats in the Burnett-Mary section of the GBRWHA were in a relatively healthy state with monitoring indicating that major changes were likely related to the amount of tidal exposure, temperature and solar irradiance. Major areas of seagrass habitat in the region generally face low levels of anthropogenic threat, especially compared with seagrasses to the north in the Fitzroy NRM.

Information Gaps

None of the coastal *Halodule* meadows important to dugong are monitored in this region. However, these meadow types are monitored just to the north within the Fitzroy NRM region.

The following is excerpted from Rasheed *et al.* (2007d):

“Of the four regions identified as facing a ‘very high’ threat level, three have excellent capture in the current program (Cairns, Gladstone and Mourilyan). The detailed information on status and trends collected in these regions has been made possible through partnership programs with the port authorities that operate within these areas (Ports Corporation of Queensland; Cairns Port Authority; Central Queensland Ports Authority) and some local community volunteers. Some expansion of monitoring activities in the Townsville region may be warranted as at present only intertidal information from Seagrass Watch sites is regularly collected. Currently no information on subtidal seagrass or fine-scale assessments of changes to seagrass meadow area and abundance are regularly collected in this very high threat region.

“Outside of the four highest threat regions, no regular monitoring or assessment of subtidal seagrasses is being conducted. While some regions have detailed baseline information collected on subtidal seagrass, regular monitoring is only collected as part of Seagrass Watch, which operates in intertidal areas. The Whitsunday region for example has a good coverage of information on intertidal seagrass changes but little information is available on subtidal seagrass meadows that make up an important component of the overall seagrass resources. Subtidal seagrass meadows are particularly important to monitor as often they are the first regions to be affected by changes to water quality, such as increased turbidity.

“To strengthen our monitoring of at-risk seagrass areas, the MTSRF program has established a fine-scale baseline survey for southern Hinchinbrook (Herbert River area) in year one (March 2007). Preliminary results of the baseline survey have identified suitable intertidal and subtidal seagrass meadows to develop a fine-scale annual monitoring program for the area. There is an obvious gap in the status and trends program for seagrasses north of Port Douglas, with monitoring in the area from Cape York to Port Douglas confined to only one Seagrass-Watch location (Archer Point). Many of the regions within this area have only

broad-scale seagrass information that was collected more than twenty years ago, or they have not been mapped or surveyed at all. While the majority of this area does not face particularly high threat levels, several regions do have threats that would warrant some level of monitoring, particularly key dugong feeding areas such as the seagrass meadows in the Corbett and Clack Reef region, for which there is currently no information.

“While this review has focused on high-risk areas to target for monitoring in the GBRWHA, there is merit in monitoring some seagrass areas that do not face high levels of anthropogenic threat. Monitoring in these areas would provide ‘reference regions’ to put changes observed in highly threatened areas into context. The existing status and trend program does examine some of these areas, for example Rodds Bay south of Gladstone. Collecting more information on other key representative seagrass areas in the GBRWHA at low risk would also be desirable.

“The expansion of the seagrass status and trends program into new ‘risk’ areas identified in this review is contingent on finding additional funding support for fine-scale monitoring or identifying new community groups with an interest in seagrass monitoring to establish Seagrass Watch sites. This presents a significant challenge for many regions with a low capture in the current program. Particularly in remote regions in the Cape York area, there are few local communities or industries to support seagrass monitoring activities.

“While the established program goes a long way towards assessing the status and trends of seagrasses at highest risk from human activity in the GBRWHA, we would suggest the following actions to improve the program:

- Maintain the existing fine-scale high risk seagrass monitoring locations;
- Investigate the feasibility of expanding the fine-scale monitoring program to the Townsville region to capture changes in subtidal seagrasses and changes to seagrass meadow area;
- Establish monitoring of subtidal seagrasses in the Whitsunday region (beyond the limited Seagrass Watch coverage);
- Investigate funding options to continue fine-scale monitoring of seagrasses in the southern Hinchinbrook (Herbert River mouth) area;
- Support and encourage the expansion of Seagrass Watch to Cape York communities;
- Establish baseline information and a monitoring program for seagrasses in the Corbett/Clack Reef area (Princess Charlotte Bay); and
- Investigate opportunities to fill gaps in our seagrass baseline information in the Cape York region (north of Port Douglas).”

Project 1.1.4 Dating and Mapping of Historical Changes in GBR Coral Communities

Project Leader and Host Organisation: Associate Professor Jian-xin Zhao, UQ

Rationale and Objectives

The dating and mapping of historical changes in GBR coral communities is using modern dating methods of TIMS Uranium-series to determine the age of dead coral colonies *in situ* on the GBR at a resolution of one to three years over several hundred years of history. This in turn is allowing temporal bracketing of significant mortality events back to the time of early European settlement of Queensland, and beyond. Knowledge of the age structure of the death assemblages is being related to major human developmental events and recent mass bleaching events related to global warming, so that the sources of the mortality can be

identified, and management can be directed toward ameliorating those sources. The project has three main objectives:

1. Determine the decadal death rate of massive corals over the last two hundred years (since European settlement);
2. Determine the variation in coral community structure over the past two hundred years; and
3. Correlate rates of coral mortality with major human development and recent El Niño events.

Progress – Outputs

Initial results have demonstrated the appropriateness of the methods, including dating of thirteen dead branching corals from the Swain Reefs and nine cyclone-transported coral blocks from Heron Island. The latter have recorded occurrences of several severe cyclones over the last 276 years, with dates ranging from 1734 to 1970.

Samples from the surface death assemblages and short cores (up to five metres' depth), including 42 cores and 92 surface death assemblages, were collected in May-June 2007 from near-shore reefs of central GBR. These samples are being analysed and dated in the Marine Ecology and Radiogenic Isotope Laboratories at the University of Queensland. Analytical data will become available soon.

Project 1.1.5 GBR Data Synthesis and Development of GBR Component of the Integrated Report Card¹

Project Leader and Host Organisation: Dr Alan Butler, CSIRO

Rationale and Objectives

This project has two main objectives:

1. Conceptual and statistical framework for the GBR component of the Integrated Report Card; and
2. Statistical analysis and synthesis of GBR monitoring data with particular emphasis on threats and risks and the biological implications of GBR zoning.

Progress – Outputs

The framework for the Integrated Report Card is initially being developed for Water Quality and will be extended to other issues in subsequent years. Theoretical underpinnings, the most likely indicators of GBR health to be used, and the supporting data sets have been identified. The best available data sets include biofilms, coral physiology and physical measures, benthic communities and coral recruitment, soft coral genera surveys and seagrass community data. These datasets are being used to:

- Develop a statement of what 'water quality' means as a multivariate measure for the GBR;
- Identify suitable indicators of water quality changes from existing benthic survey data: including comparisons of potential indicator measures along the water quality gradient within and between regions;

¹ **Editor's note:** From late 2007, Project 1.1.5 was retitled *Reef Atlas: Risk, Resilience and Response*, and realigned to enhance delivery of GBR-related MTSRF-wide studies of indicators, risk, and resilience.

- Develop the framework for indicators that addresses issues of validity (theoretical support for the indicator) and thresholds (sensitivity and specificity);
- Examine temporal and spatial scales for consistency of indicators; and
- Develop simple and cost-effective measures useful for monitoring and management programs.

Program 4 Species and Communities of Conservation Concern

Project 1.4.1 Condition, Trends and Projected Futures of Marine Species of Conservation Concern

Project Leader and Host Organisation: Dr Mark Hamann, JCU

The project is designed to assess the condition and trends of dugongs, marine turtles, coastal dolphins, minke whales, sea birds and sharks that occur in the GBRWHA and Torres Strait, and to evaluate management options to improve the status of these species.

Rationale and Objectives (a)

To estimate the sustainable anthropogenic harvest of dugongs for northern GBR and Torres Strait (TS) and to obtain information on the spatial distribution of dugongs and sea turtles to inform spatial assessment of risk management options. This is essential for implementation of the National Approach to Sustainable and Legal Indigenous Harvest of Dugongs in Australia, development of Traditional Use Marine Resource Agreements in the GBR, management plans for Indigenous hunting in TS and the review of the Inshore Finfish Fishery and DPAs.

This project will also obtain information on the spatial distribution of dugongs and sea turtles to inform a spatial assessment of risk management options in Project 1.4.2(e) by conducting aerial survey of dugongs and sea turtles in the northern GBR and TS and index blocks in Hervey Bay. These surveys will complete the aerial survey census that commenced in 2005 and has already surveyed from the QLD/NSW border to Cooktown. The aerial surveys will facilitate population and spatial modelling, in context of time series from early 1980s.

The following is excerpted from Marsh *et al.* (2007):

“The significance of the ... Great Barrier Reef (GBR) Region for dugongs was a reason for its World Heritage listing (GBRMPA 1981). Thus the GBR dugong stock, which is also subject to anthropogenic mortality including legal traditional harvest, is an explicit World Heritage Value and the status and trends in the distribution and abundance of dugongs is a critical information need for the management of the World Heritage Area (GBRMPA 2005) and the associated network of no-take MPAs. Consequently, GBRMPA has also supported research on dugongs since the 1980s and funded the historical surveys of dugongs in the Northern Great Barrier Reef reported here.

“Aerial surveys using the standardised techniques developed by Marsh and Sinclair (1989) have provided much of the information used to manage dugongs in Australia (Marsh *et al.* 2002). The Northern GBR Region was surveyed in 1985, 1990, 1995 and 2000; Torres Strait in 1987, 1991, 1996 [and] 2001. The objective of these surveys has been to provide an assessment of the distribution and abundance of the dugong these regions, a time series for temporal comparisons and an estimate of the annual sustainable mortality from all causes.

“The results of these surveys confirm that there is considerable temporal variability in the size and/or distribution of the dugong population of most survey regions, even though these regions have been very large (typically >30,000 km²). This variability is likely to be the result of several confounded factors: (1) temporal and spatial changes in the distribution of the dugong’s seagrass food; (2) dugong movements between survey regions exacerbated by different jurisdictions being surveyed in different years for logistical and funding reasons; (3) uncorrected fluctuations in the availability of dugongs to observers because of temporal and spatial variability in sighting conditions; and (4) temporal changes in the size of the population.

“In this report, we addressed the confounding effect of dugongs moving between regions between surveys by surveying the entire region from Cooktown through Torres Strait in November 2006. This is the first time that the Northern GBR and Torres Strait have been surveyed in the same year. We also addressed the fluctuations in the availability of dugongs to observers by using the improved methodology developed by Pollock *et al.* (2006). The results of the [2006] survey form the basis of this report on the condition, status and trends and projected futures of the dugong in the Northern GBR and Torres Strait.”

Progress – Outputs (a)

The following is excerpted from Marsh *et al.* (2007):

“This [2006] survey provides the first synopsis of the distribution and abundance of the dugong on the remote coast of Queensland from Cooktown north including Torres Strait. The results of previous surveys of sections of this region have been difficult to interpret because of the confounding influences of unpredictable dugong movements between areas within the region. Taken together, the results for the 2006 survey of the whole region of almost 56,000 km² suggest a total population of 23,963 ±1672 dugongs, close to the estimate of 21,851 ±1679 for the combined 2000 survey of the Northern GBR and 2001 surveys of Torres Strait. Both these estimates were generated using the methodology of Pollock *et al.* (2006), which corrects for the spatial heterogeneity of sighting conditions within and between regions and reduces the noise in the data that may otherwise obscure trends in the dugong population.

“All the population estimates obtained by the method of Marsh and Sinclair (1989) of the time series of aerial surveys of the Northern GBR 1985-2006 have been relatively similar (n_{\min} sensu Wade 1998 = 7,000-9,000). The results of the surveys are also robust to the methodological differences in correcting for availability bias inherent in the approaches of Pollock *et al.* (2006) and Marsh and Sinclair (1989), suggesting limited spatial and temporal variability in sighting conditions both within blocks and between surveys. Thus we conclude that the noise in the data resulting from variability in sighting conditions in this region is low relative to most other regions surveyed for dugongs.”

“Overall, these results suggest that the significant fluctuations between surveys in the size of the Torres Strait dugong population (Marsh *et al.* 1997, 2004) are unlikely to result from significant population movements between the Northern GBR and Torres Strait, a result which accords with the new genetic evidence discussed below. Nonetheless, the time series of surveys suggests considerable movement of dugongs between survey blocks within the Northern GBR region ... In addition, movement of dugongs between the Northern and Southern GBR has been established by satellite tracking (Sheppard *et al.* 2006) and is suggested by the genetic evidence below. Thus population movement between the Northern and Southern GBR may explain some of the variation in the dugong population estimates of both regions...” (Marsh *et al.* 2004)

Evaluation of the Survey Design

The approach used for the 2006 aerial survey demonstrated that it is logistically feasible to survey the entire region of nearly 56,000 km² – from Cooktown through Torres Strait – in a single month, using two aircraft and three survey crews. Nonetheless, we consider that a survey of this magnitude is at the limit of logistical feasibility given the scarcity of trained observers and suitable aircraft.

Dugong Population Structure

Recent research using mitochondrial DNA (which is maternally inherited) demonstrates regional differentiation of dugong populations (Blair *et al.* in review). Along the east coast of Queensland, three regional groups of populations are tentatively distinguished: Moreton Bay to Shoalwater Bay; Townsville to the Starcke River region; and Torres Strait. No samples are yet available for the region between Cape Melville and Torres Strait, and so the boundary between the Townsville to Starcke and Torres Strait stocks is uncertain and may not be clear cut. The region between Hunter Point and Newcastle Bay, which supports very low densities of dugongs, may form a boundary between the two regions. The regional differentiation of dugong stocks north and south of Townsville also needs further investigation.

Nonetheless, taken together with the results of this survey, the tentative genetic structure proposed by Blair *et al.* (in review) suggests that it is not unreasonable to continue to manage dugongs in the GBRWHA separately from Torres Strait, particularly given the very different jurisdictional arrangements in the two areas. However, careful consideration needs to be given to: (1) the policy for managing dugong hunting by the Northern Peninsula Area communities that straddle the boundaries of the two jurisdictions; and (2) co-ordinating management across the regions, preferably under a national Wildlife Conservation Plan as required for a listed marine species such as the dugong under the EPBC Act.

Condition, Status and Trends of Dugong Populations in the GBR

The dugong aerial surveys of the Northern GBR have not demonstrated a significant decline in dugong numbers since the mid-1980s, despite concern about the sustainability of the traditional harvest of dugongs in this region (Hudson 1985, Johannes and McFarlane 1991, Heinsohn *et al.* 2004, Marsh *et al.* 1997, 2004) and the lack of significant management arrangements to regulate this harvest to date.

However, we caution about using this result as a reason for postponing management actions. Taylor *et al.* (2007) demonstrate that scientists' ability to detect declines in marine mammal stocks is generally poor, even when the decline is precipitous. They make several recommendations to improve performance. Each of these is evaluated for the dugong surveys under Monitoring Options below.

In response to the difficulties in estimating trends in the population size of marine mammals, Wade (1998) developed the PBR method of setting targets for sustainable levels of anthropogenic mortality. The use of this methodology is now mandatory in the United States. The data generated using the PBR approach suggest annual sustainable anthropogenic mortality limits of 62-125 dugongs in the Northern GBR and 102-207 for Torres Strait. Reliable harvest estimates of current harvest are not available for either area; however, the information available (Heinsohn *et al.* 2004, Kwan *et al.* 2006, Marsh *et al.* 2004) suggests that the harvest is much higher than the sustainable levels estimated. Unless the aerial survey population estimates underestimate absolute population size, the discrepancy between the sustainable estimates of annual mortality and the information on catch levels indicate that the harvest is probably unsustainable and that management agencies need to work with the major dugong hunting communities to develop culturally acceptable measures to regulate the traditional harvest as discussed further below.

Projected Future

Irrespective of the status of the population, the dugong population size in the region is substantial (>20,000 individuals) and is genetically healthy, exhibiting high haplotypic diversity (Blair *et al.* in review). We believe there is time to work with local Traditional Owners and commercial fishers to develop appropriate management arrangements without dugongs becoming locally extinct in this region. However, the cultural value of dugongs may be reduced if they become locally depleted, as reported by some Traditional Owners. Experience with other large mammals (Johnson 2006) demonstrates that even low levels of anthropogenic mortality can drive species to extinction if all individuals in the prey population are exposed to mortality at some stage of their lives. This situation is most likely if: (1) animals are exposed to anthropogenic mortality in all the habitats in which they live; (2) if human population size does not depend strongly on access to megafauna; and (3) if animals in low density populations are still exposed to the risk of being killed. The last two of these conditions certainly apply to dugongs in Northern GBR waters. However, animals are not exposed to anthropogenic mortality everywhere in either the GBR or TS. Significant numbers of dugongs occur in areas where commercial netting and Indigenous hunting do not occur. Netting is banned from much of the dugong habitat in the Northern GBR region as explained below and hunting generally does not occur in deeper waters.

Key Threats

Dugongs are long-lived, slow to mature and subject to a number of threats. If these threats persist, they will threaten the integrity of wild populations of dugongs in Australia and elsewhere (Marsh *et al.* 2002). The main threats in the Northern GBR and TS are:

1. The bycatch of dugongs in commercial gill net fisheries (Northern GBR);
2. Unknown levels of harvest by Indigenous Australians (both regions);
3. Unknown levels of harvest by neighboring countries of the Asia/Pacific region, especially PNG (TS);
4. Illegal poaching by Australians and foreign fishers (both regions but especially TS);
5. Marine debris (unquantified but likely in both areas).

In our opinion the major threats to the dugong in this region are points 2, 3, and 4 above.

The zoning and management arrangements in operation since January 2005 have greatly reduced the risk to dugongs from commercial netting in the Northern GBR region by area closures and effort reduction. Commercial netting is now banned from approximately 64% of the high density dugong habitat, 44% of medium density dugong habitat and 31% of low density habitat. However the actual area where netting is now conducted is now much less than these figures indicate: 4% of the high density dugong habitat, 9% of medium density dugong habitat and 7% of low density habitat (Grech *et al.* in review). Grech and others have identified areas where additional spatial closures would significantly reduce the remaining risk of netting to dugongs.

Management Options

We consider that the major priority for dugong management in the Great Barrier Reef and Torres Strait is the development of culturally acceptable and scientifically robust mechanisms to manage Indigenous hunting. The 'National Partnership Approach' to the management of Indigenous hunting of turtles and dugongs is being implemented by the Commonwealth Department of the Environment and Heritage in cooperation with the relevant states and Northern Territory governments (Anon 2005). The implementation of this policy is being achieved, in part, by grants to the North Australian Indigenous Land and Sea Management Alliance (NAILSMA) and the Torres Strait Regional Authority (TSRA).

A Regional Activity Plan for Torres Strait (RAPTS) was developed by the TSRA in collaboration with the CRC Torres Strait, to guide the implementation of activities under the NAILSMA/TSRA project. The RAPTS includes four key components: community management plans, monitoring programs, catch sharing, and education and awareness-raising. The TSRA has secured funding to implement the RAPTS on a pilot basis for a two-year period from 30 January 2006. The TSRA Board has nominated eight candidate communities to take part in the pilot phase: Boigu, Badu, Iama, Mer, Erub, Mabuag, Dauan and Horn Islands.

Within the GBR region, the intention is to regulate the dugong and turtle harvest through the development of Traditional Resource Use Management Agreements (Havemann *et al.* 2005). The priorities of Indigenous peoples and government agencies are likely to be different, as Nursey-Bray (2006) has convincingly documented in her evaluation of the development and implementation of the Hope Vale Aboriginal community Green Turtle and Dugong Hunting Management Plan. Nursey-Bray showed that Indigenous people prioritised social justice community and culture whereas management agencies prioritised biodiversity conservation and species viability. Consequently, a process needs to be developed to promote the development of solutions that satisfy the needs of both groups with an associated increase in mutual understanding and trust.

Need for Co-ordinated Management at an Ecologically Appropriate Scale

The genetic, satellite tracking and aerial survey data all indicate that effective dugong management requires initiatives to be co-ordinated across jurisdictions. Despite the preliminary genetic findings that dugong populations exhibit some genetic structure along the east coast of Queensland (Blair *et al.* in review), genetically appropriate boundaries for dugong management in Australian waters have not been identified (and may not exist). Nonetheless, the genetic and movement data both indicate that the appropriate ecological scale for management is some hundreds of kilometres (Blair *et al.* 2005; Sheppard *et al.* 2006).

Even though we consider that it is not unreasonable to continue to manage dugongs in the GBRWHA separately from the TS, particularly given the very different jurisdictions operating in the two areas, priority must be given to the policy for managing dugong hunting by the Northern Peninsula Area communities and co-ordinating management across the two regions.

Is the current management of dugongs in the Northern GBR effective in terms of species conservation?

Our capacity to use the results reported here to assess the effectiveness of dugong management in the Northern GBR is compromised by the lack of explicit objectives against which to assess the species conservation outcome. The ecological objectives of dugong management should be defined for each region by developing regional dugong management plans along with the social and cultural objectives of such plans (the effectiveness of which would require separate study). These plans could be developed under the aegis of a Wildlife Conservation Plan as required for listed marine species such as the dugongs under the *Environment Protection and Biodiversity Conservation Act (Commonwealth) 1999*.

Options for Monitoring

1. **To increase the precision of the population estimates.** The precision of the dugong population estimates is already very high for marine mammal surveys (9.6% for northern GBR and 9.7% for TS) and will not be improved without a significant increase in survey effort.

2. **To reduce the noise which obscures trends.** The Pollock *et al.* (2006) method addresses this problem for dugong surveys.
3. **To reduce the area surveyed and increase the effort in the chosen area.** This approach is the rationale behind our use of Index Blocks. The problem with this approach is that it requires the strong assumption that the proportion of the total area in the Index Block is constant across time (Taylor *et al.* 2007). This assumption is not valid for dugongs. Taylor *et al.* (2007) point out an additional danger with this approach: changes in conditions may result in distributional shifts with a declining trend in population abundance.
4. **To identify demographically independent populations and survey at the level of these stocks.** The new data on the regional differentiation of dugong stocks along the east coast of Australia needs further investigation and may provide a basis for improving the design of aerial surveys.
5. **To use management decision rules which do not require large numbers of precise estimates of abundance in order to trigger warranted management actions.** This is the approach that we recommend at least in the short term.

Rationale and Objectives (b)

To determine factors influencing nesting success of female turtles and egg survivorship of green sea turtles at Raine Island, Moulter Cay (GBR) and Murray Island (TS), and recruitment of juvenile turtles into the population.

Part (b) of this project will determine the patterns, rates and causes of sand loss from Raine Island, Moulter Cay (GBR) and Murray Island (Torres Strait); calculate reproductive parameters for nesting green turtles (size range, recruitment rates, nesting success, mortality rates of nesting turtles, egg production); determine factors influencing nesting success and hatchling survivorship and recruitment rates of juvenile turtles into the population; and trial remote methods of recording human visitation at remote sites of high conservation significance. Although the green turtle nesting population has been systematically studied since the mid-1970s, there is no evidence of population trends (Limpus *et al.* 2003). However, in 1996 QPWS data revealed other biological trends that may be indicative of a population in early stages of decline (see Limpus *et al.* 2003). These indicators include declines in the average size of turtles (carapace length) breeding each year, high recruitment rates and shifts in remigration intervals. Since 1996, another major threat to the northern GBR and TS population has emerged – poor hatchling production (Limpus *et al.* 2003). QPWS service data indicate that nesting success is low (the percentage of females able to successfully lay eggs each night) and hatchling production is low. Reasons for this are thought to include accelerated erosion of the beach, alterations to the beach rock formation or other geo-morphologic processes. One suggestion is that when the Guano miners were operating on the island in the late 1800s they altered the reef flat to allow easy access and anchorage for their vessels, and now the altered platform is acting as a conduit for sand as it is washed off the beach.

Therefore Project 1.4.1 (objective b) aims:

- To determine the patterns, rates and causes of sand loss from Raine Island, Moulter Cay (GBR) and Murray Island (TS);
- To calculate reproductive parameters for nesting green turtles at Raine Island, Moulter Cay and Murray Island (size range, recruitment rates, nesting success, mortality rates [of nesting turtles], egg production);
- To determine factors influencing nesting success and hatchling survivorship of sea turtles; and

- To determine recruitment rates of juvenile turtles into the population.

Progress – Outputs (b)

Field and analytical studies are continuing. On Mer (Murray Island), two hundred turtles were tagged and 150 nest locations determined using GPS. Beach profiles were mapped on two of the three main nesting beaches (the third beach is not accessible due to cultural reasons). One air temperature logger, five nest temperature logger and ten beach temperature loggers were placed on the island to record seasonal variation in temperature.

On Raine Island, the QPWS long term turtle project is continuing, with RTK GPS employed to survey the island and baseline hydrology data on the water table and sand samples collected for a sand type assessment. On Milman Island, research has included studies of biology and nesting success of green turtles, beach profiles and sand analysis, air and sand temperature, the latter through deployment of transmitters to measure the incubation regime for nests.

The following is excerpted from Hamann and Fuentes (2007 June MTSRF Report):

Nesting Turtles

Number of turtles nesting per night

In December 2006 we monitored the three nesting beaches on Dowar Island (one of the three islands in the Mer group). This period coincided with QPWS surveys to Raine Island, Moulter Cay and Sandbanks 7 and 8. We only recorded nesting by green turtles. The number of turtles recorded per night is provided in Table 1. The average number of turtles per night for South beach were 122 ± 41 in December and 54 ± 9 in February. The average number of turtles per night for west beach were 53 ± 19 in December and 38 ± 14 in February.

One night of partial survey (3 December 2006) indicates that in the order of 150 turtles per night were using the north beach. We estimate that 300 to 500 turtles came ashore each night on Dowar Island during early December 2006.

Nesting success of females

We assessed ~75% of turtles ashore for nesting on the southern and western beaches at Dowar Island on for nesting success (i.e. whether they were successful at laying eggs). Overall the average percent nesting success for females nesting on the southern beach (n = five nights) of Dowar Island was 32% in December and 55% in February, and the nesting success of females on the west beach was 13% in December (n = four nights) and 7% in February (one night).

Size of nesting females

At Dowar Island 202 turtles and 41 turtles were tagged and measured in December 2006 and February 2007 respectively. The mean size of females was 104.2 ± 5.0 cm in December and 102.2 ± 4.7 cm in February. The mean size of nesting females from both surveys combined is 103.9 ± 5.0 cm. These sizes are statistically different (smaller) than turtles recorded nesting at Bramble Cay in 1979 (t-test; $T = -4.47$; $P < 0.001$) (Limpus *et al.* 2001). Furthermore, the mean at Dowar in 2006/2007 is lower than any of the seasonal means recorded at Raine Island between 1976 and 2001 (Limpus *et al.* 2003). Even if the 2006 February data from Dowar Island is excluded, the mean recorded at Dowar Island in December is lower than all but one seasonal mean (1996 – 104.1 cm) from 1976 to 2001. The data from Dowar is consistent with smaller turtles breeding in high density nesting seasons (Limpus *et al.* 2003).

Migration recaptures

We recorded a turtle nesting (K58192) on 2 December 2006 at Dowar that was initially tagged in a foraging area study in the northern GBR (QPWS unpublished data). We did not recapture any other turtles that were tagged as part of another turtle tagging project.

Location of nests on beach

We mapped the location of two hundred successful nests on the southern beach of Dowar Island in December 2006 to investigate relations between nest location, beach profiles and thermal conditions (e.g. Figure 2). These relationships will be determined as other data sets are analysed.

Hatchling production

Nest excavation: 25 nests were excavated at Dowar Island. The mean emergence success for these nests was $64.6 \pm 32.8\%$ (range 0 to 98.8). However, preliminary data indicate that inter- and intra- beach variation is likely (Figure 1). $n = 2$ (East open light), $n = 9$ (south open light), $n = 8$ (south shade dark) and $n = 6$ (west open dark).

Clutch disturbance: We recorded an average of 4.6 nests per night that were dug into and partially destroyed by nesting turtles. This represented a mean clutch disturbance (clutches disturbed/clutches laid) of 13.6% and a mean egg mortality per disturbed clutch of 14.6 ± 9.0 eggs. The clutch equivalent egg mortality (based on a mean clutch size of 104 eggs per clutch – Limpus *et al.* 2003) was 0.2%. This is similar to the proportion estimated at Raine Island in high-density nesting seasons (Limpus *et al.* 2003).

Egg and hatchling predation: At Dowar Island we did not witness any predation of incubating eggs or hatchlings from goannas (*Varanus indicus*) despite this species being common on the beach and they are regular predators of incubating turtle eggs at other locations. We did however observe *V. indicus* scavenging on eggs dug up by turtles.

We did not witness any avian predation on turtle hatchlings.

Several small sharks (black and white tip reef sharks) and predatory fish such as trevally were recorded preying on turtle hatchlings over the reef crest. This predation was not quantified.

Climate Change (Temperature)

Data loggers were deployed between December 2006 and March 2007. The trips to download data will occur between November 2007 and February 2008.

Beach profile mapping

Beach profile data was collected from Bramble Cay (50% complete), Dowar Island (three beaches) and Milman Island. These data are yet to be analysed.

Sand profiles

At this stage in the project we have completed the analysis of the compositional structure, texture and facies of sand samples collected at Raine Island, Moulter Cay and the two sandbanks. Analysis of samples collected at Dowar Island, Milman Island and Bramble Cay will be undertaken within the next milestone period.

Main Findings of sand sample analysis

The textural and compositional facies identified at each rookery demonstrated some important differences and similarities on the hydrodynamic environment and sites of sedimentation across the rookeries. Moulter Cay and Sandbank 7 demonstrated to be the rookeries with most energy, and therefore more susceptible to climatic events. Contrary, Raine Island and Sandbank 8 presented characteristics of low energy islands.

Raine Island

Deposit from extreme storm events to the northern beach. The predominance and high abundance of corals on the northern reef area may reflect deposition during storm events and high energy waves. Since Dawson 2006, suggests that high currents would be necessary to transport corals greater than 4mm from their source to the beach.

There is evidence to support the transport of material from the reef flat and north beach to the western beach. The high concentration of benthic foraminifera on the western beaches may represent an area of sediment supply (accretion) from i) the reef flats; and ii) longshore drift. The latter is the more probable with source material coming from the presently eroding north shore and being transported around to the northwest. A lower energy system is found on the western side. A shift in wind patterns due to climate change may have a severe effect on the erosion of the northern part of the island.

Moulter Cay

Moulter Cay has residual deposits of the most durable skeletal components. Molluscs have a high level of skeletal durability in comparison to other components (Milliman 1974; Scoffin 1992). The predominance of molluscs at Moulter Cay may reflect a residual deposit as the consistent reworking of waves breaks down most other components.

Sandbank 7

Sandbank 7 has residual deposits of the most durable skeletal components. Similarly to Moulter cay, Sandbank 7 also has a prevalence of molluscs. Intense wave energy at the southeastern beach is indicated by the high concentration of very coarse and very well sorted sediments at the south and east beaches.

Sandbank 8

Low energy at eastern beach. High abundance of Halimeda on the eastern beach indicates a low energy environment, since Halimeda is easily destroyed by mechanical abrasion and does not last through high winds and waves. There is evidence of a high energy and residual deposit on the northern and western beaches. High abundance of molluscs and corals on these regions may be explained by a residual deposit due to a high energy system.

Discussion

Biological data: There are seven main rookeries used by turtles of the northern GBR and Torres Strait green turtle population. Regular and semi-regular data exist for four of these rookeries (Raine Island, Moulter Cay and Sandbanks 7 and 8) and a comprehensive assessment is provided in Limpus *et al.* (2003). In addition, there are data from the late 1970s and occasional brief surveys for Bramble Cay (see Limpus *et al.* 2001 and 2003) and green turtle data has been collected opportunistically during hawksbill turtle surveys at Milman Island. The Islands of the Mer group represent the only major 'non coral cay' nesting habitat for the population. This study represents the first quantitative assessment of the Dowar Island green turtle rookery.

Our data from suggest that in the 2006/2007 breeding season between 300 and 500 females emerged each night during December on Dowar Island, and thus it is likely that between 500 and 800 females emerged each night in December within the Mer group (Mer, Waer and Dowar Islands). Because the average number of females breeding in 2006/2007 at Raine Island was well above average (Col Limpus pers. comm.), we assume that the nightly counts we recorded at Dowar Island also represented an above average figure.

One of the key threats that have been identified for green turtles in the northern GBR and TS population is poor ability of females to dig nesting sites and successfully lay eggs. Indeed at Raine Island the percent nesting success is generally very low in years with above average numbers of females breeding and in recent years has been regularly less than 10% (Limpus *et al.* 2003, Limpus *et al.* 2005; Col Limpus pers. comm.), even in late season nesting and in nights following rainfall (QPWS unpublished data and Hamann pers. obs.). We recorded variable nesting success among the two of the three beaches at Dowar. At the southern beach we recorded low nesting success in December (32%) and this increased to 55% in February once regular nightly rainfall had begun and the number of females ashore each night had declined. Given the low percent of nesting success at Raine Island it is important that nesting success be calculated at other rookeries so that more accurate data on hatchling production can be determined.

Similar to most marine turtle studies we found that hatchling production varies between and within rookeries. Our data from Dowar Island indicate that nests laid out on the open sand areas typically had higher success than those laid under the trees or close to the edge of the beach (rock face). Our values for hatchling emergence from Dowar Island were similar to data collected at Bramble Cay (Limpus *et al.* 2001) and Raine Island (Limpus *et al.* 2003).

The biological data collected from green turtles nesting at Dowar Island is likely to be similar to data collected from other rookeries given that the turtles are from the same population. However, we found that the mean size of turtles nesting at Dowar Island is at the lower end of the mean sizes for turtles recorded nesting between 1976 and 2001 at Raine Island. The mean size of nesting turtles fluctuates with the number of turtles breeding each year, and has been declining steadily at Raine Island (Limpus *et al.* 2003) and the Coral Sea (Harvey *et al.* 2005). A longer-term data set from Dowar Island is required to determine if similar trends exist.

Although nesting success was low in December at Raine Island we did not record any turtles switching to Dowar Island from any other study sites. This fidelity is complementary to results from previous studies on green turtles in the Torres Strait and northern GBR (Limpus *et al.* 2001 and 2003).

Geomorphology: This study presents the first assessment of sand composition for green turtle rookeries in Queensland. To date only the sand composition values for samples collected from Raine Island, Moulter Cay and the two Sandbanks have been analysed. The preliminary data from these four locations reveal both within and between island differences in sand composition. It is interesting that Raine Island has a higher percentage of forams than the other islands, as forams tend to be more buoyant than other sand components. A more detailed assessment will be possible once the sand texture and facie analysis is completed.

Baseline Evaluation of Key Threats

The northern GBR and TS green turtle population is the largest green turtle population in the world. Long term data sets collected by QPWS since 1976 reveal strong fluctuations in the number of females nesting each year, and these fluctuations make trend detection difficult (Limpus *et al.* 2003). However, since 1996 several biological indicators have been suggested

as early in warning signs that the population is in early stages of decline; for example declining size of nesting turtles. In addition, in the last ten years the proportion of females ashore on any night that successfully laid eggs, along with hatchling production, has been very low and approaching zero.

Several factors have been identified as likely or probable causes: gradual net sand loss from the island, changes to the beach rock profiles, flooding of nests, very dry sand that does not allow nest digging, or combinations of the above. Factors underlying these causes could be both natural and anthropogenic (as a result of island or reef crest alteration during the mining operations). Given that it is generally accepted that successful sea turtle populations require in order of 75% hatchling production to maintain recruitment it is clear that the low nesting success and poor hatchling production is not sustainable at current levels.

Whether or not similar patterns (nesting success and hatchling production) occur at the other main rookeries is less well known. While it is emerging that there are erosion problems at Bramble Cay, and data from other cays are non-existent or inconclusive, Raine Island and Moulter Cay support 90% of the annual nesting, so essentially what occurs on these two islands will drive the short-term future of the population. Continued monitoring of other green turtle rookeries will be necessary to develop an understanding of whether turtles are shifting from Raine Island to other rookeries.

A consequence of poor hatchling production will be reduced juvenile recruitment into the foraging areas five to ten years later. Given that the poor hatchling production was first recorded in 1996, surveys in the coming years will be crucial to assess rates of recruitment. Our baseline data (small sample size) from turtles caught within the inner islands of TS indicate that 1-2% of turtles caught are new recruits to the foraging habitat (Hamann *et al.* 2005 and unpublished data). A larger sample size is required to develop a reliable estimate of this parameter.

Project 1.4.2 Sustainable Use of Marine Species of Conservation Concern

Project Leader and Host Organisation: Professor Helene Marsh, JCU

Rationale and Objectives

This related project is evaluating the effects of acoustic alarms on behaviour of wildlife bycatch (coastal dolphins) and the economic factors related to Indigenous hunting (turtle and dugong) and its management.

Progress – Outputs

The capacity of acoustic alarms to minimise the bycatch of protected species in commercial gill nets without alienating the bycatch species from critical habitats is being assessed through experimental evaluation of the behavioural and acoustic response of three species of coastal dolphins and at least one species of sea turtles to acoustic alarms. The second component is applying hybrid economy framework (customary [non-market] state and market sectors) to an investigation of the economics of the Indigenous harvest of turtles and dugongs in the Torres Strait and northern Great Barrier Reef. The project is also investigating the economic costs and benefits (including social and health benefits) of management options available within this framework including the possible role of payment for environmental services.

The following is excerpted from Soto (2007):

Incidental bycatch from fisheries and shark-control programs are serious threats to marine wildlife (Cockcroft and Krohn 1994; Hall 1996; Hoffman 1990; Marsh *et al.* 2003; Perrin 1999; Perrin *et al.* 1994; Silvani *et al.* 1999).

Marine megafauna become entangled in fishing gear and drown (Brothers *et al.* 1999; Chan *et al.* 1989; Julian and Beeson 1998; Read 1994). GBRMPA and other governmental agencies in Queensland, particularly QDPI&F, are taking pro-active initiatives to reduce bycatch levels of wildlife – including marine species of conservation concern such as marine mammals and sea turtles – in the GBR region.

Area closures, especially those associated with the rezoning of the GBR, are the most well known example of these bycatch reduction initiatives. Such closures reduce the bycatch risk by closing off important habitat areas to commercial fisheries and netting (GBRMPA 2003). Gear modification is another mitigation measure used to reduce the incidental mortality of marine megafauna in Queensland. Important examples of this approach include: (1) the replacement of some of the shark nets set for bather protection in Queensland's Shark Control Program (QSCP) with drumlines; (2) the mandatory use of turtle excluder devices (TEDS) in the East Coast Trawl Fishery (QDPI&F 2001); and (3) the netting gear modifications associated with the Dugong Protection Areas B (Marsh 2000). Other bycatch reduction approaches being trialled by the QDPI&F include: (1) attempts to change the behaviour of fishers using acoustic tracking and detection systems to warn fishers of the presence of marine mammals; and (2) attempts to change the behaviour of marine mammals in the proximity of nets using acoustic alarms or pingers (Hodgson *et al.* 2007).

Each of these mitigation measures needs to be evaluated to determine its relevance in the overall endeavour to reduce bycatch levels in the GBR. The following report provides a comparative review of bycatch levels of marine mammals and turtles during the past decade based on the only data available, and discusses the efficacy of the mitigation measures currently used to reduce bycatch.

This report summarises temporal trends over the last ten years in the levels of bycatch of marine mammals and turtles for the eastern coast of Queensland between Cairns and the Gold Coast, with particular emphasis on the GBRWHA. The report has been compiled from published records included in the Queensland Marine Wildlife Stranding and Mortality Database compiled and published by the QPWS, plus more recent unpublished information obtained through collaboration with the Queensland Shark Control Program. The Database includes a complete record of the bycatch in the Queensland Shark Control Program but is a much less complete record of bycatch in commercial fisheries because of the challenges associated with: (1) enforcing the requirement for fishers to report bycatch when there are few observer programs; (2) detecting stranded animals, particularly in remote areas; and (3) the priority placed in some areas on investigating reports of some species of marine mammals, especially dugongs, at the expense of other species. In addition, the cause of death can not be reliably determined in about half of all cases of wildlife stranding reported. Despite these limitations, the Marine Wildlife Stranding and Mortality Database has been used as the basis of the catches reviewed here in the absence of other data, and especially because the data from the Queensland Shark Control Program are such a valuable long-term record.

Dugongs

The Queensland Marine Wildlife Stranding and Mortality Database suggests that the numbers of dugongs (*Dugong dugon*) definitely caught by float lines and ropes have remained low since 2000 (Greenland and Limpus 2005a), averaging three individuals per year and ranging from no dugongs in 2002 and 2003, to a maximum of nine individuals killed in 1999 (Greenland and Limpus 2005a). Unfortunately, these reports do not specify the

locations of this bycatch, thus values for the GBRWHA *per se* are unknown. On average 26 dugongs per year are recorded as dying from unknown causes from an annual average recorded mortality of 45 individuals. Thus the cause of death of 60% of the dugong mortality recorded by the QEPA in the past decade is unknown. These undetermined annual mortality rates have decreased by 34% since 2000. Even so, latest annual reports indicate 32% higher mortalities than a decade ago (Greenland and Limpus 2005a).

The total number of dugongs reported and recorded by the Queensland Marine Wildlife Stranding and Mortality Database is much less than the estimated level of natural mortality for the Queensland Coast from Cooktown South, based on the aerial survey results of Marsh *et al.* (2006). These suggest a minimum population estimate (N_{\min} *sensu* Wade 1998) of ~4500. Assuming a natural mortality rate of 4%, the total annual natural mortality for the region would be 180 animals, excluding anthropogenic mortalities, confirming the incompleteness of the Queensland Marine Wildlife Stranding and Mortality Database as a record of dugong mortality.

In contrast, the Queensland Marine Wildlife Stranding and Mortality Database is a comprehensive record of the bycatch of dugongs in the Queensland Shark Control Program. Changes in the catch per unit effort of dugong bycatch in the government shark control program on the east coast of Queensland indicate that the numbers of dugongs caught in shark nets at six locations between Cairns and Brisbane declined at an average of 8.7% per year between 1962 and 1999, an overall decline to three percent of initial catch rates over the sampling period (Marsh *et al.* 2005). If the changes in the populations sampled by the shark nets are representative of the overall population, this result indicates that dugong numbers declined precipitously along the urban coast of Queensland in the last half of the twentieth century (Marsh *et al.* 2005), demonstrating the long-term value of the dataset. The reasons for this decline are complex and include habitat degradation, accidental death in commercial and illegal gill and mesh nets and in shark nets set for bather protection, vessel strike and Indigenous hunting (Marsh 2000).

Whales and Dolphins

The Action Plans for Australian Cetaceans and Seals (Bannister *et al.* 1996; Shaughnessy 1999) recognise incidental take, entanglement and interaction with fisheries as threatening to marine mammals. The Actions Plan for Australian Cetaceans identifies a series of marine mammal species as vulnerable or endangered, including humpback whales (*Megaptera novaeangliae*), southern right whales (*Eubalena australis*) and blue whales (*B. m. musculus*), and these species are officially listed as threatened under the regulations associated with the *Environment Protection and Biodiversity Conservation Act (Commonwealth) 1999* (EPBC Act) and the *Nature Conservation Act Queensland 1992*. Most other species of cetaceans are listed as data deficient under Commonwealth legislation (or rare under Queensland legislation), and thus it is difficult to develop effective conservation plans for them for both political and scientific reasons (Banister *et al.* 1996). Even though all cetaceans are protected under the EPBC Act via the Australian Whale Sanctuary, cetacean bycatch occurs in trawls (Fisheries WA 2001), traps (Costello and Coughran 2000), purse seines (Staunton-Smith and Ward 2000) and gill nets including shark nets set for bather protection by the Queensland Shark Protection Program (Gribble *et al.* 1998). Most information on the bycatch of cetaceans in the Australian Fishing Zone (AFZ) in the past twenty years has been based on the northern drift net fishery. Estimates from observer programs reported 14,000 animals killed in this fishery during the early 1980s, before it was permanently closed (Harwood and Hembree 1987; Harwood *et al.* 1984). Even though these numbers do not reflect catches in the GBR region, they may be from the same stocks (Corkeron *et al.* 1997; Parra *et al.* 2002) as coastal dolphins such as Indo-Pacific humpback dolphins (*Sousa chinensis*) and Australian snubfin dolphins (*Orcaella heinsohni*) were among the species caught by driftnets (Shaughnessy *et al.* 2003).

The records of the Queensland Marine Wildlife Stranding and Mortality Database suggest that the bycatch levels of marine mammals on the urban coast of Queensland have been low in recent years, with an average of fifteen individuals per year caught since 2000. Common dolphins (*Delphinus delphis*) are the species most often reported caught in Queensland, and represent all cases reported from the Queensland Shark Control Program. All records are from outside the GBRWHA. Common dolphins represent almost half of the total annual bycatch recorded by the Queensland Marine Wildlife Stranding and Mortality database over the past six years (38 individuals), equalling the bycatch numbers of bottlenose dolphins (*Tursiops* sp.) and dugongs combined for the same period – 38 and 18 individuals respectively. Common dolphins are considered at low conservation risk at a global, national and state level, as a result of their large population sizes. However, bycatch levels for this dolphin are high within a localised area around the Gold Coast, which may be cause for concern. It is not known whether the common dolphins caught in the Gold Coast shark nets also spend part of their life in the GBRWHA.

The largest proportion of mortalities reported from the Queensland Marine Wildlife Stranding and Mortality Database since 1998 are from the Queensland Shark Control Program (Greenland and Limpus 2005b). These records represent 75% of reports of dolphin bycatch mortality in Queensland since 2000 (see Table 1). Records of bycatch from commercial netting average only three individuals per year during this period, with half this number in 2004 and 2005 (Greenland and Limpus 2005b; Greenland *et al.* 2004). These values must be viewed with caution given the limitations outlined above

Indo-pacific humpback dolphins and Australian snubfin dolphins are priority species for conservation at a national level (Action Plan for Australian Cetaceans, Ross 2006) and within the GBRWHA (Great Barrier Reef Marine Park Authority 2000). Even the low levels of bycatch levels shown in Table 1, are cause for concern especially as local populations are small (Parra *et al.* 2006). For example, population studies show that in Cleveland Bay near Townsville, the populations of these dolphins are so small (Parra *et al.* 2006) that the sustainable anthropogenic mortality is <1 per year (calculated using the Potential Biological Removal method of Wade 1998). A similar study of the population biology of the coastal cetaceans should be a priority in waters surrounding Cairns, where most of the bycatch of both humpback and snubfin dolphins reported by the Queensland Shark Control Program occurs (Wayne Sumpton, pers. comm.) Spinner dolphins (*Stellena longirostris*) should also be a priority as identified by the Action Plan for Australian Cetaceans (Ross 2006).

Sea Turtles

Studies on turtle capture in the Northern Prawn Fishery before the introduction of mandatory Turtle Excluder Devices (TEDS) estimated between 2000 and 5000 turtles caught each year (Poiner *et al.* 1990). This catch would have included turtles that journeyed to the GBRWHA to nest. Catch rates and mortality varied between species and water depths. For instance, flatback turtles (*Natator depressa*) had the highest catch rate but the lowest mortality, while hawksbill turtles (*Eretmochelys imbricata*) had the lowest catch rates but highest mortality (Poiner and Harris 1996). The species composition of turtles caught in trawls nets gradually changes from north to south along the Queensland coast, reflecting the distribution and density of flatback, green and loggerhead turtles (*Caretta caretta*) along the GBR (Robins 1995). Green turtles (*Chelonia mydas*) are common in both tropical and warm-temperate areas (Georges *et al.* 1993), thus are more vulnerable to trawl capture along the whole Queensland coast (Robins 1995). The impact of the bycatch in the prawn fishery on loggerheads was of particular concern because records of nesting turtle numbers suggest that the population of loggerhead turtles was declining (Limpus and Reimer 1994).

The Queensland Marine Wildlife Stranding and Mortality database is incomplete with respect to marine turtles. Mortality is only reported from 1999 to 2002, and there are no bycatch

values reported from trawls or commercial netting. The percentage of mortality due to unknown sources reported in these documents is as high as 68% (Greenland *et al.* 2002).

The Queensland Shark Control Program is the source of most of the bycatch data in these reports, although the distribution of records from the GBRWHA is unclear. Green turtles account for about 60% of all sea turtle bycatch in the past six years (167 individuals). This species is categorised as vulnerable at a state and national scales and endangered at a global scale. The annual average for all species killed in nets (24 turtles) does not include mortality due to boat strikes (50% of all reported mortality from known causes every year) (Greenland *et al.* 2002).

Updated records provided by the Queensland Shark Control Program on incidental capture of marine turtles in the GBR region for the last decade (1997-2006) show an average capture of 11.5 sea turtles per year for the whole region (Cairns to the Gold Coast). Cumulative capture during this period was higher in Townsville and Mackay with a total of 32 turtles each, followed by Cairns with 26 individuals and Gladstone with 21 turtles. Bycatch occurred in both nets and drumlines, with no significant difference between these two gear types. From a total of 115 turtles caught in this period, 61% were green turtles; with about half of them were reported alive when released, especially in Mackay and Townsville (Wayne Sumpton, pers. comm.).

Mitigation Measures

A series of mitigation measures has been developed to reduce the bycatch of marine wildlife including: multilateral initiatives and international agreements, observer programs, bycatch impact assessments, protected areas and time-area enclosures, and fisheries practices and gear modifications (Hall *et al.* 2000; Lewison *et al.* 2004). Gear modifications are integral to reducing bycatch, as demonstrated by the successful introduction of TEDs in the shrimp trawl fishery off the coasts of the United States (Magnuson *et al.* 1990) and later in Australia. For marine mammals, gear modifications exist for purse seines (National Research Council 1992), trawls (Fertl and Leatherwood 1997) and gillnets (Perrin *et al.* 1994).

Area Closures

As explained before, the dugong population is believed to have declined significantly along the urban coast of Queensland since the mid 1960s (Marsh *et al.* 2005). The Australian and Queensland governments implemented several measures to stop this decline in 1997, the most controversial initiative being the establishment of two systems of Dugong Protection Areas (DPAs). Set or drift nets were prohibited in seven Zone A DPAs in the GBR region (2,407 km²), including river set nets in two of these areas, while less restrictive modifications were set in eight Zone B DPAs (2,243 km²). (*Fisheries Regulation (No. 11) 1997 (Queensland)*) (Marsh 2000). The fishers opposed this initiative, as 38 commercial fishing licenses were cancelled through a competitive license buy-out scheme to avoid effort displacement (Tidsell and Harrison 1999). However, if the changes to the netting regulations were effectively enforced, the introduction of Zone A DPAs alone should have decreased dugong mortality from commercial nets in the GBR region south of Innisfail by between 42% and 55%, assuming that habitat quality is maintained (Marsh 2000).

A series of factors may affect the effectiveness of Queensland's Zone A DPAs, such as increased boat traffic, habitat degradation, and the Zone A DPAs being too far apart to provide adequate gene flow (Marsh 2000). Even if the DPAs were effective, the recovery of dugong population in response to these management initiatives will be slow, because the estimated maximum rate of increase of a dugong population is about 5% per year (Marsh 1995). Therefore, population censuses will not show immediate positive results, as is thought to be the case with the Hector's dolphin dilemma in protected areas in New Zealand (Cameron *et al.* 1999; Slooten *et al.* 2000). Studies show that after a change in survival

rates, the size of marine mammal populations tend to fluctuate for several years until the age composition stabilizes (Slooten and Lad 1991). In the case of the DPAs, the large scale movements of dugongs between habitats reduces scientific capacity to measure a response to the DPAs (Marsh *et al.* 2006).

The rezoning of the GBRMP from 2004 greatly expanded the areas where gillnets are limited or prohibited (Great Barrier Reef Marine Park Authority 2003). The rezoning increased the proportion of the Park zoned 'no-take' from 4.5% to 33% and included a commitment to ensure that about 50% of high priority dugong habitats were closed to commercial fishing activities, including gill and mesh nets used in Queensland East Coast Inshore Fin Fish Fishery (Fernandes *et al.* 2005). While population studies may not have the capacity to record the response of the dugong population to this increase in protected areas, a spatial risk assessment approach circumvents some of the difficulties innate to evaluations of the effectiveness of area closure effectiveness, such as large area sizes, area remoteness and partial observer programs (Grech *et al.* in review). The zoning and management arrangements in operation since January 2005 ban commercial netting from approximately 67% of the dugong habitat of high conservation value identified by Grech and Marsh (2007), a relative increase of 56% from the previous arrangements. Currently, no netting is allowed in the high conservation value dugong habitat along the urban coast and in 36% of the corresponding habitat off remote Cape York. Netting is allowed in half of the dugong habitats of medium conservation value, (5% on the urban coast and 49% off remote Cape York), a 20% relative decrease over the previous arrangements. Commercial netting is still allowed in 66% of dugong habitat of low conservation value (Grech *et al.* in review).

Only about 7% of the high conservation value and 11% of the medium conservation value dugong habitats where commercial netting is banned in the GBRWHA are now within DPAs. DPAs now play a relatively minor role in the overall protection of dugongs in the GBRWHA despite their iconic status. This result is a consequence of most of the habitats of high conservation value to dugongs being off the remote Cape York coast and all the designated DPAs being along the urban coast (Grech *et al.* in review).

Gear Modification

Fishers in the Australian trawl industry had used systems to reduce the bycatch of jellyfish for many years, but still resisted the introduction of TEDs, citing handling and safety concerns as well as potential loss of prawns (Mounsey *et al.* 1995). In the early 1990s, Australia introduced TEDs in the prawn fisheries of at least three states, with variable response from fishermen. Eventually Australia legislated, over a period of three years, for TEDs to be used for turtle exclusion or bycatch reduction. TED use in the Queensland east coast fishery began in selected areas in 1999. By 2000 it was mandatory in the northern prawn fishery (Epperly 2003).

Apart from TEDs and the limitations on gear in the DPAs, there has been limited use of gear modification to reduce bycatch of marine species in the fisheries of the GBR region. However, the Queensland Shark Control Program implemented strategies to reduce the impact of the program on non-target species, including the mixed use of nets and drumlines, overall reduction of nets and establishment of rescue squads (Department of Primary Industries 2001). Recent studies from the Shark Control Program show that as many sea turtles, especially green turtles, are caught in drumlines as in nets. Dolphins, on the other hand, are almost never caught in drumlines in the GBR. Since 1999, the only reports of dolphins caught in drumlines are from one unidentified dolphin in the Capricorn Coast, and two in Townsville: a spinner dolphin and an Australian snubfin dolphin, all of them released alive except for the spinner dolphin.

Changing Behaviour

The QDPI&F is currently developing two main approaches to reduce the incidental capture of marine mammals in gillnets: avoidance and minimisation.

Avoidance and Acoustic Behaviour

The avoidance approach focuses on a simple passive acoustic tracking system to allow fishers to identify and track dolphins and small whales. The idea is that fishers will be able to pull their gear or avoid setting it if dolphins or whales are close by or travelling towards them. This approach is particularly important for fishing at night, when the dolphins cannot be seen, but assumes that all or most dolphins vocalise strongly during their nocturnal activities. This assumption will be tested in MTSRF Project 1.4.2.

Minimisation and the Use of Acoustic Alarms

This second approach used by QDPI&F aims to minimise the interaction between dolphins and fishers by alerting the animals to the presence of gillnets, using acoustic alarms known as pingers. Pingers are sound-emitting electrical devices attached to fishing gear designed to deter marine wildlife, especially mammals of gillnets, or warn them of the presence of potentially dangerous barriers, to reduce entanglement and death from bycatch (Dawson *et al.* 1998; Reeves *et al.* 1996).

Pingers have been successful in reducing bycatch of harbour porpoises in populations throughout their range (Barlow and Cameron 2003; Kraus *et al.* 1997; Trippel *et al.* 1999). The deterrent mechanisms are not well understood (Kraus *et al.* 1997), but in field trials and in captive studies the sounds produced by pingers appear to be aversive to harbour porpoises (Culik *et al.* 2001; Kastelein *et al.* 2000; Laake *et al.* 1998), leading to concern that the animals are displaced from critical habitats.

Despite their success in reducing the bycatch of harbour porpoises, pingers may not elicit the same response from other cetacean species (Dawson 1994). For instance, the use of active and passive acoustic deterrents showed little to no effect on net entanglement of Dall's porpoises (Hatakeyama *et al.* 1994). On the other hand, pingers displaced bottlenose dolphins from gillnets in a subtle manner (Cox *et al.* 2003). *Tursiops* tend to explore new acoustic stimuli (Cox *et al.* 2003), so it is possible that this species might learn to associate pingers with a food source, in a response similar to Pavlov's "dinner bell" effect (Richardson *et al.* 1995), like pinnipeds off the northwest coast of the United States (Mate and Harvey 1987). This variation in behavioural responses among species indicates that fisheries cannot regard pingers as a universal solution to a multi-species incidental bycatch problem. It is clear that potential solutions such as pingers, should only be considered effective if they both: (1) reduce entanglements at least one species, and (2) have no adverse effects on population of any other species of concern (Hodgson *et al.* 2007)

A behavioural study showed that dugongs in southeast Queensland were not alienated from their feeding grounds by 10 or 4 kHz pingers (Hodgson *et al.* 2007). Indeed, these pingers did not elicit any detectable response from dugongs, a result which indicates that this method is unlikely to be effective in reducing incidental capture of dugongs (Hodgson *et al.* 2007). Dugongs appear not to have learned to avoid shark nets set for bather protection in Queensland since the 1960s, a result attributed to: (1) their limited capacity to learn from other dugongs because studies to date suggest that mother-calf pairs are the only stable social groups (Hodgson 2004); and (2) the low rate of successful release of dugongs from nets.

This conclusion is supported by the observation that the catch is not biased towards young animals, as would be expected if dugongs learned from experience (Marsh *et al.* 2005).

Given the apparently limited capacity for dugongs to learn to avoid nets in fixed locations such as those set by the Shark Control Program, dugongs are expected to be even less likely to avoid nets set by commercial fisheries which are constantly being moved (Hodgson *et al.* 2007).

There is no knowledge of how Australian snubfin dolphins respond to pingers, while Indo-Pacific humpback dolphins showed a limited response in South Africa (Peddemors *et al.* 1999) and have been caught in nets with pingers in Queensland (McPherson *et al.* 2004). The response of both these species to pingers is being investigated in MTSRF Project 1.4.2.

Conclusion

It is clear that trends in bycatch in commercial fisheries in the GBRWHA cannot be extrapolated from data currently recorded in Queensland Marine Wildlife Stranding and Mortality Database. However, this Database provides an invaluable long-term record of the catches and mortality of marine wildlife in the Queensland Shark Control Program. From the perspective of monitoring fisheries bycatch, the chief problems with the Database arise from: (1) the difficulties in enforcing compliance with the requirement that fishers and other non-government stakeholders report catches and mortalities; (2) the remoteness of much of the region; and (3) the difficulty in determining the cause of death of many of the stranded animals because of carcass decomposition. The problems caused by the remoteness of much of the region are probably impossible to address, except perhaps within a risk management framework as outlined below. Major improvement in the proportion of reported mortalities whose cause of death is identified is unlikely. The Marine Mammal Rescue and Mortality Response operated by the Fish and Wildlife Research Institute of the Florida Fish and Wildlife Conservation Commission is arguably the most well-resourced marine wildlife stranding program in the world. This program operates in a region which is much smaller, more densely populated and generally climatically cooler than much of Queensland. The causes of death of 30% of reported mortalities 1986-2003 could not be determined (Chip Deutsch *pers comm.* 2005). This statistic suggests that it is highly unlikely that a program in Queensland could establish the cause of mortality in >70% of stranded marine wildlife.

Given the conditions in the GBRWHA, spatial risk assessment approaches using geographic information systems should be encouraged. This approach could be applied in several ways to identify: (1) potential sites for further area closures, especially locations in which commercial fishing activities that cause bycatch are still allowed in habitat of high or medium conservation value to species of conservation concern, as suggested by Grech *et al.* (in review); (2) areas where compliance activities should be focused, such as areas of high risk for turtles being caught in trawls when fishers fail to use TEDS (Robins 2002); (3) areas where efforts to determine the causes of death of marine wildlife should be focused, such as areas close to major sites where stranded wildlife is likely to be found and reported by the general public, and where the capacity exists to conduct necropsies. The long-term recording of wildlife mortality by the Queensland Shark Protection Program provides an invaluable data set and should be continued.

The marine bycatch problem is diverse, affecting all types of fisheries and all type of marine wildlife, including seabirds, sea turtles and marine mammals (Julian and Beeson 1998; Paterson 1990; Perrin *et al.* 1994). Although the impact of the bycatch problem is sometimes underestimated because of the low probability of an individual fisher incidentally catching a non-target species in any fishery on a given day, the widespread increase in effort in most fisheries around the world and the depleted state of many stocks of marine wildlife affected by bycatch renders it a crucial problem that needs urgent attention.

The variability of the problem requires the involvement of all stakeholders to evaluate the applicability of the toolbox of available solutions to the problem in individual fisheries.

Scientists and managers need to co-operate with fishers, to develop practical mitigation measures and regulations that allow the process of positive change to continue (Hall *et al.* 2000). The solutions are as diverse as the problem itself. From protected areas to gear modifications, all approaches need to be tested and applied cooperatively, to obtain the highest degree of success.

The options aimed at changing the fishers' behaviour are likely to be more effective, as it should be easier to change human behaviour than to change the behaviour of wild animals. The rezoning of the GBR is an excellent example of this approach. Changing the behaviour of bycatch species is much more complex, as exemplified by the issues involved in the implementation of acoustic alarms or pingers (IWC 2000). The variation in behavioural responses among individuals of different species of marine wildlife means that fishers and fisheries managers cannot regard acoustic alarms (pingers) as a universal solution to a multi-species incidental bycatch problem. To test the effectiveness of pingers to reduce marine mammal bycatch, research studies need to consider the behavioural responses of all local populations of cetaceans within the target fisheries' range. The implementation of pingers to reduce bycatch should also consider potential side effects such as the habituation of the bycatch species so that individuals no longer respond to the pingers, and the displacement of by catch species from their key habitats. These side effects may negate the effectiveness of this mitigation measure. If stakeholders choose to continue exploring methods to modify cetacean behaviour to reduce bycatch, all issues pertaining to the implementation of acoustic alarms must be carefully addressed before their use becomes mandatory at local or global scales (Dawson *et al.* 1998; Hodgson *et al.* 2007; IWC 2000; Kraus 1999).

Theme 2: Risks and Threats

Program 5i: Climate Change

This program is focused from regional to local scale and from the processes to the organism-responses, the latter including physiological and genetic potential for rapid adaptation.

Project 2.5i.1 Regional climate scenarios

Project Leader and Host Organisation: Dr Andreas Schiller, CSIRO

Rationale and Objectives

'Regional climate scenarios' will downscale physical climate change scenarios from global to reef-scale, producing scenarios (ocean and atmosphere), eddy-resolving regional ocean simulations and sub-km/reef-scale ocean simulations of climate change. This will form a cornerstone for informing ecosystem assessment and support management decisions in response to coral bleaching. There is one key objective: To downscale climate change signals to reef-scale (sub-km scale) through the nesting of local models and forcing from an eddy-resolving/ten-kilometre scale hydrodynamic model.

Physical oceanographic data were collected from over sixty instruments deployed in the Capricorn Bunker Group between August 2004 and April 2006 as part of an AIMS project "Physical controls on bleaching". Although these data were not collected as part of the current MTSRF Project 2.5i.2, they will assist this research.

Progress – Outputs

Remote sensed data from MODIS Aqua thermal infrared and ocean colour at one-kilometre resolution have been acquired by the University of Queensland from NASA for period July 2002 to present. MODIS Terra thermal infrared have similarly been acquired for 2005 to present, hence providing thermal coverage four times daily. These data continue to be acquired in the forward stream. Terra ocean colour (2000-present) and Terra thermal infrared (2000-2004) are at one-kilometre resolution.

The following text and figures are excerpted from Schiller (MTRSF Milestone Report June 2007):

Background

A pilot nested modelling suite has been developed to downscale global scale model simulations to the reef scale, for the purpose of investigating climate change on coral bleaching. The focus for coral bleaching analysis was chosen to be the vicinity of Heron Island, hence a nesting strategy was required that enabled major oceanographic processes in the GBR to be propagated into a high resolution model domain surrounding this site.

The general circulation of the GBR region is described by Burrage *et al.* (1996). The South Equatorial Current flows into the Coral Sea where it splits into two as it approaches the northeast Australian shelf. A southern arm flows south, trapped against the slope, to form the East Australian Current (EAC).

The northern arm flows on the shelf edge in the northern GBR to form a semi-closed cyclonic eddy in the Coral Sea. In the northern GBR upwelling due to fluctuations in geostrophic currents or northeast monsoon winds transports cool water along the bottom of the central GBR shelf to the seaward edge of the GBR lagoon. This cool water does not create a surface signature. However, the cool water may reach the surface via upwelling due to internal or barotropic shelf edge tides, island wakes, topographically induced eddies or bottom Ekman pumping. A review of physical processes that may impact on the GBR is also provided by Steinberg (2007).

The circulation and thermal characteristics of the model region have been studied by Griffin *et al.* (1987). The Capricorn Channel is associated with large tides of amplitude approaching 4 m at the coast. The tide is of semidiurnal nature in the north, progressing to equal diurnal and semidiurnal behaviour in the south near Lady Elliot Island. Flood tide directions have a strong alongshore component in the GBR lagoon, becoming stronger and later further north. Non-tidal circulation is complex and highly variable. Generally, circulation off the shelf break is dominated by pulses of north-westward flow greater than 0.3 ms^{-1} , having a period of 6 – 10 days. This large flow is due to the cumulative effect of several baroclinic coastally trapped wave modes (Griffin and Middleton 1986) and gives rise to a mean north to north-westward current, predominantly parallel to the isobaths. The origin of these coastally trapped waves is further south beyond Fraser Island. Local wind stress contributes to circulation on the shelf, and to a lesser extent to mean flow on the shelf break. Griffin *et al.* (1987) postulated the presence of a large cyclonic eddy located at the southern mouth of the Capricorn Channel, generated by the EAC. This results in a north-westward backflow on the shelf break in the vicinity of Lady Musgrave Island. The appearance and disappearance of this eddy in response to EAC fluctuations may give rise to a long period (90 day) variation in the mean current on the shelf break.

Near the coast the temperature does not fluctuate in response to the tide. In shallow water near reef edges, diurnal fluctuations of up to 4°C were observed by Griffin *et al.* (1987) and attributed to solar heating effects. Further offshore a tidal oscillation of up to 2°C was observed on a flood spring tide. Larger temperature oscillations are observed in deeper

waters and are attributed to tidal pumping. The temperature lags the offshore current component by 90° (temperature minima occur at the end of the incoming tide). Griffin *et al.* (1987) show that a tidal current of 0.25 ms^{-1} may induce a vertical displacement of 60 m resulting in $\sim 1.5^\circ\text{C}$ temperature variation. The thermocline also oscillates on longer timescales (6-10 days) on the shelf break and slope. These fluctuations were shown by Griffin and Middleton (1986) to be related to the alongshore current, due to coastally trapped waves resembling an internal Kelvin wave.

The Model

The model used in this study, SHOC (Sparse Hydrodynamic Ocean Code; Herzfeld *et al.* 2006b, Herzfeld and Waring 2006), is a general purpose model applicable to scales ranging from estuaries to regional ocean domains, and has been successfully applied to a variety of applications encompassing these scales (e.g. Walker 1997, Herzfeld *et al.* 2006a). This model is a three-dimensional finite difference hydrodynamic model based on the primitive equations. Outputs from the model include three-dimensional distributions of velocity, temperature, salinity, density, passive tracers, mixing coefficients and sea level. Inputs required by the model include forcing due to wind, atmospheric pressure gradients, surface heat and water fluxes and open boundary conditions (e.g. tides). SHOC is based on the three dimensional equations of momentum, continuity and conservation of heat and salt, employing the hydrostatic and Boussinesq assumptions. The equations of motion are discretised on a finite difference stencil corresponding to the Arakawa C grid.

The model uses a curvilinear orthogonal grid in the horizontal and a choice of fixed 'z' coordinates or terrain-following coordinates in the vertical. The 'z' vertical system allows for wetting and drying of surface cells, useful for modelling regions such as tidal flats where large areas are periodically dry. The current implementation of the model uses z-coordinates. The bottom topography is represented using partial cells. SHOC has a free surface and uses mode splitting to separate the two dimensional (2D) mode from the three dimensional (3D) mode. This allows fast moving gravity waves to be solved independently from the slower-moving internal waves, allowing the 2D and 3D modes to operate on different time-steps, resulting in a considerable contribution to computational efficiency. The model uses explicit time-stepping throughout except for the vertical diffusion scheme which is implicit. A Laplacian diffusion scheme is employed in the horizontal on geopotential surfaces. Smagorinsky mixing coefficients may be utilised in the horizontal.

The ocean model can invoke several turbulence closure schemes, including k, Mellor-Yamada 2.0 and Csanady type parameterizations. A variety of advection schemes may be used on tracers, and first or second order can be used for momentum. The model also contains a suite of open boundary conditions, including radiation, extrapolation, sponge and direct data-forcing. A generous suite of diagnostics is included in the model. The equations of motion in SHOC are similar to those described in Blumberg and Herring (1987). Details of the model equations can be found in Herzfeld (2006a).

Model Grids

It is desirable that all the dominant physical processes are captured in a local model domain of Heron Island. For this to be accomplished, a three grid nesting strategy was employed (Figure 1).

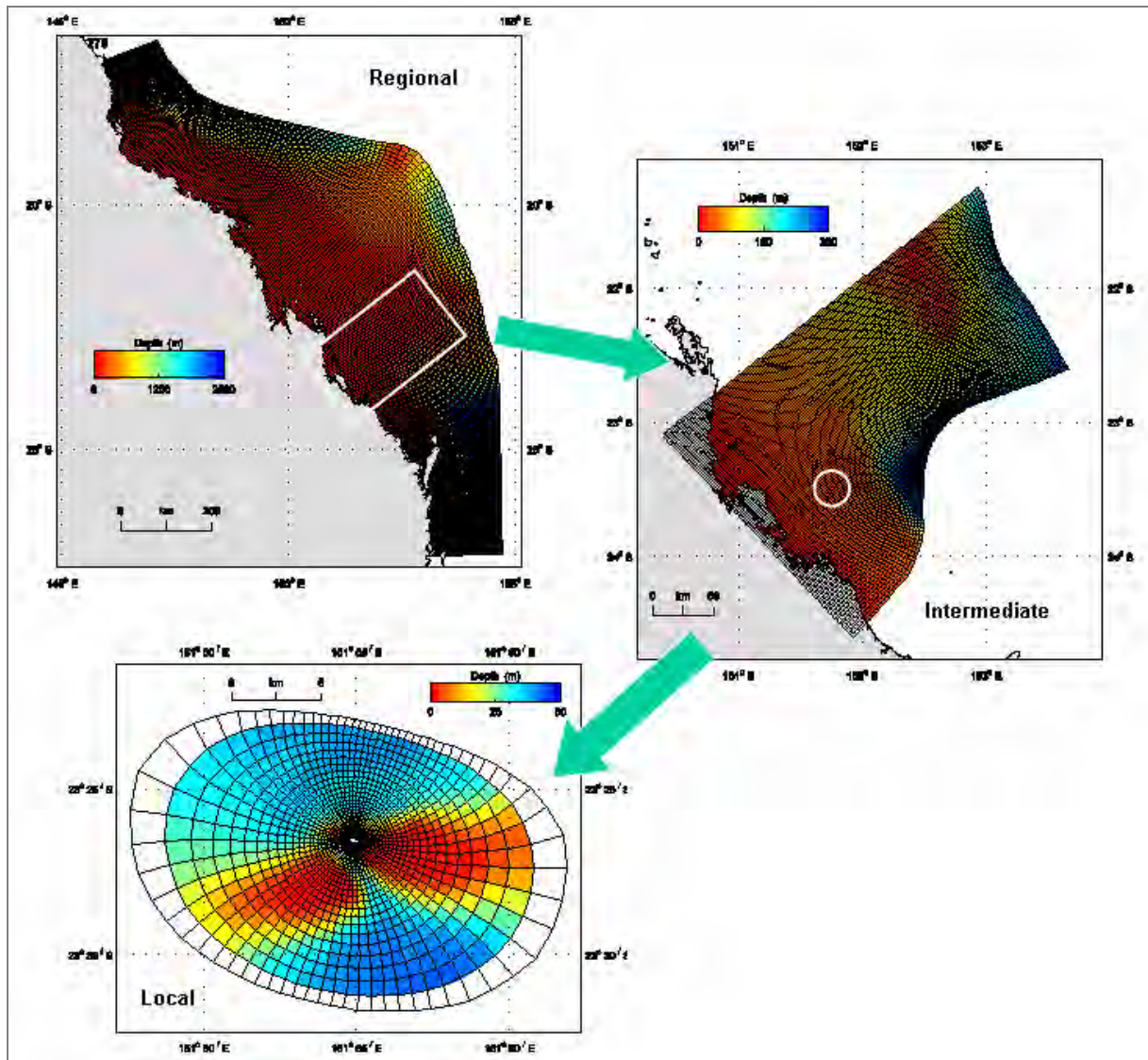


Figure 1: Model nesting strategy.

The large scale (regional) grid is designed to capture EAC intrusions onto the shelf and resolve the northward propagation of coastally trapped waves south off Fraser Island. These internal waves are hypothesised to collide with Fraser Island, and degenerate into higher frequency modes that continue to propagate northwards. The resolution of global model products (e.g. BRAN reanalysis) is too coarse (10 km) to adequately resolve these higher frequency waves; hence the resolution of the regional model (3-6 km in this region) must fulfil this role. This grid has a minimum depth of 2 m imposed at the coast, and maximum depth is 2500 m. An intermediate model of the Capricorn Group acts as a nesting vehicle to allow boundary conditions to be downscaled to a resolution applicable to driving the local Heron Island grid, and incorporates the influence of tides. Resolution of this grid varies from 800 m to 4 km, with a maximum depth in the domain of 320 m. Finally, the local grid is a cyclic polar grid that maintains high resolution (down to 12 m) around Heron Island, increasing to ~2 km at the grid edge to accept boundary forcing from the intermediate grid. The maximum depth of this grid is 44 m.

The maximum depth of the models impacts on the gravity wave speed, hence the time step used for the 2D mode and consequently the run time of the model. The regional model has 3D/2D time-steps of 200/4 s respectively. The grid size is 100 x 270 with 38 layers in the

vertical, with ~33% of the grid containing wet cells. This results in a run-time ratio of ~110:1 using parallel processing over two partitions. The intermediate grid is considerably slower. The size of this grid is 110 x 170 with 34 vertical layers, with ~68% wet cells. The 3D/2D time-steps are 104/4 s, resulting in run-time ratios of ~40:1 when parallel processed over 4 partitions.

Finally the local grid has a size of 70 x 37 with 22 vertical layers (~42% wet cells) and 3D/2D time-steps of 6/1 s. Without parallel processing this grid has a run-time ratio of ~25:1, making it suitable only for shorter term seasonal simulations.

All grids use 'z' vertical discretization with exponentially increasing grid spacing near the surface and constant spacing at depth. Surface layer thickness is 1, 0.3 and 0.2 m for the regional, intermediate and local grids respectively. The bathymetry for all grids is smoothed with a 9 point convolution filter, and a maximum gradient of 0.05 is imposed. All models use the higher order upwind advection scheme of Van Leer (1979).

The regional model is forced with global model products. Alternatively, altimeter / climatology based products may be used (e.g. synTS), but since these products rely on climatology to project surface values to depth, they are not able to represent internal oscillations of the thermocline. The pilot models were simulated for September 2004, during which an AIMS field program was in place to produce a sufficient quantity of measurements for comparison to model output. The regional model was nested in BRAN1.5 for this period. When BRAN2.0 products become available, the simulation period will shift to July 05 to July 06, when data from an expanded AIMS field program are available. The summer period in this timeframe will be the focus of coral bleaching analysis, and hence of model calibration. Currently atmospheric forcing products (wind, pressure) are supplied by the RAMS atmospheric model. Forcing products from MESOLAPS are currently being assembled for forcing the 05/06 period (e.g. Figure 2 showing cyclone Larry impinging the coast). This modelled product is preferable to spatially interpolated meteorological data supplied by BOM weather stations for surface forcing, since its spatial detail is superior.

Stable model simulations were achieved for the three grids for September 2004. Examples of model output are supplied in Figure 3 for the local grid, and a high resolution image of the flow around Heron Island is shown in Figure 4.

Observational Data Summary

AIMS have been collecting oceanographic data in the Capricorn Bunker Group continuously since August 2004. These data will form the basis for the model calibration. The instrument array peaked over the summer of 2005/06 with sixty instruments. These consist of current meter and temperature mooring transects across the shelf and slope near Heron Island (Figure 5) and Lady Musgrave Island, temperature transects around and across Heron Island (Figure 6), and a meteorological buoy measuring incoming and outgoing short and long wave radiation and standard meteorological parameters. A more detailed summary is available as an appendix to this report.

The data are being analysed in collaboration with AIMS@JCU student Severine Choukroun, and compared with MODIS satellite imagery in collaboration with Scarla Weeks from the related Project 2.5i.2 "Early warning and assessment system for thermal stress on the GBR".

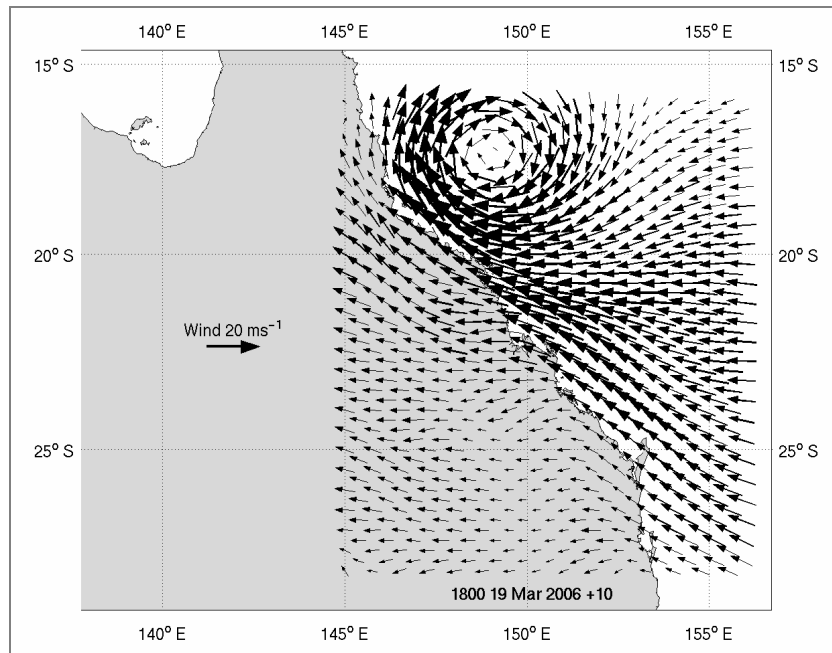


Figure2: MESOLAPS winds for Cyclone *Larry*.

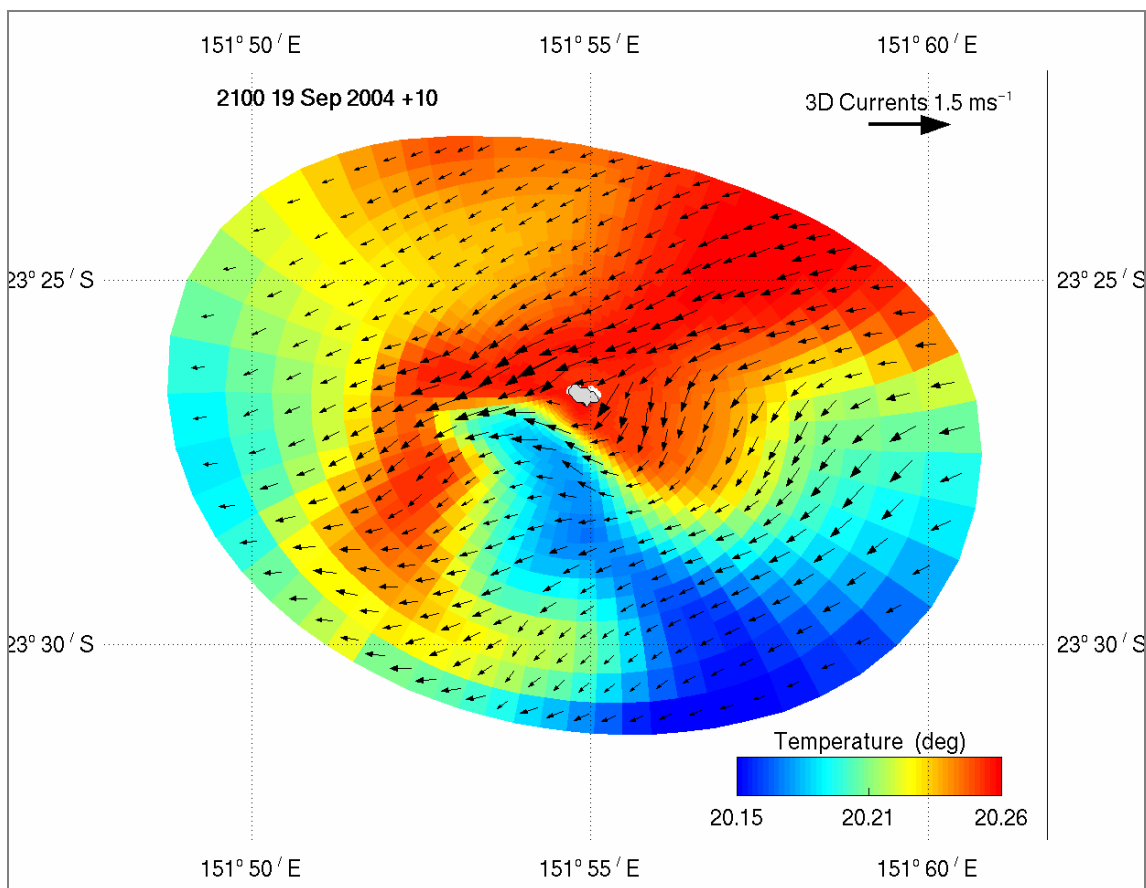


Figure 3: Snapshot of surface temperature with currents overlaid for the local grid.

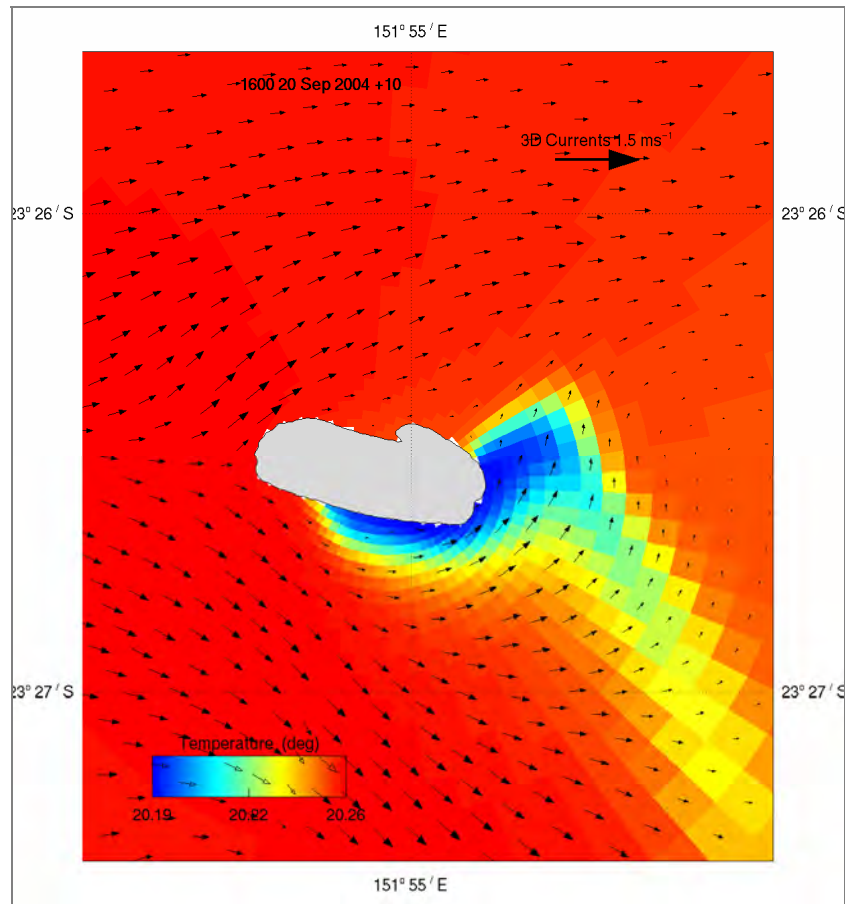


Figure 4: Surface currents and temperature around Heron Island.

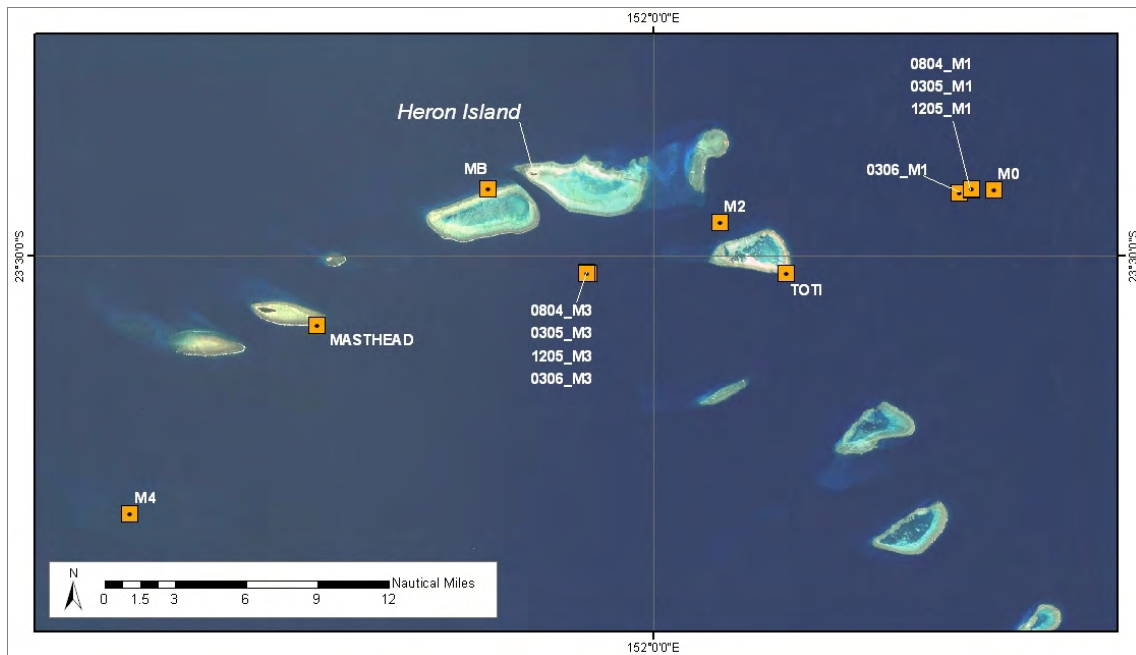


Figure 5: Heron Island cross-shelf moorings transect 2005/2006.

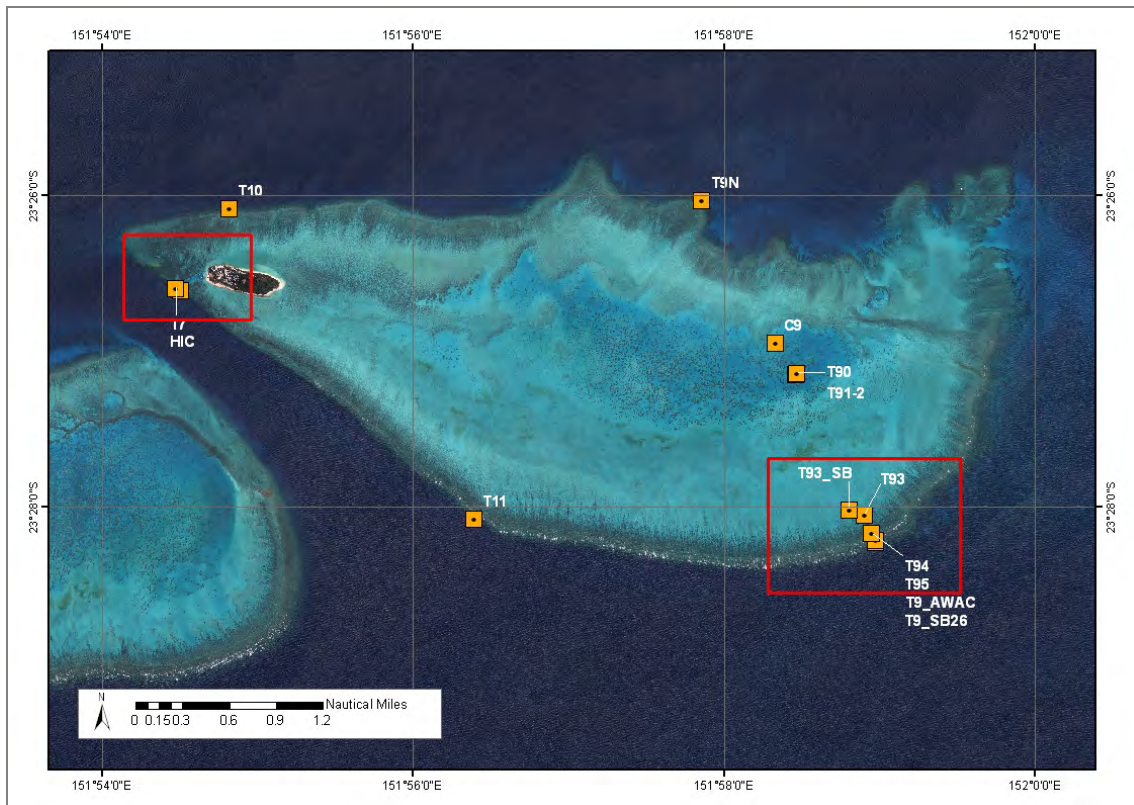


Figure 6: Heron Island temperature logger transects.

Project 2.5i.2 Early warning and assessment system for thermal stress on the GBR

Project Leader and Host Organisation: Professor Ove Hoegh-Guldberg, UQ

Rationale and Objectives

Present understanding of the relationship between sea temperatures and bleaching risks of coral assemblages is predicated on the assumption that thermal thresholds for bleaching are stable within geographical regions and coral taxa. Also, current models do not formally account for interactions between temperature and other environmental factors in determining bleaching risks.

To improve detection and projection capabilities of bleaching risks in the future, the potential acclimatization and the role of historical adaptation and interactions between key environmental variables, new models are being developed. The models will be calibrated using controlled laboratory and raceway experiments in which the responses of a range of coral species to combinations of temperature, light, water quality and UltraViolet Radiation (UVR) will be determined. These laboratory experiments will be complemented by detailed analyses of historical data of thermal histories, bleaching severity and success of recovery to better understand the associated risks of coral mortality. The project has two key objectives:

- Refine threshold values for coral bleaching; and
- Determine the role of mesoscale oceanographic variability in mass coral bleaching patterns, and on higher trophic levels.

These have several complementary components:

- To provide threshold values for input into an early warning system;
- To define the genetic bases of current bleaching thresholds,
- To improve understanding of how water quality affects outcomes from bleaching (e.g. risk of dying, recovery potential);
- To provide better predictive capability with respect to bleaching and related climate disturbances;
- To determine short-term, seasonal and inter-annual variability in GBR waters, and regional physical and biological responses to climatic perturbations;
- To improve understanding of mesoscale oceanographic influences on patterns of bleaching;
- To identify productivity hotspots of relevance to higher trophic levels; and
- To improve understanding of how these fronts may vary with projected climate change.

The results will be used to develop integrated, multivariate stress algorithms (based on the degree–heating day principle), and risk-based approaches to modeling (e.g. Anthony *et al.* 2006, in press). These thresholds will be incorporated into projection models of how reefs might change as seas warm (Project 2.5i.1 Regional climate scenarios, and Project 2.5i.4 Tools to support resilience-based management in the face of climate change).

In addition to work done on refining thresholds, research will identify how different genetic varieties (ie species and 'ecotypes') of the endo-symbiont zooxanthellae *Symbiodinium* affect the thermal tolerance in corals, by exploring the heritability of key genetic traits within corals and their symbionts. This information will provide more accurate estimates of the trajectory of GBR coral communities under rapid climate change.

The rationale for the second major objective, to determine the role of mesoscale oceanographic variability in mass coral bleaching patterns and on higher trophic levels, is that climate change is predicted to lead to changes in ocean currents and the physical dynamics and biological processes that impact the GBR continental shelf. An improved understanding of the key processes that drive the GBR ecosystem and of the regional physical and biological responses to climatic perturbations requires the routine acquisition of high quality spatial and temporal observations. Moderate resolution (1 km) data from satellites that provide daily synoptic coverage of the ocean have been available over the past few years. This objective will generate an historic archive of selected geophysical parameters (sea surface temperature, chlorophyll concentration, attenuation coefficient) from 1 km resolution SeaWiFS and MODIS data for GBR regional waters, in close collaboration with NASA. An analysis of the time series will be undertaken for the selected geophysical parameters. Seasonal and inter-annual climatologies and anomalies will be generated to derive physical and biological oceanographic patterns, and the relationship of mesoscale variability to mass coral bleaching will be explored. Four specific questions will be addressed in the analysis:

- a) Does the GBR regional circulation display short-term, seasonal and interannual variability, as deduced from MODIS satellite data?
- b) Are the dynamics reflected in remotely-sensed patterns of phytoplankton biomass (chlorophyll a concentration)?
- c) To what extent can physical processes explain spatial thermal stress variability?
- d) Can hotspots be identified in GBR regional waters from MODIS satellite data?

Specific events will be examined in detail (e.g. 2002 vs. 2006 coral bleaching periods) to identify the evolution of processes involved.

Finally, selected geophysical satellite products will be determined for routine generation on an ongoing basis. A *modus operandi* will be developed in collaboration with NASA and GBRMPA whereby these products may provide input into the early warning and assessment system, thus providing remotely sensed oceanographic monitoring of the upper layer dynamics of GBR regional waters.

Progress – Outputs

Data have been compiled on the vulnerability of corals to different stressors. Physical oceanographic data were collected from over 60 instruments deployed in the Capricorn Bunker Group of reefs between August 2004 to April 2006 as part of an AIMS project "Physical controls on bleaching". Although not collected as part of the current MTSRF Project 2.5i.2, these data will assist the present research effort. MODIS Aqua thermal infrared and ocean colour at 1 km resolution have been acquired by UQ from NASA for period July 2002 to present. MODIS Terra thermal infrared have similarly been acquired for 2005 to present, hence providing thermal coverage four times daily. These data continue to be acquired in the forward stream. Terra ocean colour (2000-present) and Terra thermal infrared (2000–2004) are at one-kilometre resolution are being compiled and processed by NASA and will be available in the near future.

The following is excerpted from Hoegh-Guldberg (2007):

1. Early Warning Systems (Berkelmans)

A review of the efficacy and accuracy of the time-integrated bleaching thresholds was conducted using statistical and empirical techniques. Preliminary results show that time-integrated bleaching thresholds remain an appropriate and useful method for modelling thermal stress in corals. The original bleaching thresholds developed after the 1998 bleaching event accurately predicted the 2002 bleaching event and separated bleaching from non-bleaching years up to that time. However, since 2002 it is clear that a number of reefs have become more resistant to thermal stress. These locations included Myrmdon Reef, Davies Reef, Magnetic Island, Chicken Reef and Daydream Island, which experienced warmer conditions in 2004 and/or 2005 than in the bleaching year of 1998, but without bleaching. A number of plausible explanations have been examined and additional data (UV and light) were obtained and analysed. The strong conclusion remains that these reefs have become more tolerant after (and possibly because of) the 2002 bleaching event.

Mortality thresholds were derived for six reefs that suffered high (>50%) mortality during past bleaching events. An analysis of these thresholds in relation to their bleaching thresholds indicates that at most of these sites thermally sensitive taxa die <1°C above their bleaching threshold, and many <0.5°C above their bleaching threshold. These results highlight the fine line that exists between recovery and death of thermally sensitive corals following bleaching.

The results of this project have been submitted as a chapter for the book, "Coral Bleaching: Patterns, Processes, Causes and Consequences (van Oppen, M. J. H. and Lough, J. M., eds.), Springer, due out in late 2007/early 2008.

Regular updates on conditions were provided to GBRMPA during the 2006/2007 summer. The 2006/2007 temperatures were unusually cool compared to the last ten years and bleaching thresholds were not exceeded (or even approached) at any of our real-time monitoring stations.

2. Heritability of Thermal Tolerance (van Oppen)

The first heritability experiment on a Magnetic Island population of the coral *Acropora millepora* has been completed. Four hundred nubbins from a total of 20 coral colonies were used during the experiment. Half of the 400 nubbins were removed from the aquarium tanks once the nubbins had acclimatized to the tank conditions after two weeks, and are used as the baseline values for future protein expression analysis (these serve as additional host and symbiont traits). The remaining 200 nubbins were investigated under control (27°C), sub-bleaching (31°C), and bleaching (32°C) conditions as outlined below before preparation for the protein analysis. During each first stage, photosynthetic efficiencies of *in hospite* zooxanthellae under various temperature regimes were assessed as a trait indicative of both algal- and holobiont health using an Imaging–Pulse Amplitude Modulated (I-PAM) fluorometer. The maximum quantum yield was calculated as an indication of the efficiency of photosynthesis. The effective quantum yield was measured as an indication of the overall efficiency of open PSII reaction centres in the light. In addition, growth rate of coral nubbins as a direct host trait and a quantitative measurement of stress was measured using the buoyant weighing technique.

Genetic identity of the coral colonies examined was verified using DNA microsatellite loci. In order to ensure the presence of the same species of zooxanthellae among and within every coral colony, genetic identification of zooxanthellae was performed based on the internally transcribed spacer region 1 of the nuclear ribosomal DNA.

The proportion of the observed phenotypic variation that was due to genetic factors (the broad-sense heritability; h^2) was high for both the decrease in maximum capacity of zooxanthella photosystem II (Fv/Fm) under 31°C ($h^2=0.47$), and 32°C ($h^2=0.5$), as well as for the coral growth rates under the same temperatures ($h^2=0.62$ and 0.55, respectively). In contrast, genetic factors did not contribute that much to the variance observed in both Fv/Fm ($h^2=0.24$) and growth rates ($h^2=0.16$) under control conditions (27°C). Both traits were always positively correlated, however, only exposure to 32°C yielded such results to a moderately large extent ($r=0.32$).

This is the first study to show that the variation in thermal tolerance in corals has an underlying genetic component and is not solely due to environmental factors. Despite this, our results suggest that, for this one population (Magnetic Island) and trait (maximum quantum yield of fluorescence), the change from one generation to the next due to selection is expected to be relatively small. The expected response to selection of other photophysiological traits, growth and the expression levels of a suite of proteins is currently being analysed.

3. Physiological Response Modelling (Anthony, Hoegh-Guldberg, Dove)

The relationship between bleaching, reduced productivity and genet, as opposed to ramet mortality risk amongst and within coral species, is being addressed. Currently, thermal tolerance and bleaching tolerance are used interchangeably in the literature; yet it is also appreciated that some corals that bleach in response to elevated temperature survive and grow rapidly once the stress is removed; whilst some corals that don't bleach grow more slowly and/or die either during or after the stress. It is understood in the plant literature that some types of 'bleaching' represent acclimations that enable plants to improve either more immediate productivity or long-term annual productivity in response to environmental change; but that other types of 'bleaching' are destructive precursors to or coincide with organism death. Gardeners are familiar with the fact that some plants are darker green in the winter than in summer; and it is hard not to observe that some trees (deciduous trees) lose their leaves, sometimes drop limbs for parts of the year only to flourish in the other part of the year. The avid gardener also knows that some plants grow better if you regularly prune them. Similarly, especially given the current drought, we are familiar with some plants, especially non-native species, turning brown as the organism dies. When it comes to determining coral thermal thresholds and genet mortality risks therefore, it is important to understand which of the different types of 'bleaching' is being exhibited as we increase temperatures, and the influence of light, and other physical variables on this response. Equally however, it is important to assess the annual productivity (growth) and mortality risks of corals that do not bleach.

In this first year of funding, we have sought to understand, (1) how bleaching affects immediate productivity in a coral species that sometimes expresses large concentrations of host pigmentation in addition to the dinoflagellate pigmentation that is lost when a coral is said to bleach; (2) we have conducted long term monitoring of coral colonies in the field through naturally occurring 'elevated temperature' events to determine whether ramet (explant) mortality is necessarily preceded by bleaching; and (3) we are developing a new modelling framework that allows a more quantitative and mechanistic treatment of thermal and light stress on coral symbioses, and better predictions of ecological consequences of bleaching.

- (i) We have investigated how host pigmentation may sustain productivity despite highly significant (80%) reductions in dinoflagellate pigmentation in the coral *Montipora monasteriata*. The study is currently under review with *Plant, Cell and Environment* and is summarised as follows:

“In corals, just as in plants, photosynthesis is conducted intracellularly within chloroplasts. Yet, whilst architecture and non-chloroplast based pigments (phytochromes) in mature plants are seen as essential for optimising productivity; the concept that this may also be true of corals has not been embraced. Reef corals occur in a range of colour morphs due to the presence of host pigments, but little is known about their physiological or ecological significance. We examined the hypothesis that host pigments provide an alternative mechanism for photoacclimating the coral holobiont. We demonstrated that some host pigments are responsive to changes in external irradiances, and that the presence of these host pigments is correlated either with changes in photosynthetic efficiency, or with the ability of the holobiont to sustain areal productivity despite experiencing highly significant reduction in the population of photosynthetic endosymbionts. Our study suggests that heavily host pigmented coral operating at elevated temperatures can be severely, but not detrimentally ‘bleached’.”

- (ii) We have investigated how control and transplanted colonies of *Pocillopora damicornis*, and *Stylophora pistillata* responded to both a prolonged stress resulting from transplantation to a deeper and darker light environment; and a short term stress observed as thermally anomalous temperatures observed in the Wistari Channel (southern GBR) in 2006. A manuscript is currently being prepared for submission to an international journal. The study forms part of the PhD thesis of Eugenia Sampayo that is currently under examination. The results clearly show that both species experienced high colony mortality in the months following the ‘thermal stress’ event, but that only colonies of *S. pistillata* visibly bleached during that stress event. Furthermore, in *S. pistillata* survival was strongly linked to the symbiont type dominantly hosted by the explant at the start of the three year experiment, with those explants initially hosting symbiont type C8/a seemingly resistant to all forms of stress. Interestingly, colonies that shuffled to a dominant C8/a prior to the thermal anomaly were no more resistant to that anomaly than those hosting other symbiont types. The effects of symbiont type and stress on colony growth for these experimental explants are currently under analysis.
- (iii) Work during the first year of funding has also resulted in two papers on light-temperature thresholds for corals, in part using coral productivity and survival as the key response variables. One paper has produced the first quantitative relationship between bleaching status, photosynthetic capacity and metabolic rate. This allows direct assessment of the energetic consequences of bleaching for the coral physiology, and has implications for coral survival during and following a thermal stress event. The second paper is a mathematical modelling study of how the processes of thermal bleaching are coupled to energy balance, energy stores, and mortality risk. This theoretical framework forms a strong basis for developing improved threshold models. By the end of the year, we expect to have a more comprehensive understanding of threshold mechanisms from experimental and modelling work.

4. Mesoscale oceanography and remote sensing (Weeks, Steinberg and Maynard)

Thermal infrared and relevant ocean colour data from the Moderate Resolution Imaging Spectroradiometer (MODIS) have been acquired directly from NASA for the entire Terra and Aqua satellite missions (2000-present) at full one-kilometre resolution, and remains ongoing in quasi-realtime. Time series of MODIS three-day, weekly and monthly sea surface temperature (SST) and chlorophyll *a* have been generated for the GBR and southern GBR regions for analysis.

Relative sea surface temperature anomalies and coral bleaching patterns were determined using MODIS Terra satellite data for the 2001/2002 and 2005/2006 periods. AVHRR Pathfinder data was acquired and used to generate a seventeen-year climatological baseline.

Coral bleaching spread across the southern GBR in January 2006 after sea temperatures were shown to reach climatological summer maxima two months before normal. The current "Hotspots" prediction methodology failed to predict the 2006 bleaching conditions despite major impacts observed on coral reefs. It is shown that such problems can be ameliorated if seasonal variation in thermal tolerance, likely a result of physiological acclimation, is taken into account. This allows bleaching arising due to abrupt warming in early summer to be forecast by using thermal thresholds that appropriately reflect the long-term mean pattern in seasonal variation (Weeks *et al.*).

Issues related to climatology standardization in predicting and assessing bleaching events on the GBR are being addressed by (1) investigating resampling techniques, (2) using relatively short (~10-15 years) rather than long-term (~20-30 years) climatologies, and (3) using a running average on a relatively short-term climatology. For the GBRMPA *ReefTemp* there was significant grid misalignment when overlaying the 2 km update to the 4 km climatology data. Only 20% of the grid cells were not impacted by the weighted average used to produce the new higher-res climatology grid. Maynard *et al.* (in review) has found that corals have acclimated to local thermal regimes and their tolerance to thermal stress has, at least in part, come as a direct result of temperatures experienced during recent years. Effectively, given rates of temperature increase, a longer-term climatology will be greatly impacted by averaging with years that were far cooler than what reefs now experience consistently. A shorter-term climatology may be greatly underestimating bleaching risk. A standard approach to regional climatology implications of using short-term recent climatology data rather than longer-term climatologies is being advanced.

The long-term oceanographic array around Heron Island was serviced and re-deployed on two cruises on the RV Lady Basten during October 2006 and April 2007. This will provide the necessary data to assist in validating and interpreting satellite remote sensing data and calibrating a hydrodynamic model of the region. AIMS@JCU PhD student, Severine Choukroun, is using the UQ MODIS satellite data for validation and interpretation of AIMS in situ data, in collaboration with Weeks and Steinberg.

A review of relevant physical processes of the GBR with regard to coral bleaching has been undertaken (Steinberg *et al.*). The analysis will enable the determination of the relevant oceanographic processes that need to be considered in characterising the thermal environment around coral reefs. Long-term, on-going current meter observations, and an intensive temperature logger array deployed in the Capricorn/Bunker Group during the 2006 bleaching, will be used to help analyse the cause and distribution of heat stress. These results, together with model calibrations, will feed directly into the related Project 2.5i.1 Regional Climate Scenarios, and assist in the assessment of mesoscale variability from MODIS imagery by Weeks (above).

Project 2.5i.3 Resilience to climate change

Project Leader and Host Organisation: Professor Terry Hughes, JCU.

Rationale and Objectives

The project is examining the resilience of coral and reef fish assemblages to climate change, and how the impacts of climate change will interact with other human-induced stresses to influence the resilience of reef ecosystems. The project is utilising existing strengths in the population genetics of corals and their algal endosymbionts, in the population, community and ecosystem ecology of corals and reef fishes, and in mechanistic modeling. A key outcome will be an integrated, multilevel, assessment of climate change effects on GBR corals and fishes. Key components of the life history, community ecology and functional capacity of corals and reef fishes will be targeted to determine how individuals, populations

and communities will respond to climate change, and to assess the feedback that these impacts will have on the resilience of coral reef ecosystems within the GBRMP.

The Project has six key objectives with differing research protocols:

- (a) Estimate genetic connectivity among GBR populations of coral and their algal endosymbionts to determine their potential for replenishment following disturbances associated with climate change. Because successful migrants leave a genetic signature of their movements, inference of connectivity can be made using population genetic methods – analysis of DNA microsatellite loci. This information will be linked to hydrodynamic models to provide improved estimates of reef connectivity.
- (b) Identify mechanisms of adaptation available to local coral populations to understand their potential for adaptation to climate change. This will be assessed for fast diverging genes (that are therefore likely to be under selection) in a GBR coral species showing a latitudinal gradient in thermal tolerance, using DNA microarray technologies. DNA sequence analysis of a subset of the genes identified as fast-evolving will reveal whether selection on the DNA sequences themselves has occurred in these populations. Theoretical models of the potential for corals to evolve greater bleaching resistance in response to climate change will be developed as part of this objective.
- (c) Identify links between thermal anomalies and coral disease dynamics to predict the response of coral assemblages to ocean warming associated with climate change. A modeling approach will be used to evaluate metrics of thermal anomalies based on NOAA satellite data that best explain spatial and temporal patterns in the prevalence of coral disease on the GBR. The relationship between peaks in disease prevalence and thermal anomalies will be analysed to determine thermal thresholds associated with outbreaks of coral disease. Interactions between bleaching and disease will be examined. Algorithms to (i) relate temperature to past disease outbreaks, and (ii) develop a product that provides predictive outlooks for outbreaks of key coral diseases, similar to the NOAA hotspot algorithm that predicts bleaching events, will be developed.
- (d) Quantify current levels of herbivory by reef fishes on the GBR and evaluate the extent to which reefs across the GBR shelf are vulnerable to ecosystem phase-shifts and domination by macro-algae as a result of climate change. Existing research and new data of the distribution and abundance of herbivorous fishes across the GBR will be used to quantify current rates of herbivory. These data will be combined with direct experimental analyses of fish-algal interactions that will enable estimates of the current capacity of GBR reef fish populations to maintain low macro-algal cover on mid and outer reefs.
- (e) Identify critical thresholds in macro-algal phase shifts and evaluate alternate management strategies in order to limit the impacts of climate change on the ability of fish assemblages to prevent ecosystem phase-shifts on coral reefs. A modeling approach will be used to estimate critical thresholds in the coral – macro-algal phase shift and to evaluate alternative management strategies to respond to changes in macro-algal distributions. Results from (d) above will be combined with existing algal distribution data and algal growth trajectories to model fish-algal interactions and outcomes under a range of climate change scenarios, providing an indication of the relative resilience of different components of the GBR ecosystem. In particular, it will indicate to what extent the current stands of macro-algae on inshore reefs reflect a state of heightened vulnerability to climate change.
- (f) Evaluate the long-term recovery and resilience of reef fish communities to climate change-induced habitat degradation. A detailed analysis of the recovery and resilience

of fish assemblages will be undertaken at Trunk Reef, central GBR, severely impacted by coral bleaching in 2001-2002. Changes in the structure and dynamics of fish communities will be monitored annually and directly compared to temporal changes in the physical and biological structure of benthic habitats.

Progress – Outputs

(a) *Estimates of genetic connectivity:*

Genetic connectivity among populations of *Symbiodinium* hosted by the soft coral *Sinularia flexibilis* was assessed for variation at four DNA microsatellite loci. Continuing evaluation of this genetic variation will illuminate the relationship between the genetic differentiation and the geographic distance separating reefs.

(b) *Mechanisms / rates of adaptation for bleaching resistance:*

Some field evidence for the potential for shifts in temperature tolerance suggests scope for adaptation of bleaching resistance in the coral – zooxanthellae holobiont. Examination of the factors that may accelerate or impede the rate at which additional resistance to bleaching (ie an increased bleaching threshold temperature) might evolve is underway. Different model scenarios are being developed for the patterns of vertical versus horizontal transmission of symbionts, the effects of dissociation versus death of combinations of symbionts and host, and the interactive effects of host and symbiont genomes. The utility of the model to test the plausibility, and under what conditions, adaptive bleaching might evolve is being explored.

(d) *Status of herbivory patterns by fishes on the GBR:*

A literature review of publications on GBR herbivory indicated it accounts for 4% of research publications, despite its critical role in ecosystem processes (Cvitanovic *et al.* 2007). Research on the GBR has shifted, with the Caribbean now assuming a greater proportion of the literature. Work on herbivory on the GBR has been centred in two areas, Lizard Island and Orpheus Island, thus understanding of herbivory is geographically limited with few studies investigating large-scale differences in the process. Studies that have identified potential critical thresholds and vulnerability were, almost invariably, undertaken at relatively small spatial scales.

Furthermore, in the recent years there has been a dramatic shift in our understanding of herbivory with large numbers of fishes being classified as detritivores. This has led to a reappraisal of the nature of herbivory on the GBR. Understanding of herbivory is changing fast as studies shift from a fish-oriented to system-oriented approach.

The following is excerpted from Cvitanovic *et al.* (2007):

The future of research on herbivory and implications for management

Over the last five years, the herbivory research agenda has come to be dominated by a new perspective: one that acknowledges the role of herbivores in precipitating phase-shifts on reefs, but which also places new demands on our understanding of herbivory at the micro level. Recent literature examining the process of reef degradation has advocated a system-level approach to managing coral reefs (e.g. Nyström *et al.* 2000, Bellwood *et al.* 2004, Hughes *et al.* 2005). This approach sees reef dynamics in terms of a non-equilibrium environment with multiple stable states. Events such as global warming, eutrophication or over-fishing have become re-cast as disturbance factors that have the potential to dislodge the system from its initial position and shift it to a new state (Nyström *et al.* 2000, Bellwood *et al.* 2004). The resilience of the reef system reflects the size of disturbance that can be absorbed by the system without causing a shift to a new, usually undesirable state (Nyström

et al. 2000). Herbivores confer resilience to the extent they exert a grazing impact that maintains a balance between corals and algae.

Herbivory from the system perspective is not just a process of energy transfer, but rather a composite function of the individual impacts that each herbivorous species has on the system. The ability of a reef to withstand disturbance events and avoid shifts to alternate states is dependent on having the right functional composition of herbivores. Understanding the role and relative importance of herbivorous species requires a knowledge of the quantitative impact that each species and where it exerts that functional impact. As recent reviews have emphasised, the current dataset of quantitative ecosystem impacts of individual taxa is limited (McManus and Polsenberg 2004). Exceptions for the GBR include measurement of bioerosion rates and contribution to sediment production for individual species of excavating parrotfish (Bellwood 1995a, b, Bellwood *et al.* 2003), estimation of ingestion rates of algae for individual species of scraping parrotfishes (Klumpp and Polunin 1989, Polunin *et al.* 1995), estimation of ingestion rates of algae for one surgeonfish species (Polunin and Klumpp 1992), and for three damselfish species (Klumpp and Polunin 1989, Polunin and Klumpp 1992).

Recent research has therefore been aimed at adding to our understanding of the quantitative functional impacts of individual species of herbivores and of their trophodynamic context (e.g. see Choat *et al.* 2002, 2004, Crossman *et al.* 2005). Understanding what food is being eaten and assimilated by whom and at what rate will enable us to better understand reef processes. In addition, remote underwater video technology is being used in field studies of herbivores to provide an insight into the process of herbivory in the absence of divers (Bellwood *et al.* 2006). The technique is proving to be a revealing one, showing that the removal of macroalgae from reefs cannot be assumed to be the exclusive reserve of 'traditional' macroalgal feeders (Bellwood *et al.* 2006). Undoubtedly, further use can be made of this methodology to reveal an added dimension to herbivory and further our understanding of the GBR's herbivore populations and those species which are intrinsic to the maintenance of a healthy balance between corals and algae.

Summary

The GBR exhibits considerable species richness at the herbivorous and nominally herbivorous trophic level. In low diversity systems, such as the Caribbean, minor changes in biodiversity can have dramatic impacts on the ecosystem. However, it is not necessarily safe to assume that the corollary is true. High species diversity, such as that displayed by the GBR, does not necessarily confer greater resilience and high diversity systems can still display limited functional redundancy (Bellwood *et al.* 2003, Fox and Bellwood in press). An increased understanding of the functional role played by individual species of herbivore will be crucial if we are to make prescriptions for the prevention (and reversal) of phase shifts on coral reefs.

The focus of recent research on herbivory on the GBR has now shifted to view the process as one of a number of factors determining the resilience of coral reefs. This new focus has revealed some crucial gaps in our understanding of herbivory. We know much of what herbivores as a group do on reefs qualitatively speaking, but little about the individual functional components of the group and their quantitative effects. Viewed from the perspective of the overall reef system, however, it is precisely this quantitative understanding of ecosystem function that will provide the next insights into the process of herbivory on coral reefs.

The practical requirements of this new research agenda are considerable. It will require a fully integrated knowledge of the individual species: their ontogeny, their interactions with the substratum, their ability to consume and remove algae and their relationship to current

distribution patterns of algae across the GBR. The predominant message emerging from recent studies is that the process of herbivory is a more subtle one than previously imagined and can show variation even at the scale of neighbouring reefs. Understanding herbivory on the GBR at the gross scale will not be enough to make predictions about individual systems. Estimates of existing abundances of herbivores and associated benthic algal communities should be extended to a more diverse collection of sites across the GBR and investigations of the process of herbivory should incorporate methods that allow us to witness feeding behaviour in the absence of divers.

Project 2.5i.4 Tools to Support Resilience-based Management in the Face of Climate Change

Project Leader and Host Organisation: Dr Scott Wooldridge, AIMS.

Rationale and Objectives

While the causes of climate change are beyond the direct influence of management agencies and individual stakeholders, a range of options are emerging for minimising its impacts on the ecosystem and the industries and regional communities that depend on it. A critical step is the development of spatially explicit, sub-regional scale information about the risks posed by climate change and variability in resilience. This project will provide this information by developing an atlas of climate change risk for key elements of the GBR social-ecological system (SES). This will enable managers to incorporate climate-related threats into future management policies and activities, most of which are spatially explicit. It will also enable managers and stakeholders to identify areas where ecological or socioeconomic values are most at risk. For example, such an atlas might guide the distribution of RWQPP resources toward catchments where adjacent reefs are more susceptible to damage from coral bleaching. This project has two main objectives:

- a) An atlas of climate change risk and resilience for the GBR social-ecological system; and
- b) Integrative knowledge for prioritising management responses to climate change.

The atlas will comprise maps of risk and resilience of priority elements of the GBR SES. Spatial analysis and modeling of key system variables (and causative interactions) will generate GIS map layers describing:

- Physico-chemical drivers affected by climate change (hazard);
- Synergistic (non-climate) stressors, e.g. water quality (interactions);
- Distributions of key elements of the GBR social-ecological system (exposure); and
- Susceptibility of elements to climate change (sensitivity).

Temporal projections of identified spatial patterns (hazard, interactions, exposure, sensitivity) will be generated on the basis of plausible climate change scenarios, adaptation measures and management activities. An integrative modeling approach, based on Bayesian belief networks, will be used to represent the dynamic linkages and inter-dependencies of the many components of the GBR SES, and examine their vulnerability to climate change and their responsiveness to different management interventions. The model will enable end-users to test alternative scenarios for future climate, management actions and adaptation measures. This will add fundamental capacity to the ability of managers to test the cost-benefit ratio of alternative management responses as a basis for identifying strategies that deliver the best outcomes at the lowest cost. For example, reef managers might use the

model to decide whether to prioritise investment toward restoring water quality or excluding human activities from key refugia for important reef species.

Progress – Outputs

A spatial database for the inshore reefs of the GBR study area has been developed using ArcGIS software. The database covers the environmental attributes of thermal regime, water quality, species richness, and bleaching impact. Two areas have been chosen for socioeconomic analysis: the Townsville coastal region and Cairns coastal region. For these two areas, a socioeconomic profile provides information about population, demography, economic activity and other primary variables. These data will assist future efforts to characterise ‘spatially-explicit’ patterns of resource dependency, economic value and socioeconomic vulnerability for the communities and infrastructure that service the urban, industry, agricultural, fishing, tourism and recreational sectors.

Program 6: Invasive Pests

Project 2.6.1 Understanding Threats and Impacts of Invasive Pests on the GBR

Project Leader and Host Organisation: Dr David Blair, JCU.

Rationale and Objectives

The first step in dealing with risks posed by invasive species is an understanding of what species are actually (and potentially) present. Once alerted to the presence of these species, end users can institute measures for surveillance and control. As introduced above, the CRC Reef and QDPI&F have undertaken marine pest baseline surveys in ports and elsewhere in recent years. This has resulted in identification of a number of dinoflagellate species in GBR waters, but nothing has been done beyond basic identification. This project will build on this baseline knowledge of species present and link with the expertise of the Queensland-based Consortium of Expertise in Tropical Marine Pest Assessment and Management. There are two main objectives:

- (a) Support detection, eradication, monitoring and management of key pests in at-risk habitats for the GBR region and adjacent coastal habitats.
- (b) Assess the presence of toxic microalgae in the GBR, the potential threats posed by these and management responses.

Further components of the study will:

- Assess the impact of disturbances to marine sediments on the potential distribution of toxic algae and their cysts by developing a fast detection strategy to identify genotypes of particular toxic microalgae;
- Compile an atlas of relevant marine microalgae; and
- Develop molecular probes for species known to have potential for toxin production to enable risk assessment for particular regions and to develop effective preventative measures.

Theme 4: Sustainable Use and Management

Program 8: Sustainable Use and Management of Marine Resources of the GBR

This Program has three major biodiversity-related projects (Projects 4.8.1 to 4.8.3) and three socio-economic projects (4.8.4 to 4.8.6), the former five of which have a strong fisheries focus, while the latter is focused on tourism. These are each reviewed concurrently below.

Project 4.8.1 Resilience and connectivity

Project Leader and Host Organisation: Professor Terry Hughes, JCU.

Rationale and Objectives

Understanding the scale of larval dispersal is a major challenge in marine ecology and it is clear that management of marine fishes, including by marine protected areas (MPAs), must incorporate the scales over which their populations are connected by larval dispersal. MPAs (green zones) in the GBR promote the abundance, size and reproductive potential of exploited fishes within their boundaries, but an important question remains unanswered - Do green zones provide a recruitment subsidy to exploited fish populations such as coral trout beyond their boundaries (blue zones), thereby promoting the resilience and sustainable exploitation of fish resources?

The project 'Resilience and connectivity' (Project 4.8.1) has two main objectives:

- (a) Develop and test realistic larval-fish dispersal models for the GBR. Biophysical dispersal models for larval fishes on the GBR will be developed by integrating new biological data on larval-fish behaviour into an upgraded, existing physical dispersal model. This will give the first realistic predictions of larval fish dispersal and hence population connectivity for reef fishes. These estimates of scale (dispersal kernels, or the spatial probability of dispersal) are essential for understanding how GBR fish populations are structured and for their efficient management. Outcomes are biophysical models to predict and hindcast dispersal and connectivity, and better understanding and management of GBR fish populations.
- (b) Develop and test methods to ground-truth larval-fish dispersal models for the GBR. The models will be empirically tested using two new techniques that revolutionise the direct assessment of larval dispersal. The otoliths (ear bones) of larval fish can now be safely marked by maternal transmission of stable isotopes. Also, the paternity of recruits can be established by sampling their DNA and matching it to putative parents. These two techniques will be applied to coral trout in a series of capture, mark and release programs at spawning sites within selected green zones. Larvae retained within or moving beyond green zones will be identified and the direction and extent of dispersal compared with model predictions. This approach will provide the first empirical test of larval dispersal models, and will establish whether green zones augment larval supply to exploited fish populations.

Achieving these objectives should provide answers to the following questions critical to the assessment of the effectiveness of the GBR Zoning model:

1. What is the spatial scale of connectivity by larval fish dispersal within the GBR?

2. How much do green zones contribute to the recruitment of coral trout and other fish species in blue zones (via larval connectivity)?
3. To what extent are populations in green zones sustained by their own reproduction (via larval retention)?
4. Are particular areas especially important sources of larvae for blue zones?
5. Are particular areas sustained by retention or by dispersal?

Progress – Outputs

The following is excerpted from Hughes (June 2007b):

Part A Physical model – We have decided to focus initially on the Lizard Island area and work out the details of the model and make sure it functions properly, and then scale up. The initial component of developing a 3D model for the Lizard Island area is the set-up of computational grids at desired resolutions. From previous work by Luciano and co-workers, a grid for the entire GBR already exists. This grid has a resolution of 1' (minute of arc) and when run in 2D mode was sufficiently refined to estimate broad scale inter-reef connectivity assuming passive larval behaviour during the pre-competent pelagic period. In the present project we are setting up a grid with 0.2' (370 m) resolution and perhaps 0.04' (74 m) around Lizard Island, to allow us to simulate and track the fine scale of dispersal of fish larvae.

The usual sources of high resolution digital bathymetric data for the region, such as previously digitised charts or LADS, excluded Lizard Island. Fortunately, Lizard Island was surveyed for the GBRMPA in 1982 and is available in hard copy format. This survey comes on ten large format sheets which have been scanned and are in the process of manual digitisation. Once this process is complete the fine resolutions grids of Lizard Island will be produced.

MMUTRACK is the lagrangian tracking model previously used to compute inter-reef connectivity by tracking the movement of neutrally buoyant and passive particles. MMUTRACK was limited to tracking particles within a stored 2D current fields produced by a single hydrodynamic model grid. In previous projects the movement of fish larvae within the GBRWHA was studied by storing 2D currents from one grid that encompassed the entire GBR region. However in the present project, the objective is to use multiple nested grids that accurately resolve horizontal and vertical distribution of currents at a finer scale, initially near Lizard Island. Using this multiple grid system will result in sets of current data with varying orientations, timesteps and horizontal and vertical resolutions. To accommodate this new system, a new version of the particle tracking model has been written that allows particles to be seamlessly tracked through the multiple current fields. At present the new tracking model is only set-up for 2D currents but will soon be able to accommodate 3D current fields. This will be followed by the addition of behavioural algorithms in the form of species-specific behavioural modules.

Part A Theoretical framework for a biophysical dispersal model – Only certain types of behaviours are relevant to predicting dispersal of fish larvae (e.g. swimming behaviour is relevant, but feeding behaviour is not), and because behaviour, like morphology, develops and changes during the larval phase, information on behaviour at different stages in larval development is required. Thus, behavioural capabilities are dependent on the stage of development: larval size, rather than age, is the best proxy for this.

However, dispersal operates over a given period of time (ie, the duration of the pelagic larval stage, or PLD) so we must be able to link time (typically measured in days since hatching) to size. Thus, it is necessary to include larval growth rates in the model. Independent of size (or age), larva behaviour may vary with spatial or temporal factors (eg, proximity to a reef, or

time of day), and these factors must be included in the model. In addition, choice rules have to be developed. For example, for a spatially-determined behaviour, to which of several reefs in an area will the larva respond - the closest? the largest? the one with optimal settlement habitat? Finally, temperature must be taken into account, as some biological items (e.g. PLD, swimming speed) are temperature-dependent. This has implications for both seasonal and climate change inputs. The theoretical framework developed for the dispersal model takes these factors into account, and combines them with the appropriate behaviour for the size (age) of the larva, and the correct spatial, temporal and biological inputs. As the model is developed further, and the biological inputs integrated with the physical ones, the theoretical framework will be further modified and refined.

The behavioural data are derived from two principal sources: published information, much of it by Leis and co-workers, and unpublished data from Leis' previous ARC-funded research (much of which required additional processing and analysis for it to be suitable for the model). The data are assembled into a standard format for each species to facilitate incorporation into the model.

The biophysical dispersal model will be configured to incorporate species-specific behavioural modules (a background document that details the types of information to be incorporated is attached), as behaviour differs among species, as does the duration of the pelagic larval stage (which then determines the time period over which the model is to be run). The species for which behavioural modules are developed are those for which the best behavioural information is available. In the first instance, these include the following reef-fish species that cover a wide taxonomic and life history range: Pomacentridae, *Amblyglyphidodon curacao* (Staghorn Damsel); Lutjanidae, *Lutjanus malabaricus* (Saddletail Snapper); Serranidae, *Epinephelus coioides* (Goldspotted Rockcod), *Epinephelus fuscoguttatus* (Flowery Rockcod). Eventually, we hope to be able to include a behavioural module for coral trout (*Plectropomus leopardus*) if we can obtain information on behaviour of younger larvae, but this is dependent on identifying a reliable source of reared larvae. In addition, if time permits or end users would prefer, species-specific behavioural models can also be developed for the several species for which we have data on behaviour over a range of development stages: Ehippididae, *Platax teira* (Roundface Batfish); Carangidae, *Caranx ignobilis* (Giant Trevally); Leiognathidae, *Leiognathus equulus* (Common Ponyfish); and Polynemidae, *Eleutheronema tetradactylum* (Blue Threadfin). Finally, Leis has extensive behavioural information on the settlement-stage larvae of a wide variety of reef-fish species, and it will be possible to include these species if assumptions are made about their behaviour earlier in development (eg, if the behaviour of the younger larvae of related species can be used). We now have this level of information on *Lutjanus carponotatus* (Stripey) analysed and available for model incorporation based on work performed by Ms G  elle Qu  r  , an intern from the University of Paris in Leis' lab. This fits in with the work on this species planned in Part B (see below).

The two species for which behavioural information is currently prepared are: *Amblyglyphidodon curacao* and *Lutjanus malabaricus*.

Part B of Project: Complete validation of larval marking and genetic techniques. Analyse data from larval marking validation experiments and prepare publications

Results – All research activities planned for part B of this project have progressed according to the milestone schedule. This work represents a team effort involving G. Jones (JCU), G. Russ (JCU), S. Thorrold (Woods Hole), L. van Herwerden (JCU) and three graduate students partially supported by MTSRF funding (D. Williamson, R. Evans, T. Mannering). The foundation for this project was provided by the paper fully describing a new technique for marking larval fishes using a low dosage of enriched stable isotopes of barium chloride

(BaCl₂) injected into females prior to spawning (published in the first reporting period of the MTSRF project, Thorrold *et al.*, 2006, *Can. J. Fish. Aquat. Sci.*). It showed that a barium marker is transmitted to developing eggs and is subsequently detectable in larvae and juveniles. During the current reporting period, co-workers associated with the MTSRF project have published a paper establishing that this technique can successfully be applied in the field and can establish local scales of larval dispersal in small reef fishes (see Almany *et al.* 2007, *Science*).

The validation procedures and baseline surveys necessary prior to conducting a mass-marking experiment in the field (Part B) have been divided into five sub-projects:

- (1) Effects of BaCl₂ injections on adult coral trout (*P. maculatus*) and health risks: In an experiment conducted at the JCU MARFU aquarium facility, we have now demonstrated that injections of BaCl₂ solution at dosages up to 4 mg Ba²⁺/kg of fish body weight produce no detectable effects on the physiology or condition of injected fish and present no risk to humans who may consume injected fish. This work was submitted for publication in May 2007 (see Williamson *et al.*, in review).
 - (2) Validation of BaCl₂ injections for marking grouper larvae (Pisces: Serranidae): In an experiment conducted at the Research Institute for Mariculture in Bali, Indonesia, we have established that injections of enriched isotope BaCl₂ produce effective markers in the otoliths of fishes closely allied to coral trout (family Serranidae). This experiment has shown that application of the isotope produces no negative effects on the growth, survival or development of larvae (see Williamson *et al.*, in prep).
 - (3) Effects of BaCl₂ injections on adult stripey sea perch (*Lutjanus carponotatus*) and health risks: In an experiment conducted at Orpheus Island Research Station, we have shown that injections of BaCl₂ at doses sufficient to mark larvae provide no negative effects on the adult survival or body condition (data currently being analysed).
 - (4) Identifying microsatellite markers to examine population connectivity in coral trout and stripey sea perch. Development of both mtDNA and microsatellite markers has been completed. Genetic samples collected in the Keppel, Whitsunday and Palm Island groups are set to provide insight into the broad-scale population connectivity of the two species between inshore reefs of GBRMP (Evans *et al.* in prep).
 - (5) Baseline surveys of adult spawning aggregation sites and juvenile nursery sites for both coral trout and stripey sea perch at the Keppel Islands: The Keppel Group has been selected as the location for the first field experiment which aims to track dispersal of larval coral trout and stripey sea perch from natal marine reserve reefs to surrounding fished reefs (Year 2). We have completed underwater visual censuses (UVC) of fish and benthic communities on fringing reefs of the Keppel Island group. Underwater surveys of *P. maculatus* and *L. carponotatus* have identified the locations of spawning aggregation sites, the timing of spawning and identified areas of high larval recruitment. Accurate estimates of mean adult and recruit abundances have also been calculated from UVC data. Samples collected during 2006 are providing information on recruitment dynamics and first year growth rates of the target species (Williamson *et al.* in prep).
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Project 4.8.2 Influence of the GBR Zoning Plan on Inshore Habitats and Biodiversity, of Which Fish and Corals are Indicators

Project Leader and Host Organisation: Dr Peter Doherty, AIMS.

Rationale and Objectives

This project forms part of the wider performance assessment of the 2004 GBR Zoning Plan, and is investigating the same questions for coastal habitats (where the major pressure is from recreational fishing) as Project 1.1.1 of Program 1 Status and Trends of the GBR (Section 4 of this report). While the emphasis in both projects is the impact of the 2004 rezoning on biodiversity, especially the response of fish populations when released from fishing pressure, the wider study is also addressing impacts of the Zoning Plan upon fishers and the tourism industry. Social and economic dimensions of this problem will be studied through Projects 4.8.4 and Project 4.8.5.

This Project has two main objectives:

- a) Measure the response of biological communities (fish and benthos) to differential zoning of human use on inshore coral reefs; and
- b) Measure the response of biological communities (fish and benthos) to differential zoning of human use on inshore shoals.

(a) Inshore reefs (G. Russ, D. Williamson and R. Evans)

Given that earlier work by Russ and colleagues had clearly demonstrated that mean abundance and size of predatory reef fish was significantly greater in no-take reserves than adjacent fished areas on inshore reefs, a logical development for the project was to examine the potential trophic effects on the fish community. Graham *et al.* (2003) examined the relationship between predator and prey population abundance in protected and fished zones of the Palm and Whitsunday Island groups. The study detected a significant negative correlation between the mean biomass of *Plectropomus* spp. and the abundance of fish species known to be prey of coral trout. Eight of the nine species of prey fish examined were found to be more abundant in fished zones than in protected zones, six significantly so. The results suggested that predation may be playing a strong role in structuring reef fish communities on these inshore reefs. Further investigation of trophic effects of reserve protection on these inshore reefs is clearly required. However, the study effectively highlights the potential ecosystem implications of the use of no-take marine reserves as conservation and fisheries management tools. More specifically, it is one of the few clear examples that management zoning in the GBRMP can affect community structure and diversity of reef fish species.

During 2003/2004 this monitoring program was further expanded on the inshore fringing reefs of the GBRMP. Baseline fish and benthic community data were collected using UVC in 44 new sites in the Palm, Magnetic, Whitsunday and Keppel Island groups. Twenty-two of the sites were on reefs which were to be closed to fishing in the July 2004 RAP rezoning, and 22 sites to remain open to fishing after the rezoning.

This sampling, whilst spatially limited, was the only systematic attempt by any research group working on the GBR to collect baseline fish and benthic data at coral reef sites *before* they became no-take under RAP in 2004. We are thus in a position to carry out a Before-After-Control-Impact-Pair (BACIP) study, a standard sampling design for most environmental impact surveys.

Repeat UVC surveys were conducted in the Palm, Whitsunday and Keppel Island groups during 2006, 1½ to two years after the implementation of RAP. Preliminary data on the effects of rezoning on fish populations in the Whitsunday Island group has been reported in Evans *et al.* (2006). The remainder of this report will focus on data obtained from the Palm, Whitsunday and Keppel Island groups between 2003 (baseline, pre-RAP) and 2006 (post-RAP).

Abundance of a wide range of fish and benthic invertebrates is being monitored at a large number of sites on coastal reefs in the three main groups of islands: Palms Is., Whitsunday Is. and Keppel Is. The main data set consists of paired sets of sites: 50 sites changed from fished to un-fished (blue to green) in 2004 matched with fifty control sites that remained open to fishing (blue). In addition, long-term data from another fifty sites will be included, half of which were closed to fishing in the first Zoning Plan (old green), with potential to expand the coverage of new green to other island groups along the coast (e.g. Frankland and Barnard Is.), representing a further fifty paired contrasts. Half of these two hundred sites will be monitored each year. The counts will include both large and small fish species. Local stocks of the former can be expected to benefit from protection but this may be accompanied by trophic cascades where more predators mean fewer prey with possible consequences flowing on to invertebrate biodiversity. The final output due in 2010 is a definitive report on the impact of no-take zones upon biological communities, including trophic cascades.

(b) Inshore shoals

Submerged 'shoals' and low-relief seabed features are becoming intensified targets for commercial and recreational fishing. In the coastal zone, there was evidence of effort shift in the recreational fishery from shallow reefs to deeper waters away from the immediate vicinity of emergent and island fringing reefs. While part of this shift in effort may have been in response to the high fishing pressure placed upon accessible and popular reefs, technology creep (e.g. affordable colour echo sounders and GPS units) that have allowed recreational fishers to find and return to small habitat features supporting alternative species, especially the high value red snappers (red emperor, small- and large-mouth nannygais), appear to be driving factors. Fisheries managers are not well equipped to deal with this shift in fishing effort in either domain because there is almost no information about the distribution and nature of these submerged seabed habitats and their biology.

The sub-project will find, map, characterise and monitor a set of seabed shoals off Townsville (Magnetic Shoals) that were popular targets for recreational fishing prior to rezoning in July 2004 and compare them with adjacent controls that remain open to fishing in the new Zoning Plan. Site selection will be extremely important for the reasons given above. In addition, 'treatments' and 'controls' must be sufficiently isolated that they do not exchange fish with each other on a regular basis, nor with other habitats belonging to the opposite zoning category (i.e., suspect possible edge effects across zoning boundaries). The sampling strategy will follow the prescription for a robust design established by the pilot studies, ie assemble knowledge base from interviews of local fishers, swath map a range of likely targets, characterise the habitat of a subset sharing the most similar physical aspects, and finally sample the most similar pairs (blue/green) with baited videos replicated in space and time.

Progress – Outputs

(a) Inshore reefs

To date the four island groups surveyed in 2003/2004 prior to the rezoning, have been resurveyed in 2006/2007 (Whitsunday Islands, Palm Islands, Keppel Islands and Magnetic Island). The findings to date from this project are similar to the Whitsundays report presented to the DEH in 2006 (Evans *et al.* 2006).

Major declines in coral cover occurred in the Palm and Keppel islands where overall mean live hard coral cover decreased by approximately 49% and 40% respectively. Both target fish groups, *Plectropomus* spp. and *L. carponotatus*, increased in biomass in the newly protected areas. In the Keppel Island group, the biomass of *Plectropomus* spp. remained relatively stable in the protected areas, whereas the mean biomass of *L. carponotatus* decreased slightly in the protected areas. Additionally, mean *Plectropomus* spp. biomass slightly declined in the fished areas of all three island groups between 2003/2004 and 2006. This pattern was also consistent for *L. carponotatus* in the fished areas of the Palm and Keppel Islands; however, there was a slight increase in mean biomass in fished areas of the Whitsunday Island group. Mean *Chaetodon* abundance declined significantly in fished areas of the Palm Island group (66.7% decline) and in fished and protected areas of the Keppel group (mean decline of 60.5% for both zones combined). These declines in the abundance of chaetodontids may be due to the large reductions in live hard coral cover observed in both the Palm and Keppel Island groups. On Magnetic Island, mean abundance and biomass of *Plectropomus* spp. and *L. carponotatus* increased in newly protected zones of fringing reefs, consistent with results obtained previously for both the Palm and Whitsunday Island groups. Although this project has now demonstrated consistent patterns across regions, it is important to note that low spatial replication of sites within zones, and infrequent temporal replication across years has meant that the results presented here must be viewed as preliminary.

(b) Inshore shoals

A baseline survey of green zone sites on Magnetic Shoal, together with sites open to fishing in the adjacent blue-zoned areas of the marine park has been completed (Speare and Stowar 2007a). The following is excerpted and summarized from the latter report.

The blue sites, nominally representing controls for the no-take green sites, were selected on cross-shelf position/depth (the strongest biological gradient on the GBR) and location. Monitoring of seasonal effects on the fish and benthic communities is underway.

The topography, especially on Magnetic Shoal, is subtle and while this can be revealed and visualised through acoustic survey data these have not, to date, provided clues as to the location of the epibenthic communities. This has required the deployment of more time consuming towed video with little preliminary 'intelligence'.

Many fish species were common to sites both on Magnetic Shoal and in the blue zones, yet the concept of control-treatment contrasts cannot be readily applied in this study; as some blue sites included habitat features not present on Magnetic Shoal – artificial habitat (a wreck), calcareous reefal substrate and dense filter feeding communities. Temporal monitoring should focus on the trajectories of each site, as simple metrics of abundance and size may be confounded by the disparity between habitats and fish-habitat associations.

Results to date have underlined the importance of very accurate deployment of sampling gear, especially in respect of on-going temporal monitoring. Achieving precision in counts may prove difficult due to the movements and schooling behaviour of some species, including several targeted by fishers.

Size monitoring, provided adequate samples can be obtained, may provide discrimination between take and no-take zones in the marine park. Size monitoring requires substantial processing of the captured imagery and a greater investment in this technology is required to realise efficiency dividends. This is necessary before this equipment can be routinely deployed as the tool of choice for the dual role of securing abundance indices and size monitoring. The present approach of stationary deployments is also limited in such a patchy habitat owing to the fact that the relatively small number of fish from localised habitat patches

continually re-enter the field of view. Development of a mobile tool for survey of fishes may have advantages in gaining greater breadth of coverage for a given sampling effort.

The following is excerpted from Speare and Stowar (2007b):

This report encompasses the baseline studies of fish and habitats on shoal ground in the Cardwell and Cairns regions of the GBR and seasonal monitoring of an established set of contrasting sites (closed and open to fishing) in the vicinity of Townsville. Acoustic mapping techniques were utilised to provide the topographical imagery of all study sites for the purposes of directing towed video for habitat classification and the deployment of Baited Remote Underwater Video Stations (BRUVS) for the acquisition of fish species and their relative abundance in habitats on these shoal areas.

(a) Townsville

All sites in the Townsville region were from unconsolidated sandy sediments supporting marine plants with patches of structurally more complex and diverse epibenthic communities of filter feeders and some hard corals. One site, RAP 4, was centred on the wreck of a wooden trawler.

BRUVS sampled 150 species from 39 families of fish over four discreet sampling events between July 2006 and March 2007. There was ~ twice the number of species recorded from each set on complex habitat compared to the surrounding habitat (109 vs. 71 species overall). Species richness did not vary with the level of protection or throughout the sampling period.

The distribution and relative abundance of fish assemblages varied with protection and location on each of the two principal habitat types. There was an interaction between these two factors which was due to the fish assemblages in the complex habitat on Magnetic Shoal having greater similarity to those on the Mackerel Patch, and the fish assemblages over sand at RAP 4 and RAP16 being distinct from those in the green zone and Magnetic Shoal.

The distributions and relative abundances of 22 species potentially targeted by fishers were similarly influenced by the level of protection but possibly because of a confounded site effect. There was believable evidence of an increase in the abundance of *Plectropomus maculatus* and *Choerodon venustus* in the new green zone.

(a) Cardwell

The shoal study sites off Cardwell are founded on rocky substrate with surrounding fine sand sediments. Their inshore and relatively shallow water attributes ensure relatively turbid conditions in response to wind driven wave and tidal movements.

BRUVS sampled 65 species from 27 families with, on average, twelve species from the rocky substrates and six species from the muddy sand bottom surrounding these outcrops. While there were site associated differences in the fish communities (distribution and relative abundance), the greatest dissimilarity between fish assemblages could be attributed to the two principal habitat divisions (hard rock and soft sediment). *Parupeneus indicus*, *Plectropomus maculatus*, *Choerodon schoenleinii* and *Scarus ghobban* were strongly correlated with hard bottom habitat whereas *Scomberomorus queenslandicus*, *Carangoides coeruleopinnatus* and *Nemipterus furcosus* were indicative of open bottom habitat. Fish communities were similar across sites on rocky substrate, but there was a site effect in relation to fish assemblages over the soft sediments that was attributed to the more mobile species inhabiting these areas.

Of fourteen targeted species, there was evidence that *Lutjanus erythropterus*, *Epinephelus coioides*, *Scomberomorus queenslandicus* and *Choerodon schoenleinii* and *Lethrinus laticaudis* were more abundant at Brook Shoal, which was protected from fishing in 2004.

The limited extent of rocky habitat at both Brook Shoal and Forty Foot Rock precluded extensive sampling effort, which means that more temporal effort must be employed to resolve any zoning effects.

(c) Cairns

Three paired sites with contrasting zoning were established in the Cairns region on deep-water shoals in the vicinity of emergent coral reefs. In general, all sites offered similar habitats except that the sites adjacent to Green Island lacked marine plants, possibly in response to lower light levels coincident with higher turbidity.

Cairns sites shared 140 fish species from diverse taxonomic and trophic functional groups. Fish assemblages had a strong association with either the sandy open bottom or the structurally and biologically diverse reef habitats, with more than twice the number of species associating with the complex habitat.

The distributions and relative abundances of twenty-four species of interest to fishers were not discriminated simply on the basis of protection because of interactions between location and habitat effects. *Plectropomus leopardus* and *Lethrinus lentjan* were more abundant at the protected site adjacent to Michaelmas reef and *Argyrops spinifer* at the protected site adjacent to Green Island, but thus far the effects of the rezoning have not had a large impact upon the fish communities of reefs near to Cairns.

Project 4.8.3 Evaluation of the Resiliency of Key Inter-reefal Fish Species

Project Leader and Host Organisation: Dr Colin Simpfendorfer, JCU.

The following is excerpted from Simpfendorfer *et al.* (2007a, b):

Rationale and Objectives

The project aims to develop a cross-shelf, inter-reef habitat model to capture the population dynamics and resource use of key inter-reef fish species that comprise the 'other reef fish' species group in the GBR line fishery.

The Project will significantly value-add to the data collections of the CRC Reef Effects of Line Fishing (ELF) research and build on the existing modelling simulation framework developed by the CRC Reef/JCU Fishing and Fisheries team and CSIRO to evaluate effects of fishing on the reef and inter-reef (i.e. shoals) fish resources of the GBR.

Recent changes to management of the fishery have resulted in the implementation of an Individual Transferable catch Quota (ITQ) system for the management of all harvested reef fish, where the 'other reef fish' comprise one third of the total quota; highlighting the importance of this ecological resource. However, very little is known about patterns and motivation in resource use or biology of species in this group, as historically most attention has focused on the main target species in the fishery (i.e. coral trout and red throat emperor). Consequently, there is a need to document historic and present resource use of 'other reef fish' to monitor shifts in targeting behaviour of fishers with the introduction of the new GBR Zoning Plan and ITQ system. There is also an urgent need to obtain basic biological parameters for at least the key species within the 'other reef fish' group to assess their vulnerability to increased resource use and alternate management arrangements.

This project will provide direct benefits to the management of reef fish stocks in Queensland. Specifically, this project will provide necessary information for the QDPI&F to assess the efficacy of the recently implemented multi-species quota in the Coral Reef Fin Fish Fishery (CRFFF), including information on shifts in harvest patterns and relative vulnerability of species in the 'other reef fish' group. Such information will assist QDPI&F in the development of an ecological risk assessment for 'other reef fish' and to comply with the requirements of the EPBC Act. Management agencies (QDPI&F and GBRMPA) and commercial, recreational and charter fishers will benefit from improved management of reef fish stocks, and sustainable harvests of reef fish.

The project has two key objectives:

- (a) Document the harvest patterns and resource use of 'other reef fish' species in the GBR, and identify key ecologically and economically important inter-reef fish species. A description of historic and current patterns in resource use of key inter-reef fish species will be obtained from all available data sources. An analysis of current and past market values and catch levels will identify key species in the 'other reef fish' group that may be subject to increased resource use in the future in response to the introduction of the GBR Zoning Plan and ITQ system.
- (b) Estimate biological parameters for key inter-reef fish species likely to render them vulnerable to over-harvest. Archived otolith and gonad samples collected during the ELF catch surveys for many species of "other reef fish" will be processed and analysed to estimate a range of critical population parameters that may indicate potential ecological resilience and vulnerability to resource use.

These parameters will also be key inputs into the inter-reef habitat model, including longevity, sexual pathway (i.e. gonochorism, protogyny) and size at maturity. Additional samples for species with low sample numbers will be supplemented from QDPI&F observer surveys, fishery-independent surveys and fleet sampling. CapReef and other community groups and fishing clubs will also be engaged to provide additional samples as required.

The full list of species (key species indicated by greyed areas) to be examined and the current number of samples available for analysis is:

Family	Genus	Species	Otolith samples	Gonad samples
Labridae	<i>Cheilinus</i>	<i>undulatus</i>	71	80
Labridae	<i>Choerodon</i>	<i>venustus</i>	20	20
Lethrinidae	<i>Lethrinus</i>	<i>atkinsoni</i>	1850	727
Lethrinidae	<i>Lethrinus</i>	<i>lentjan</i>	73	74
Lethrinidae	<i>Lethrinus</i>	<i>nebulosus</i>	494	328
Lethrinidae	<i>Lethrinus</i>	<i>olivaceus</i>	70	32
Lutjanidae	<i>Aprion</i>	<i>virescens</i>	108	80
Lutjanidae	<i>Lutjanus</i>	<i>adettii</i>	150	55
Lutjanidae	<i>Lutjanus</i>	<i>bohar</i>	976	279
Lutjanidae	<i>Lutjanus</i>	<i>carponotatus</i>	4183	
Lutjanidae	<i>Lutjanus</i>	<i>fulviflamma</i>	80	51
Lutjanidae	<i>Lutjanus</i>	<i>gibbus</i>	100	67
Lutjanidae	<i>Symphorus</i>	<i>nematophorus</i>	175	63

Family	Genus	Species	Otolith samples	Gonad samples
Serranidae	<i>Aethaloperca</i>	<i>roga</i>	4	3
Serranidae	<i>Anyperodon</i>	<i>leucogrammicus</i>	75	35
Serranidae	<i>Cephalopholis</i>	<i>argus</i>	139	85
Serranidae	<i>Cephalopholis</i>	<i>cyanostigma</i>	2656	727
Serranidae	<i>Cephalopholis</i>	<i>miniata</i>	34	13
Serranidae	<i>Cromileptes</i>	<i>altivelis</i>	128	150
Serranidae	<i>Epinephelus</i>	<i>cyanopodus</i>	81	73
Serranidae	<i>Epinephelus</i>	<i>fasciatus</i>	848	452
Serranidae	<i>Epinephelus</i>	<i>fuscoguttatus</i>	187	213
Serranidae	<i>Epinephelus</i>	<i>maculatus</i>	82	69
Serranidae	<i>Epinephelus</i>	<i>merra</i>	23	250
Serranidae	<i>Epinephelus</i>	<i>ongus</i>	805	434
Serranidae	<i>Epinephelus</i>	<i>polyphekadion</i>	130	101
Serranidae	<i>Epinephelus</i>	<i>quoyanus</i>	183	69
Serranidae	<i>Variola</i>	<i>albimarginata</i>	39	39
Serranidae	<i>Variola</i>	<i>louti</i>	134	99

Progress – Outputs

An article introducing this project was published in the December 2006 issue of the Fishing and Fisheries newsletter and a briefing report outlining the background, objectives and benefits of the project to stakeholders has been completed and circulated to key stakeholder groups.

A number of data sources were collated to characterise inter-reef fish resources on the GBR, including:

- CFISH data (commercial and charter fishing catch and effort data);
- RFISH data (recreational fishing catch and effort data);
- AIMS Baited Remote Underwater Video Station data; and
- Tagging data from SUNTAG.

These data were used to document the resource use of 'other reef fish' species in the GBR, and identify key ecologically and economically important inter-reef fish species. Harvest patterns from commercial, charter and recreational sectors of the key inter-reefal species (ie those that comprise the 'other species' quota group) captured in the CRFFF were assessed (Simpfendorfer *et al.* 2007a). The following is excerpted and summarized from the latter report.

Twenty-one species or species groups were identified as the key components of the 'other species' catch in the CRFFF, the focus for further investigation. There are substantial differences in harvest patterns between the commercial, charter and recreational sectors, with these sector differences being much greater than inter-annual differences within sectors. These differences were most likely due to fishing behaviour / access; species targeted, and gear and bait types.

In the commercial harvest, the total catch increased over the period from 1988 to 2002, peaking at ~4,000 tonnes annually, with a proportionally larger increase in the 'other species' group during this period (from approximately 15% to 35%). Substantial drops in the reported catch in all components were recorded in 2003 and 2004, returning to similar levels as those of 1988. The rise in annual catch from 1988 to 2002 corresponded to several major changes in the CRFFF, including the transition to a fishery dominated by the live export of coral trout (most boats participated in the 'live' fishery by 1995) and the development and implementation of a major management plan for the fishery in which a transition to a quota management system occurred. The management plan was implemented in late 2003, but the period for qualification for quota allocation occurred prior to this date, and may have changed the way in which fishermen reported their catch.

The reported commercial catch of 'other species' by region within the GBR followed a similar pattern to the overall catch, with a general increase in all regions from 1995 through 2002, followed by a substantial drop at the end of the time series. Prior to 1995, reported catches of the 'other species' group were relatively constant at around 400,000 kg. The increases during the second half of the 1990s were most pronounced in the Capricorn Bunker, Swains, Townsville and Cairns regions. Peak catches during the late 1990s and early 2000s were in the order of 1,400,000 kg, more than triple what they had been in early 1990s.

The annual charter catches of 'other species' increased slightly during the period that logbook data were available, with reported catches increasing from approximately 100,000 kg in the mid 1990s to 130,000 kg in the mid 2000s. The trends were similar across regions to the overall trend, with the Capricorn Bunker, Swains and Cairns regions providing the majority of the catch. The charter sector also underwent significant changes at the end of 2003 with the implementation of new management, and this may have resulted in the lower catch in 2004. The changes that affected the charter sector were mostly in relation to bag and trip limits for a variety of reef species.

Estimated recreational reef fish catches in 1997, 1999 and 2002 were relatively stable, at ~3,913 tonnes, 4,247 tonnes and 4,024 tonnes. Unlike the commercial fishery where 'other species' made up a relatively small component of the overall catch, in the recreational fishery they made up between 76% and 80%.

Comparison of reported catches by sector (commercial, charter, recreational) for years in which comparable data are available (ie years in which recreational surveys were conducted) show that recreational fishers take the majority of this species group. Given that there are no recreational data available outside of the period when commercial catch had dramatically increased prior to the finalisation of the new management, it seems likely that the current recreational proportion of the catch is even greater than the 75-80% indicated by the available data.

The species composition of the commercial sector of the CRFFF is dominated by coral trout and red throat emperor. The charter sector was less dominated by these species, although they were still the main components of the catch in most regions. These were less important in the recreational catch, contributing between 12-36% of the overall catch by region. Other species that were important included emperor (unspecified), red emperor, cod (unspecified), Moses perch and nannygai (unspecified).

For the majority of the twelve species or species-groups with at least one annual commercial catch of greater than 10,000 kg from 1998 to 2004, there was a general increasing trend in catch, especially after 1995, prior to a substantial decline from 2003. There were regional differences in the harvest patterns of many species, attributable to the biogeography of the fish themselves, different fishing practices and differences in reporting. Catch composition in

the Capricorn Bunker region is significantly different to the remainder, where there is a greater than 75% similarity among regions.

Project 4.8.4 Evaluation of the impacts from industry and community uses on inshore biodiversity

Project Leader and Host Organisation: Dr. Ashley Williams, JCU.

Rationale and Objectives

This project will directly address the key MTSRF goal of sustainable use and management of natural resources by providing an understanding of the current and potential industry and community uses of inshore biodiversity and natural resources with respect to ecological sustainability. It will also provide information and options to assist managers, industry and communities to optimise the use of biodiversity resources and minimise adverse impacts where they occur.

The project will evaluate the impacts on inshore biodiversity arising from industry and community uses. Fishing is the primary extractive use of inshore marine species by industry and the wider community, but currently the ecological, social and economic sustainability of this use and associated impacts on the inshore biodiversity is unknown.

There are five key objectives:

- (a) Characterise the industry and community use of inshore biodiversity.
- (b) Evaluate the effects of current management arrangements, in particular the GBR 2004 Zoning Plan, on industry and community use of inshore biodiversity resources.
- (c) Derive biological parameters, determine stock structure and identify critical habitats for key inshore species, in particular sharks, used by industry and the community. Biological samples from key species will be collected during observer surveys. Otoliths (fin fish), vertebrae (sharks) and gonads will be extracted and processed to provide estimates of age, sex and stage of sexual development. Additional features will be measured for sharks including clasper length and rigidity and presence of sperm in sperm ducts for males, and uterus width and presence of eggs or pups for females. These data will be used to estimate longevity, growth rates, mortality rates, size and age at first maturity and fecundity for key species or species groups. Fin clips from samples will be used for genetic analysis using mitochondrial and microsatellite markers to examine the stock structure and potential movements of key species, in particular sharks. Additional information on dietary preferences will be obtained where possible from stomach contents.
- (d) Evaluate the impacts of industry and community use on key inshore marine species, such as sharks, within the GBRWHA by identifying vulnerable species or species groups and assessing potential risks.
- (e) Assess potential strategies to mitigate the impacts of industry and community use on inshore resources within the GBRWHA.

In respect of the East Coast Inshore Finfish Fishery (ECIFF) for example:

“Most biological research on species caught in the ECIFF has focused on barramundi, with little attention given to the large number of other species in the fishery, particularly sharks and rays. Consequently, there is a significant gap in our knowledge of the biology of many species caught in the ECIFF. Although QDPI&F publish annual status reports for the ECIFF, there has been no detailed species-specific or regional analysis of the harvest patterns for the fishery since Williams (2002) reviewed the 1988-2000 commercial and recreational fishers catch data. There have been substantial changes to management arrangements for many fisheries in the GBRWHA since 2000 that may have impacted on the ECIFF. Consequently, the species-specific and regional harvest patterns for inshore species may have changed also. The objectives of this report were twofold: 1) to review the available catch data for the commercial, recreational and charter sectors of the ECIFF, with the aim to identify annual, seasonal and regional patterns. From this, we determine the inshore species of most importance to industry and the community and identify the knowledge gaps from current reporting practices; 2) to review available biological information on key fish, shark and ray species in the ECIFF. From this we identify knowledge gaps and suggest priority areas for future collection of biological information.” (Simpfendorfer *et al.* 2007b)

Progress – Outputs

The project has been discussed with key commercial fisher representatives, including the Queensland Seafood Industry Association. An article introducing the project has been published in the Fishing and Fisheries newsletter (December 2006) and circulated to over 2000 fishery end users in Queensland. A plan for the observer survey program and data sheets have been developed. Five regions (Far Northern, Northern, Central, Southern, Far Southern) were identified for dividing observer surveys spatially to encompass the broad range of inshore fisheries on the east coast. It is intended to focus observer surveys in each of these regions at different times of the year, depending on fishing activity.

A range of data and information have been collated to characterise the inshore fishery, including:

- CFISH – QDPI&F Commercial Fisheries Information System Program. This program provides estimates of commercial catch and effort data;
- RFISH – QDPI&F Recreational Fisheries Information System Program. This program provides estimates of recreational catch and effort data;
- QDPI&F: Assessment and Monitoring – Observer Program. This program uses onboard observers to collect fisheries dependent data from Queensland fisheries. Data from this program will be made available to this project.

Associated projects (non-MTSRF funded) include FRDC 2001-077 and FRDC 2002-064: “Northern Australian sharks and rays: The sustainability of target and bycatch fisheries, Phases 1 and 2”; and CapReef: A community monitoring program for the fisheries in the Capricorn region of the GBR.

Observer surveys will focus on each of these fisheries except the shark fishery, which is currently being covered by the QDPI&F observer program. Observer surveys may include the far southern region for the shark fishery, which is currently not covered by QDPI&F. The bait fishery will be a lower priority and only surveyed if time/funds permit.

In respect of coastal fisheries resource monitoring, preliminary results, primarily from Normanby River (Princess Charlotte Bay) and Trinity Inlet, indicate:

- Fifty-six coastal shark species and 25 ray species, with 36 shark species from fisheries landings, twelve species of which account for about 90% of landings;

- Similar mix of dominant species, with fewer species in inshore shallow water;
- Difficulty in distinguishing between *C. tilstoni* and *C. limbatus*. No morphological features (possibly fin shape) – need to use vertebrae counts or genetics.
- Most *S. lewini* are young of the year and most are <0.5m; these comprise a large part of the inshore and offshore catch, mostly in summer.
- Catch compositions and number of species encountered vary by locations and by different habitat types.
- *C. plumbeus* and *C. obscurus* included as species of interest but are very rare on the east coast. May be more in southern Queensland.
- Sawfish not recorded on east coast. Correct species delineation yet to be completed for some sawfish species. Green sawfish occur as far south as Sydney; high concern for east coast sawfish species.
- Species of concern: *S. lewini*, *C. leucas*, *R. taylori*, *R. australiae*, *R. typus*.
- *C. leucas* may be a good indicator species, due to its wide distribution across different habitats. However, this species is mainly estuarine/fresh water. *C. leucas* used to be a problem for netters in the Gulf, but now they don't appear to be an issue. It is thought this is due to FFV fishing.
- Should tie in with the shark control program for upper end sizes for age/growth studies. Need also to link with several UQ students already working on some of these shark species.
- Current field guides do not include many of the species identified in this study.
- Fourteen species of sharks and rays and nine species of finfish were identified as species for which information is lacking for Queensland east coast:

The following is excerpted from Williams (2007):

1. Status Reports

A status report has been completed that reviews the current knowledge of industry and community use of inshore GBR biodiversity and the existing biological information for inshore species. The report also highlights the current gaps in our knowledge and identifies potential mechanisms for filling these gaps.

2. Newsletter Article

An article introducing the project was published in the first issue (May 2007) of the MTSRF Program 8 newsletter.

3. Observer Survey Schedule

We commenced placing observers on board commercial net boats in April 2007 in an attempt to refine data collection techniques before the observer program for this project was scheduled to be fully underway. This process has highlighted the significant support for the project from commercial fishers and has allowed us to establish a substantial list of commercial fishers for future observer surveys.

It is not possible to develop a detailed schedule for the observer surveys due to the unpredictable nature of the commercial fishery. Therefore, observers will be placed on commercial fishers on an opportunistic basis. At the workshop held in September 2006, we divided the inshore fishery into five sub-fisheries (Barramundi, Mixed estuary, Grey mackerel, Shark and Bait) and the GBRWHA coastline into five regions (Far North, Cairns, Townsville,

Mackay and Capricorn; see Figure 1). We will attempt to spread the observer surveys across these sub-fisheries and regions as best as possible.

Data sheets have been developed for the collection of data from observer surveys. The data to be collected during observer surveys includes the following:

- Target species;
- Mesh type and size;
- Number and lengths of nets;
- Time spent fishing (time nets in water);
- Fishing location (Latitude and Longitude). Data will be reported at an aggregated level (e.g. 6' grids);
- Water depth;
- Description of habitat;
- Species composition of the harvest and bycatch;
- Lengths of all species caught; and
- Condition of discards.

Biological samples from key species will also be collected during observer surveys, which will allow the estimation of key biological parameters. Otoliths (scale fish), vertebrae (sharks) and gonads will be extracted and processed to provide estimates of age, sex and stage of sexual development. Additional features will be measured for sharks including clasper length and rigidity and presence of sperm in sperm ducts for males, and uterus width and presence of eggs or pups for females.

These data will be used to estimate longevity, growth rates, mortality rates, size and age at first maturity and fecundity for key species or species groups. Fin clips from samples will be used for genetic analysis using mitochondrial and microsatellite markers to examine the stock structure and potential movements of key species, in particular sharks. Additional information on dietary preferences will be obtained where possible from stomach contents.

4. Boat Ramp Survey Schedule

Researchers will survey recreational fishers at boat ramps between Cardwell and Bowen commencing in July 2007 and continuing until June 2009. Surveys will take place at the major boat ramps in this region and at peak fishing times (weekends and school holidays) to maximise the amount of data collected from each survey. Initially, surveys will be scheduled for one day every second weekend, but this will be reviewed within the first three months based on the quantity and quality of data collected. Data to be collected from each survey will include:

- Boat ramp location;
- Number of fishers;
- Home town;
- Fishing method;
- Time spent fishing;
- Fishing locations;
- Species composition of the kept and released catch; and
- Length of species kept.

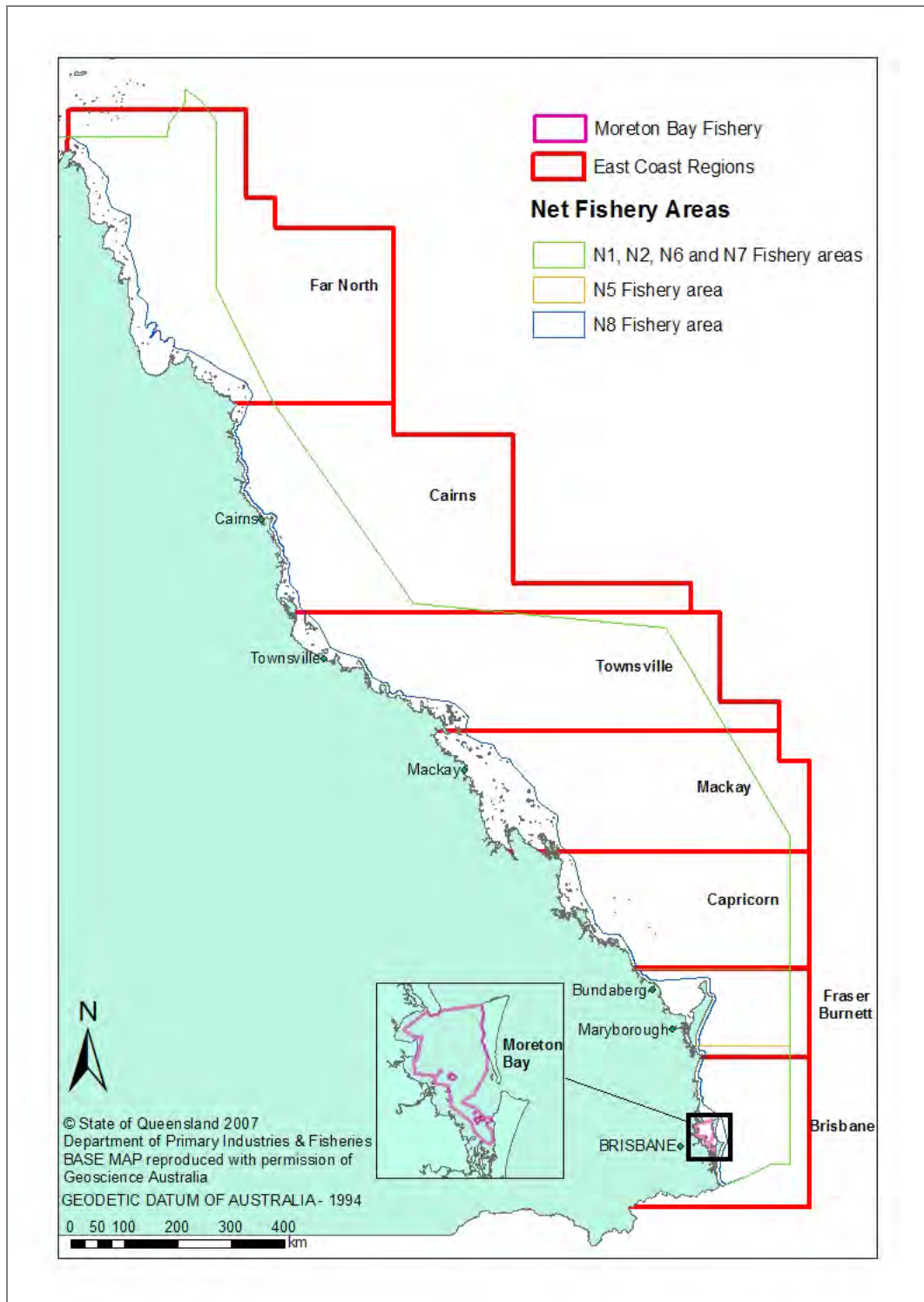


Figure 1: Map of Queensland east coast indicating regions identified for structuring observer surveys on commercial net boats.

5. Biological Sample Collection

The biological samples collected from observer surveys will be supplemented by samples of biological material from seafood processors. Biological samples from key species will be collected from a number of seafood processors in each of the five regions in the GBRWHA outlined in Figure 1. This will allow estimates of biological parameters of key species to be estimated on a regional basis. Where possible, samples will also be collected on a monthly basis to examine seasonality in reproductive development and validation of age estimates from marginal increment analysis.

The following is excerpted from Simpfendorfer *et al.* (2007b), a comprehensive review of recent harvest patterns and biology of key inshore species within the GBRWHA:

The results identify the major species groups that are harvested in the commercial and charter inshore fisheries and the spatial and temporal patterns of this harvest. This information provides a solid foundation for the continued field observer program being conducted as part of the MTSRF Project 4.8.4, and for targeted sampling of specific species for biological research. The report also highlights some of the areas where data are currently lacking or could be better understood. The major improvement that is required is better resolution in the identification of species. This is particularly an issue for sharks, as a large proportion of the total shark catch is reported as 'shark-unspecified'. Other species groups such as jewfish, trevally and whiting also need better resolution in species composition, although 'mackerel-unspecified' has noticeably decreased since 2003, suggesting better reporting to species level for that category.

The greatest challenge in analysing the data sets from each of the different sectors was in defining the inshore fishery. We have used criteria based on a combination of gear types, species and reporting catch grid sites to do this for the commercial and charter sectors in a logical manner. However, we were not able to reconcile differences in how the recreational catch data were derived to make sensible comparisons with the other sectors. Recording of catch in numbers means that weight estimates would need to be derived using an estimate of average harvest weight to compare against harvest from the other sectors. This is possible but would require further efforts in obtaining relevant data. Defining the inshore portion of the recreational sector is not possible with the current data, as location information for catches is not available. Species information could be used, but without location data to filter records, as is possible with both the charter and commercial records, estimates of catch would not be comparable. Estimates of average harvest weights would also enable better estimation of the charter catch, which is currently likely to be under-estimated due to the conversion factors used in converting catch from numbers to weight.

A single complete document of the history of the inshore fishery, describing any changes in management or known changes in fishing behaviour, would greatly assist in explaining the patterns in the data beyond what we have been able to do here. The MDS analysis of annual species composition for the commercial sector, for example, identifies three time distinct periods during the time series of available fisheries data.

Project 4.8.5 Incorporating Stakeholders and their Values, Knowledge and Aspirations in the Care and Development of the GBRMP

Project Leader and Host Organisation: Dr Stephen Sutton, JCU.

Rationale and Objectives

The overarching goal is to enhance capacity to incorporate social considerations in decision making, predict, evaluate and mitigate negative social impacts of changes in policy or resource condition, and facilitate the development of community partnerships and community engagement in research and management of the GBRWHA. This Project links to Project 4.8.6 and will benefit from the capacity building component of Theme 5 (Enhancing Delivery).

There are three specific objectives:

- (a) Understand and document the influence of the 2004 GBR Zoning Plan on use (tourism, recreation, and fishing) of the GBRWHA and users.
- (b) Develop, test, and parameterise a set of indicators that can be used to assess change in the socio-economic environment of GBRWHA use in response to policy or environmental changes, utilizing the framework currently being developed through the MTSRF Interim Funding program.
- (c) Explore and document the social values, attitudes, perceptions, knowledge, concerns and aspirations related to the GBRMP and its use, management, and conservation held by Marine Park users and the wider community.

Progress – Outputs

The GBR user survey and sampling plan was developed. Analysis of existing data and GBR user survey is underway. A report outlining preliminary findings and identified knowledge gaps has been produced (see below). The survey of recreational fishers has been designed and implemented, and the surveys for the other sectors (commercial fishing, charter fishing, and tourism) will be commenced. Briefings have been given to DEW, GBRMPA RACs, CapReef, and industry. A set of potential indicators has been developed.

The following is excerpted from Sutton (2007):

Preliminary findings of assessment of existing data of influences of Zoning Plan on the use of GBRWHA and users including identification of gaps in knowledge.

1. Commercial Fishers

a) Potential impacts

Numerous reports outlined potential impacts of the RAP on commercial fishers. General predictions of impacts from these reports include:

- While all industries operating in the Marine Park are potentially affected by the proposed changes in zoning, the commercial fishing industry is likely to be most affected. However, there may be long-term benefits to the commercial fishing industry in the GBR.
- Impacts of closures will affect approximately 10% of GVP, ranging from \$10.3 million and \$13.7 million annually. On a value-added basis (VA, ie the value over and above the costs of fishing effort) the value of the areas to be closed to fishing is estimated at about \$2.59 million per annum.
- The average potential impact per town is where approximately 10% in commercial fishing GVP, with individual estimated impacts ranging from 6.7% to 12.9%. However, in

some cases the estimated impact is small in absolute terms, or the commercial fishery has alternate sources of catch outside the GBRMP.

- The total GVP from fisheries constitutes less than one percent of the GBR catchment economy although the impacts on persons in the fishing industry adversely affected by changes are obviously of great significance to those individuals concerned. Commercial fishers are located right along the GBR coastal strip. Commercial fishing has strong historical links in coastal communities, and for many is considered a defining industry in the livelihood and character of the region. Fishing businesses tend to be small, owner-operated family businesses, often with a strong generational link to particular fishing grounds. A comprehensive understanding of social impacts would require targeted research at the community level, including surveys and community consultation.
- There is a range of possible responses from individual fishers to reductions in resource access. These responses for individuals include:
 - Changing their fishing location;
 - Increasing effort to maintain production;
 - Changing the nature of their operation, for example, shifting operations to higher value outputs such as offered through the live fish trade;
 - Leaving the fishing industry altogether.
- Previous studies of social impacts in fisheries have pointed to the clear preference shown by fishers to remain in the industry, even in the face of declining returns. Increased pressures on business viability and reduced disposable income are likely to be felt both at the family and the broader community level. If individuals and their families leave the industry, and possibly the region, this will have impacts on diversity and social capital, potentially making the region more reliant on remaining industries and more vulnerable to short-term downturns in remaining industries. The strong self-identification of fishers with their industry also points to the potential for increased feelings of alienation if commercial fishing options are no longer available. Responses such as shifting effort can involve increased travel and running costs, and potentially lead to greater pressure on remaining areas and greater competition with commercial and recreational fishers for access.
- The extent to which the proposed zoning plan will impact on some fishers will vary depending on:
 - The percentage of the fishery being located in the new protected zones;
 - The sustainability of fisheries under existing fisheries management arrangements and industry practices;
 - The availability of alternative fishing grounds;
 - Search costs associated with locating suitable new fishing grounds;
 - The mobility of fishers;
 - Impact of changes in patterns of fishing effort in those areas where fishing activity may be displaced;
 - Spillover and recruitment benefits from protected areas;
 - Dependence of fishers on GBR fisheries income compared with other sources of income;
 - Recent Queensland fishery management changes;
 - Age of fishers;
 - Number of dependents;
 - Diversity and robustness of the local economy.
- There are potential social impacts on those fishing communities with high dependency on the GBRMP. Changes to resource access can be expected to have the greatest

potential social impact for those thirteen towns that rely solely or heavily on the GBRMP for their commercial fishing activity (based on information from Fenton and Marshall 2001). Factors which will influence the level of impact on individuals and specific fisheries are:

- Their capacity to shift effort;
 - Ability to change the nature of their fishing operations; or
 - Ability to take other mitigating action; and
 - Their individual resilience to change.
- These factors were considered through a mobility index based on capacity to shift efforts and a family resiliency measure (which included socio-demographic factors such as age and family structure, income, housing and employment, and education) to examine the ability of fishing families operating in the GBRMP to manage changes in the level of access to fisheries resources.
 - When comparing the mobility of fisheries using a Grid Mobility Index, 10 of the 20 Town Resource Clusters had comparably high levels of mobility, indicating greater capacity to offset potential impacts to production through changes to fishing locations. Those with higher mobility also tended to be those with higher absolute gross values of production, consistent with greater production reflected in increased area of operation. Those Town Resource Clusters with fisheries characterised as having low mobility, and which also had a high level of activity in the Marine Park for their commercial fishing activities, were Airlie Beach, Ayr, Bowen, Cooktown, Innisfail, Lucinda, Port Douglas and Yeppoon.
 - Regarding the family resilience measure, fishing families least resilient to change are those in Bowen, Cooktown, Maryborough and Yeppoon. However, with the exception of Bowen, these towns have a low level of employment in agriculture, fisheries and forestry and account for only a very small amount of the total value of fishing in the Marine Park.
 - Communities also vary in terms of their resilience to change depending on their social and economic characteristics and this will influence the way they respond to changes in the value of fishery production. A regional-based index of resilience to change (comprising variables such as housing, age, labour force, occupation, weekly incomes, and education, family and Indigenous persons) was used to assess likely regional impacts.
 - Of the regions and communities identified as less resilient, potential impacts for Bowen appear higher than for other areas. Within other regions, such as Yeppoon, there may be substantial impacts on individuals or particular fisheries, due to differing dependence on rezoned areas.
 - However, the impact on individuals and communities cannot be quantified without further analysis.
 - The level of fishing activity is likely to be unaffected by the Zoning Plan, only the catch rates. This may affect profitability.
 - Analysis at the Town Resource Cluster level does not allow for impacts on individual fishers to be fully assessed. A township's commercial fishing activity may comprise a range of fisheries with different spatial coverage and hence potentially variable zoning impacts, different characteristics in terms of equipment and infrastructure and different options in terms of mobility.

b) *What is known?*

- Of 583 tenders received by QRAA, 114 licences plus four additional separate RQ endorsements with quota attached were purchased at a cost of \$31,849,689 (QSIA 2004).
- Effort reduction targets were met for the whole of the marine park, but there is some variability in the amount of effort purchased at the regional level relative to the impact of the rezoning. Some regions had a lot more buy-outs than was targeted for, others less than the target (QSIA 2004).

c) *Knowledge gaps*

- What is the cost of GBRCMP? Most reports seem to think inshore fisheries will feel minimal impact from RAP, but the Coast Marine Park was not considered.
- What is the effect of yellow zones?
- There is a lot of information on potential impacts (positive and negative), but no investigation of actual impacts.
- It is unknown how related changes in numbers of licenses are to the RAP.
- There was no analysis of buy-outs within the line fishery specifically due to confounding issue of quota introduction – the effect of RAP needs assessing by talking to fishers.
- Don't know how many fishers wanted to be bought out but were unsuccessful in their tenders. Some of these may have later sold their licences – need to talk to these fishers.
- Information on which most pre-RAP reports were based on is from Fenton and Marshall 2001. No post-RAP information to the same level or collecting similar information.
- Buy-out information is for business address, not fishing location. Need to investigate effort reductions in actual fished areas, including whether there is now effort concentration in some areas and how that affects fishers.

2. Charter Fishers

a) *Potential impacts*

Hand (2003) provided a report by PDP Australia to estimate the potential impacts of RAP prior to implementation. They found:

- The annual GVP of the charter and game fishers that operate in the Marine Park is approximately \$50 million. Revised Zoning Plan closes 13% of sites that charter fishers may currently access, and covers 17% of days fished prior to RAP implementation.
- They suggested the charter fishery had a high degree of adaptability to RAP, based on:
 - Offshore and coral reef components of the charter fishery are highly mobile and can use alternative areas if areas they now fish are zoned green;
 - A significant amount of income is derived from non-fishing passengers - for example, some boats may be chartered for dive trips;
 - Charter boats operating in areas adjoining protected areas will, over time, experience positive spillovers as abundance of target species is expected to increase in these areas;
 - Most coastal and estuarine charters will not be affected by the zoning proposed in the Zoning Plan Because rivers, creeks and intertidal areas are not in the Marine Park; and
 - Management changes in the recreational coral reef finfish and Spanish mackerel fisheries introduced by the Queensland Government.

- The components of the charter fishery that operate in the Marine Park with the least potential to adjust their local operations are inshore boats from coastal communities that target local fishing spots and some single-day reef fishing charters that can reach inshore reefs.
- Most of the potential affect of the Zoning Plan is in the offshore Gladstone/Mackay area in the Capricorn Bunker Group of Reefs and Swains Reef complex, and some specific localities in the Whitsunday area and reefs off Cairns.

b) *What is known?*

- Number of charter fishing permits in years pre- and post-RAP are available. We have requested this information from QDPI&F but have not yet received it.

c) *Knowledge gaps*

- How do the expected changes in fishing days and area compare to actual changes? Have fishers been able to successfully move operations from previously fished areas that are no in no-take zones?
- How mobile are charter fishers? This will affect the level of impact.
- What is the impact on inshore charter fishers from the GBRCMP?
- If there is a change in permit number, how is this related to RAP? Need to talk to the fishers, including those that left the industry post-RAP.
- What are fishers' attitudes towards RAP?

3. Recreational Fishers

a) *Potential impacts*

GBRMPA (2003) and Hand (2003) provided an estimate of potential impacts of RAP on recreational fishers. They found:

- Based on three sets of data (Suntag, boat ramp information and RFISH data), all indicate that the revised Zoning Plan will have minimal impact on recreational fishers even if anecdotal information suggests that these data are slight underestimates.
- GBRMPA has estimated that new areas within the Marine Park where recreational fishing would not be permitted under the Zoning Plan are located where approximately 4% of recreational fishing takes place. Hence negative impacts on recreational fishers are expected to be low.
 - The Sunfish tag data consisting of point data – In the proposed Zoning Plan, Marine National Park, Preservation and Scientific Research zones are also closed to recreational fishing. There are 485 fishing locations representing approximately 1% of total fishing locations within these zones. From these data, it may be concluded that the proposed Zoning Plan will have minimal impact on recreational fishers.
 - Boat ramp point data from Queensland Transport (QT) and Surf Life Saving Club (SLSC) Association showed some 169 km² (or 4%) of closed zones are situated within 5 km of Queensland Transport boat ramps. Assuming the location of recreational fishing activity is linked to proximity to boat ramps, these data suggest that under the Zoning Plan, green zones would be placed where less than 5% of recreational fishing activity occurs. While use of boat ramp data in this way is an imprecise means of estimating impacts on recreational fishing, it indicates likely low impact given that 80% of recreational fishing vessels are under 5.1 m in length, and therefore unlikely to travel great distances from shore. The National Recreational Fishing Survey [2003] also showed that only 6% of recreational fishing effort in

Queensland occurred more than five kilometres from shore, including fishing effort originating from communities adjacent to the Marine Park.

- GBRMPA concluded that less than one in ten fishing spots in the Marine Park may be unavailable for fishing and that, regardless, most of the fishing happens in creeks and estuaries outside the GBRMP.
- The main recreational fishing areas affected by the Zoning Plan are inshore areas in the Rockhampton, Whitsunday, Townsville, Innisfail and Cairns regions, and reefal and shoal areas in the Capricornia Bunker reefs area off Gladstone, Townsville and Cairns.
- Conversely, in Conservation Park Zones (Yellow Zones) recreational listing will still be permitted (subject to restrictions) but only limited commercial fishing will be permitted. Some recreational fishers may therefore experience less conflict with other fishers and therefore may realise benefits from introduction of the Zoning Plan. Further, with less fishing effort in Yellow Zones, some recreational fishers may experience higher quality fishing experiences due to the possibility of increased abundance of target species.
- The number and location of registered vessels is a good indicator of the importance of recreational fishing to regional economies.

b) What is known?

More data exist for the recreational fishing sector than for the other sectors. Recreational fishing data come primarily from the Queensland Government's RFISH surveys, and from two recent social surveys of recreational fishers in Queensland funded by the CRC Reef Research Centre. One of these CRC Reef surveys was conducted shortly before RAP was implemented, the other is currently being conducted in conjunction with the CapReef project to assess the social impacts of RAP on recreational fishers. Preliminary results of that survey indicate that the majority (70%) of recreational fishers in the GBR area support the idea of rezoning the GBR and that most (75%) believe the new zoning plan will help maintain the GBR in healthy condition. Approximately 50% of recreational fishers reported experiencing no impacts from the rezoning; 25% reported experiencing negative impacts, and 25% reported experiencing positive impacts. Although support for the rezoning plan was high among recreational fishers, only 40% believed that the concerns of recreational fishers were adequately considered in the rezoning process.

Vessel Registration Levels for GBR Coastal Communities is available on the web at: http://www.gbrmpa.gov.au/corp_site/key_issues/tourism/management/gbr_visitation/rec_vessels. This site shows a steady increase in the total number of registered motor boats since 2001, with no obvious change in July 2004 when RAP was introduced (Figure 1).

However, when the graphs for vessels over five metres are examined, there is a sharper increase in number of registered vessels since RAP introduction (though not necessary immediately after RAP introduction) particularly for the larger boats (over 8 m; Figure 2).

c) Knowledge gaps

- What amount of fishing area is affected by the mirroring GBRCMP?
- What is the actual change in fishing area? Has this affected fishing activity?
- What are the changes in recreational fishing effort distribution and other activity patterns due to new zoning?
- Have there been positive effects noticed from the yellow zones?
- Is the increase in larger motorboat registration related to RAP or other factors? Are these motorboats for fishing?
- What is the level of recreational fishing participation in Queensland post-RAP (awaiting RFISH results)? Is this related to RAP?

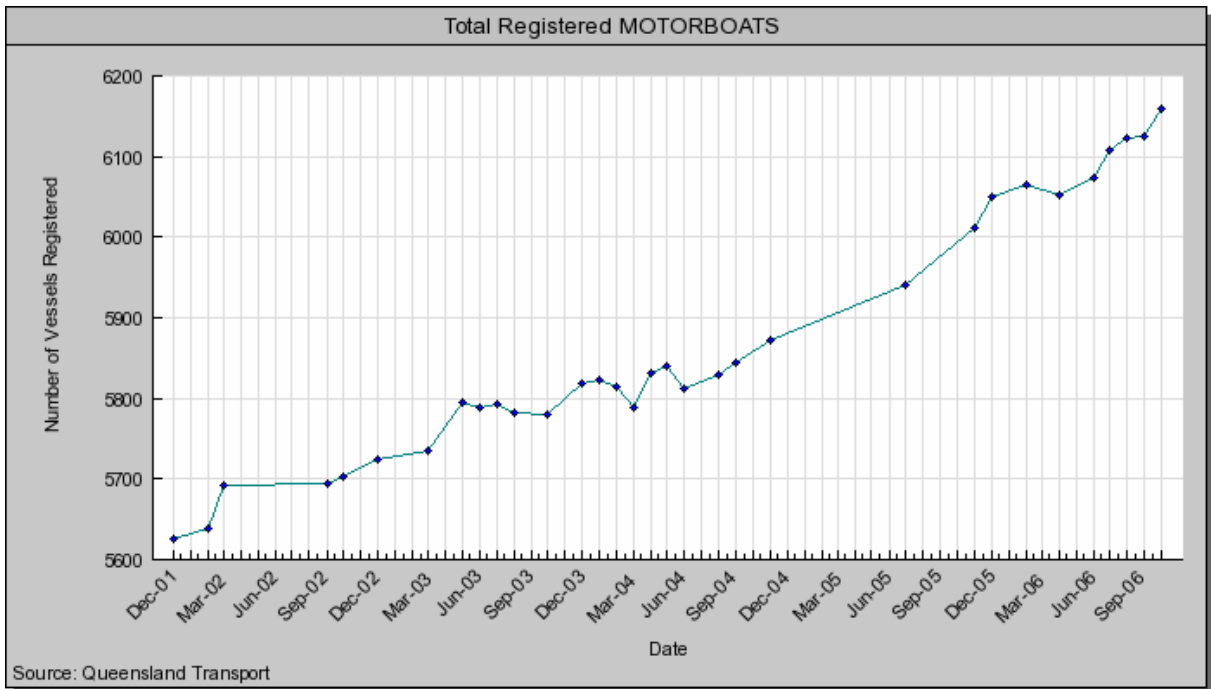


Figure 1: Total registered motorboats registered within GBR coastal communities from December 2001 to September 2006.

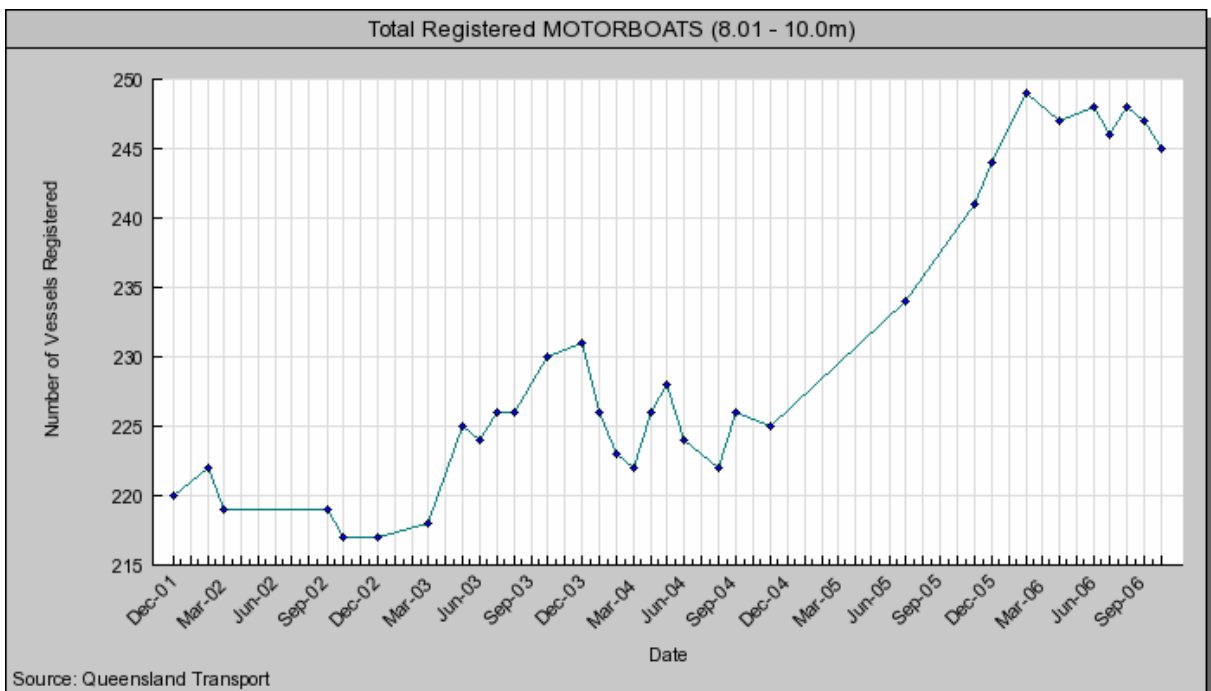


Figure 2: Number of registered motorboats, eight to ten metres in length, registered within GBR coastal communities from December 2001 to September 2006.

4. Tourism Operators

a) *Potential impacts*

GBRMPA (2003) and Hand (2003) provided an estimate of potential impacts of RAP on the tourism industry. They found:

- Tourism, the third most important industry in the GBR catchment area, was worth well over \$4,000 million GVP and will benefit from implementation of the RAP.
- A good indicator of the level of tourism in the Marine Park is the number of visitors using commercial reef-tour operators, which, in 2001-2002, was 1.8 million.
- The health of the GBR afforded by the Representative Areas Program will encourage domestic and international visitors to choose the Marine Park over other destinations. Given the increased attractiveness of a well-maintained reef ecosystem when many other reefs around the world are suffering from degradation, visitor numbers to the GBR are likely to increase. Even a minor increase in visitor numbers, such as 5%, would represent a considerable boost to the economic impact of the tourism sector in the region.
- Overall, GBR catchment tourism is forecast to grow by 15.4% over the period 2001-2010 and 30.5% over the period 2010-2020, giving total forecast growth for 2001-2020 of 50.6%.

b) *What is known?*

Permit numbers from GBRMPA:

- Table 1 shows the number of new permits granted in recent years. While there is a slight increase in the number of permits granted, this is variable year-to-year.
- The current number of valid permits is 1054, of which 711 are allowed to fish.

Visitor numbers from GBRMPA EMC data:

- There was a slight increase in visitor number for the 2003 (of which half was post-RAP) and 2004 calendar years. This decreased again in 2006, but this may be due to incomplete data entry (Gillian Goby, GBRMPA, pers. comm.; Figure 3).

Table 1: The number of new GBRMPA tourism operator permits granted in each financial year, 2003/2004 to (year to date) 2006/2007.

Financial Year	Tourism Permits	Permits involving fishing
2003/2004	244	154
2004/2005	274	173
2005/2006	256	165
2006/2007 (ytd)	282	205

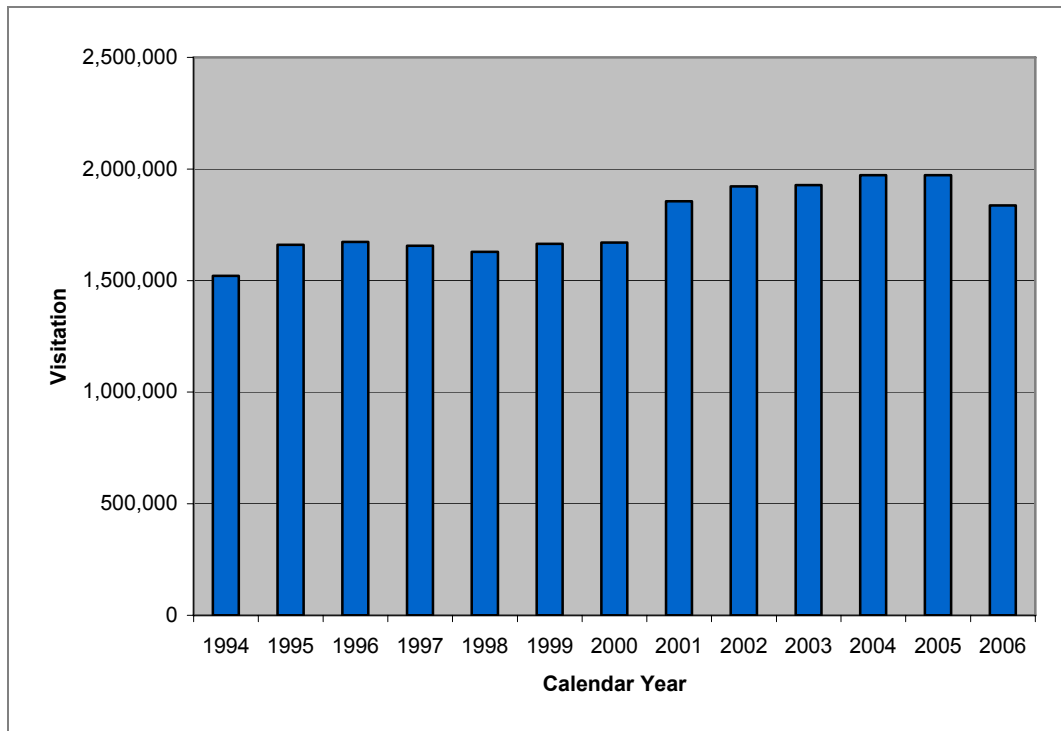


Figure 3: Reef-wide visitation to the GBR by year from 1994 to 2006 (from GBRMPA EMC data).

c) *Knowledge gaps*

- Are changes in visitor number significant? Have changes in visitor number been related to RAP? Need to collaborate with Bruce Prideaux to determine visitors' reasons for visiting the GBR.
- Have operators changed visiting areas or any of their practices as a result of RAP?
- What are operators' attitudes to RAP?

GBR User Survey

As part of MTSRF Project 4.8.5, we are conducting face-to-face interviews with a sample of recreational fishers, charter fishers, commercial fishers, and marine tourism operators to measure and document the positive and negative effects of the RAP on their use of the Marine Park. These surveys are scheduled to be conducted from June 2007 through to June 2008. Details on the design and implementation of these surveys are as follows:

Recreational Fishers

To date, we have designed, tested, and implemented the survey of recreational fishers. The primary purpose of this survey is to collect information about changes in fishing activity due to the RAP. This builds on the extensive attitudinal data already collected from the recreational sector as part of a previous CRC Reef funded project. Survey participants are being identified through contacts with fishing clubs and tackle shops. We will shortly be trialling a boat-ramp survey in the Townsville area to determine whether we can recruit survey participants in this way. The survey is currently underway in Townsville and Rockhampton (in conjunction with CapReef) with plans to expand to Cairns and Mackay-Whitsundays before the end of 2007.

Commercial Fishers, Charter Fishers and Tourism Operators

A face-to-face survey of commercial fishers, charter fishers, and tourism operators is being developed based on the recreational fishing survey. Fewer pre-existing data are available for the commercial fishers, charter fishers and tourism operators; therefore it is necessary to expand the scope of the survey for these sectors to collect additional information, especially economic data. These additional questions are being formulated in consultation with representatives of each sector. For the tourism operator sector, we will link with Project 4.8.6 to the greatest extent possible to ensure that data collection efforts are not duplicated.

We have confirmed that a list of current licensed commercial and charter fishers will be made available to us by QDPI&F. This list will be used as a sampling frame from which we will select a random sample of fishers to interview. Tourism operators will be identified through AMPTO and in consultation with MTSRF Project 4.8.6.

Project 4.8.6 Analysis of Recreational and Tourism Use and Impact on the GBR for Managing Sustainable Tourism

Project Leader and Host Organisation: Professor Bruce Prideaux, JCU.

Rationale and Objectives

This project was designed to meet the MTSRF goal of “understanding the current and potential industry and community uses of biodiversity and natural resources with respect to ecological, social and economic sustainability; and providing information and options to assist North Queensland managers, industries and communities to optimise the use of biodiversity resources and minimise adverse impacts of use where they occur”.

The project includes determination of the social values of key marine species, particularly large fish around tourist facilities, and an economic analysis of the value of no-take zones to tourism in the GBR. The economic analysis will be deferred until adequate capability has been developed in North Queensland through a CSIRO/JCU cooperative arrangement. In addition, the program will identify annual visitor usage patterns of the GBR to enable the identification of key trends and drivers of visitor patterns and economic impacts of visitation. Impacts of tourism and visitation to critical reef sites and sustainable levels of visitation to these sites will be assessed. This project will provide links with the inshore biodiversity

project (Project 4.8.7) on Irukandii movement and habits, and the risk of human encounters to Irukandji and other marine stingers that may influence tourist visitation. The project is also linked to Project 4.8.5, Objective (a) and (b): Understanding and documenting the influence of the 2004 GBR Zoning Plan on use (tourism, recreation, and fishing) of the GBRWHA and users.

This project consists of four key objectives:

- (a) Identify relative social and economic values of key marine species, particularly large fish around tourist facilities;
- (b) Undertake a bio-economic analysis of the 2004 GBR Zoning Plan to determine the value of no-take zones to tourism in the GBR. This component will be deferred until adequate capability has been developed in North Queensland through a CSIRO/JCU cooperative arrangement;
- (c) Identify impacts of tourist and visitation to key reef sites and sustainable levels of visitation to these sites; and
- (d) Identification of key trends and drivers of visitor patterns, including assessment of the economic impacts of visitation and comparison of the GBR with international reef tourist attractions.

Progress – Outputs

As part of Objective (d), an extensive literature review was undertaken in order to identify existing research. A reef tourism survey questionnaire was designed and trialed to assess tourist expectations and satisfaction levels. The questionnaires were distributed in a systematic, representative and manageable way in five regions of the GBR – Port Douglas and Cairns, Townsville, Airlie Beach and the Southern Region/Capricorn coast. Boat crews noted environmental conditions on the day that the survey was distributed and date of distribution. Operators were encouraged to distribute the surveys over a number of days and in varying conditions, to allow effects such as rough seas (and seasickness) and/or rainy days to be analysed. This information was cross-referenced with Bureau of Meteorology data. The questionnaires assessed socio-demographic characteristics of reef tourists, their motivations, activities, competing destinations, expectations and satisfaction.

The following is excerpted / summarised from the MTSRF Milestone Report for February 2007 by Dr Ali Coghlan and Prof Bruce Prideaux of James Cook University. The return of 492 completed surveys from ten operators across five regions focused on socio-demographic characteristics of reef tourists, their motivations, activities, competing destinations, expectations and satisfaction. Initial results indicate:

- A higher percentage of domestic tourists and local residents' use of reef cruises than indicated in previous research undertaken by Moscardo.
- A low percentage of certified divers and introduction divers. SCUBA diving was mentioned by only 39% (of which more than half were uncertified divers) of respondents when asked what activities they had undertaken during their reef experience. The destination imagery of the Great Barrier Reef as a snorkelling or resort diving destination is supported through content analyses of diving and travel magazines.
- The emergence of helicopter tours and glass bottom boats as popular means to experience the reef. Both were frequently cited as the best feature of the reef tour. Seasickness was the most common worst experience mentioned by respondents.
- Fifty-five percent of respondents indicated that they were not aware whether their tour operator was eco-certified, and no respondents said that they had chosen their tour operator based on environmental values.

- Satisfaction ratings remained high (8.46/10) across all operators and the majority of respondents felt that their expectations of the reef and the tour had been met.

The following text and figures, excerpted / summarised from the first MTSRF Reef Tourism Annual Report, prepared by Prideaux and Coghlan, demonstrated important similarities and differences in tourism between regions and throughout the year. The results are based on a sample size of 2,408 respondents, collected by ten operators throughout three regions, Tropical North Queensland, Townsville and the Whitsundays.

1. Respondents' socio-demographic characteristics

Origin of respondents: A large proportion of respondents are domestic visitors, although this is highly seasonal and varies between 33% and 49% according to the season as well as the region (Figure 1). Domestic rates of visitation were highest in Quarters 3 and 4 and lowest between November 2006 and April 2007. Within the domestic respondents, Queenslanders made up the largest group, with 36.25% in the last quarter and 35% overall. Other large groups of domestic respondents include respondents from New South Wales (NSW) and the Australian Capital Territory (ACT) with 32% in the last quarter and 34% overall for the year, and Victorians (21.5% and 24% overall).

Regional variations also exist with a higher proportion of domestic visitors in Townsville and the Whitsundays, than in Cairns and Port Douglas. In the case of Townsville, 51.8% of respondents were from Queensland, and 25% came from NSW, whereas the Whitsundays had a total of 39% of respondents who came from Queensland, 34.5% from NSW and 18.3% from Victoria. This pattern of a higher percentage of domestic visitors to the south remains constant throughout the year.

Employment: In terms of employment, the most common responses were *professionals* and *students*. The overall annual percentages of the more common occupations were as follows: *professional*, 26%, *student*, 16.6%, *retired*, 9.5%, *management*, 8%, and *self-employed*, 8%. Again, there are seasonality effects with retirees peaking during the summer months (not traditionally the grey nomad season) and students peaking during the winter, or the North Hemisphere summer (holiday) months (Figure 2). There are also regional differences, with a larger student sample in the Whitsundays, more retirees in Cairns and Port Douglas, and finally, more public servants in Townsville.

Age of respondents: The age of respondents remained steady over the year, with a strong tendency towards younger respondents, in the 20-29 year age bracket. Cumulatively, those within the 20-49 year age group made up 68% of the annual sample, showing little variation across quarters and regions. Again, as with the occupation of respondents, we find that there are certain differences between the international (which included a higher percentage of students and retirees) and the domestic market. Table 1 illustrates these differences, most notably the prevalence of 20-29 year olds in the international market, and respondents in the 40-49 year age bracket in the domestic market.

Table 1: Comparison of domestic and international market age groups.

Age Group	Domestic Respondents	International Respondents
< 20 years	8.0%	8.1%
20-29	29.2%	35.3%
30-39	19.9%	18.2%
40-49	19.6%	13.7%
50-59	14.9%	12.3%
60-65	4.1%	5.7%
over 65	4.2%	6.6%

2. Respondents' travel behaviour

Travel party: The majority of respondents were travelling as a couple (38%), a pattern that stayed constant throughout the year. Quarters 2 and 3 saw more respondents travelling with friends than either Quarter 1 or Quarter 4, a pattern similar to the number of student respondents across quarters (Figure 1). A comparison of international and domestic markets reveals that international respondents were far more likely to be traveling alone than domestic respondents.

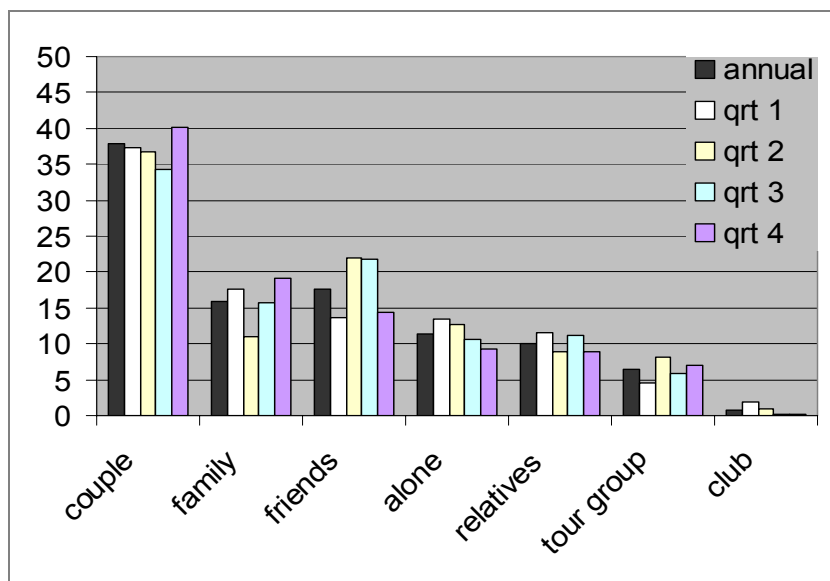


Figure 1: Travel party of survey respondents.

Previous visits and length of stay: For 72% of respondents, this was their first visit to the region. This figure is high and stays relatively constant throughout the year, with 84% of respondents on first visits in the second quarter and 69% first time visitors to the region in the fourth quarter. Repeat visitation was much higher amongst domestic respondents, accounting for 72% of repeat visitors. Of note, however, is the trend in Townsville, which has a much higher rate of revisitation (only 43.5% were on their first visit).

Accommodation and transport: Patterns of accommodation also varied between sectors although remained relatively constant across the quarters. The Whitsundays and Townsville showed the greatest variation, in the first case highlighting the high proportion of backpacker respondents, and in the latter, the strong VFR ('visiting friends and relatives') market. Seasonal patterns in the importance of holiday apartments correspond to peaks of domestic visitors during school holidays.

Patterns of transport were similar, with regional differences in the Whitsundays and Townsville, again revealing the differences in market preferences. Many backpackers were travelling through the Whitsundays by coach, whilst the VFR market in Townsville was more likely to use their private vehicles to travel to their destination. Again, there are few seasonal differences, particularly for arrivals by plane and bus and coach, although the use of private vehicles does show some peaks in the later quarters in both Townsville and the Whitsundays.

Last holiday location and alternative holiday destinations: The most popular single destinations given in response to "Where did you spend your last holiday?" are provided in Table 2 below.

Table 2: Respondents' last holiday location and alternative destinations considered.

Last holiday location of respondents	
France	3.6%
Gold Coast	3.6%
Spain	3.4%
Thailand	3.4%
New Zealand	3.4%
USA	3.2%
Alternative destinations considered	
New Zealand	5.3%
Sydney	5.3%
Cairns	4.6%
Fiji	3.8%
The Whitsundays	3.6%
Gold Coast	3.3%
Thailand	3.2%

Travel Motivations: The most important motivations (measured on a scale of 1 = not at all important, to 5 = very important) for visiting the region remain constant across regions and seasons. These include visiting the GBR (mean = 4.66/5.0), snorkeling and diving (4.14), enjoying the natural environment (3.88), resting and relaxing (3.87), and enjoying the climate (3.77).

Information sources: The most popular sources of information on the region visited were friends and relatives, followed by guidebooks and the internet (Figure 2). Few variations to this pattern exist across regions or quarters, except in the case of advertisements on TV and radio which substantially increased in the first quarter (in the six months following Tropical Cyclone *Larry*) in all the locations except Townsville, before decreasing again in the next quarters. It is also interesting to note that travel agents did not strongly influence destination selection.

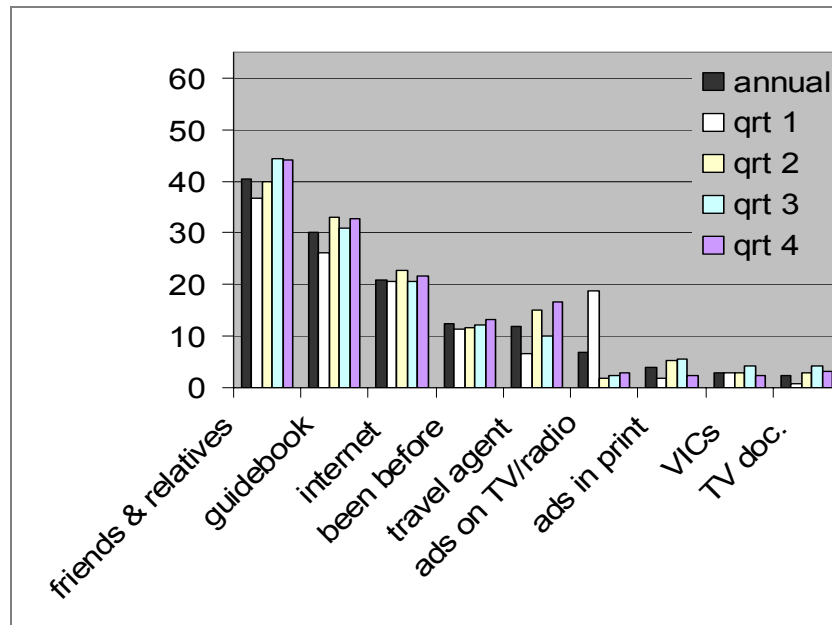


Figure 2: Information sources about the holiday destination used by respondents.

There were some slight variations in the use of information sources between domestic and international respondents, the former being more likely to rely on information gained from previous trips to the region (21.6% of domestic respondents and only 6.1% of international respondents, whilst the latter were more likely to use guidebooks (39.5% of international respondents used guidebooks, and only 15.8% of domestic respondents). Information from friends and relatives was equally important for both market segments (40%).

3. Respondents' reef experiences and satisfaction:

Previous visits to the reef: When asked if this was their first visit to the reef, the majority of respondents said yes; this was greatest in the summer months, when 73.2% said that this was first visit to the GBR and least in the winter when 69% had not been to the GBR before.

Choice of operator: The most common reasons for choosing a reef tour operator remained relatively constant throughout the year, with agents, both at respondents' accommodation and travel/tour agents being the most common reason for choosing an operator. Word of mouth was the second most important reason, whereas availability was more important than price, a trend that may become more important if length of stay continues to decrease, particularly in Townsville and the Whitsundays which have fewer operators that go to the reef than in the (combined) Cairns and Port Douglas region. In both of the former places, availability tends to be one of the more important factors in operator choice (28% and 25% respectively).

In general, domestic respondents also tended to choose operators based on their availability (16%) than international respondents (7.3%), who instead would rely on the recommendation of an agent (22.3% compared to 12.2%). No other noticeable differences existed between domestic and international respondents.

Diving Profile: The results show that when asked if they planned to dive the reef, only 36.5% of respondents said yes. This figure varied significantly between nationalities, with Europeans being the most likely to plan to dive (Figure 10). Of the respondents that did plan to dive, 31% of these respondents had no previous diving experience, 26.1% had one to four dives (i.e. were not certified divers), 12% had five to 10 dives and only 28% had more than 10 dives. This trend is repeated throughout the year, whilst Townsville and the Whitsundays have lower percentages of divers than Cairns and Port Douglas.

Visits to other reefs: Over 44% of the respondents said they had visited other coral reefs before coming to the Great Barrier Reef. In the last quarter, this figure went up to 58% in Cairns and Port Douglas. The most commonly cited alternative destinations were South East Asia, 31.2%, the Indian Ocean, 21%, the South Pacific Reefs, 19.8%, Micronesia, 17.5% and other Australian reefs². There were no clear patterns across different seasons and locations.

Activities undertaken: The most common activities undertaken during the trip are shown in Table 3.

Table 3: Activities undertaken by reef tourists during their trip.

Activity	Annual	Quarter 4	Quarter 3	Quarter 2	Quarter 1	Cairns/ Port Douglas	Townsville	Whitsundays
Snorkeling	75.3%	79.0%	73.0%	75.0%	75.5%	72.5%	87%	79%
Swimming	46.2%	50.0%	40.0%	47.0%	44.0%	47%	55%	53.5%
View marine animals	39.0%	44.5%	45.0%	46.0%	24.5%	37.5%	35.5%	55%
Glass bottom boat tour	43.6%	44.5%	40.0%	45.5%	43.0%	42%	62%	65%

* Only those operators who offer a glassbottom boat or semisubmersible tour were included in this figure.

Satisfaction levels and recommendations: Satisfaction ratings (measured on a scale of 1 to 10) and the mean satisfaction score was 8.44. This score increased over the quarters from 8.41 in the first quarter to 8.58 in the last quarter. This pattern was repeated in Cairns / Port Douglas, as well as Townsville where the satisfaction score reached 8.75 in the last quarter, and 8.6 in the Whitsundays. When asked if the trip met their expectations, over 90% said that the reef at least somewhat met their expectations, and 94% said that the trip at least somewhat met their expectations. In addition, 86% of respondents felt that they got value for money, and 92% said that they would recommend the trip to others. Interestingly, a significant drop in satisfaction was recorded when more respondents reported having experienced bad weather in response to the question about their worst experience during the trip (7.16/10 vs. 8.93/10). In addition, value for money, and recommendation rates also dropped and fewer respondents felt that the trip met their expectations in poor weather conditions, particularly in the third quarter, which is also when the travel motivation to enjoy the climate was highest.

² Other Australian reefs were sometimes interpreted as other reefs within the GBR. This figure should be interpreted with caution.

The factors that influenced satisfaction and the best and worst experiences remained consistent across seasons and locations. The most important factor that **influenced satisfaction** was the staff and the level of professionalism (at least 25% of respondents), the natural environment (15%), the weather and the sea-state affected the satisfaction of 10% of respondents in the first quarter and 21% in the last quarters. Finally, 10% of respondents cited diving and snorkeling as influencing their satisfaction. The tourists' **best experiences** on the other hand, included diving and snorkeling for one third of all respondents, regardless of location and season. The marine life was the best experience for 10% to 20% of respondents, whilst the service and staff was the best experience for 10% of respondents. The tourists' **worst experiences** were predominantly limited to the sea-state, lowest in quarter 4, 17% and highest in Quarter 3, 39%, but consistent across locations.

The following is excerpted / summarised from Birtles *et al.* (2007):

Preliminary findings of Pilot Visitor Survey (Far Northern GBR); October to December 2006

Sampling and questionnaire design: Sampling using a self-administered questionnaire was conducted on the only two live-aboard dive tourism vessels (*Undersea Explorer* and *Nimrod Explorer*) conducting regular, scheduled, specialised expeditions to the Far Northern Section of the GBRMP between October and December 2006. Key features of these trips include sightings and interactions with large (breeding) aggregations of green turtles (*Chelonia mydas*) in the vicinity of remote and significant turtle nesting islands (e.g. Raine Island), as well as relatively high concentrations of sharks and pelagic fishes, encountered opportunistically.

An additional feature of the *Undersea Explorer* Far Northern expeditions includes the capture, tagging and release of tiger sharks (*Galeocerdo cuvier*), conducted by R. Fitzpatrick as part of a satellite tracking program. The opportunity for tourists to watch the shark being tagged (from the safety of the vessel) is promoted as a highlight of the trip.

Questions in the pilot survey were designed to elicit passenger values, perceptions and experiences from their interactions with turtles, sharks, sea birds and large fishes. The importance of sightings of this wildlife was explored, including their relative attractive power for visitors to the region. Visitor expenditure patterns in the Cairns and Port Douglas region were also detailed, enabling subsequent apportioning of expenditures in the region attributable to specific wildlife groups or species. The survey instrument is attached as Appendix 1.

Data collection and response rate: A total of eight trips (four by each vessel) were sampled between 15 October and 15 December 2006. Questionnaires were distributed and collected by vessel crew towards the end of each trip, and their completion by passengers was entirely voluntary. Total passenger numbers from each trip were obtained from the dive company offices to calculate the response rate. A total of 122 passengers were carried between the two vessels over the eight trips. From these, 87 completed questionnaires were returned. An additional two questionnaires were only partially completed by passengers (and one questionnaire was completed by a crew member) and these have been excluded from the analyses. The response rate is therefore calculated as 89/122, or 73%.

Technique for estimating the regional economic 'impact' of key marine species

Economic value versus economic impact: Preliminary background: The economic 'value' of any good or service is not the same as its price, since people are often willing to pay more than the asking price to enjoy a particular good or service. In theory, the total value of a good is given by the area under its demand curve and this will equal the amount actually paid (total expenditure) plus 'consumer surplus'. It is notoriously difficult to try and

estimate this value – particularly when interested in non-priced goods (eg environmental quality, key marine species).

The preliminary visitor survey did not, therefore, attempt to collect information relating to the total economic ‘value’ of key marine species. Instead, it sought to collect information that allows researchers to estimate the economic *impact* of the tourism that relies on those key marine species. Not only does this approach exclude non-tourism values associated with the key marine species, but it also ignores the consumer surplus attributable to the tourism values. This approach thus generates an unambiguous underestimate of the total ‘value’ of the species.

Economic impact: Simplistically, the regional economic ‘impact’ of key-species tourism is equal to:

The tourist expenditure that is attributable to the species
multiplied by
The regional (Keynesian) ‘multiplier’

Researchers who wish to estimate the economic impact of key-species tourism thus need information that will allow them to determine (a) how much regional tourist expenditure is directly attributable to the species; and (b) the size of the regional multiplier. Hence the need for two surveys: the visitor surveys collect information that allows researchers to assess (a), whilst the tour-operator surveys provide information about (b).

Using visitor survey data to estimate the regional expenditure that is attributable to key marine species

This study attempts to attribute visitor expenditure to individual species in a three-step procedure:

- 1) It uses survey data to estimate the total regional expenditure of each respondent.
- 2) It uses responses to questions about the importance of the dive-boat trip to the overall decision to travel to the Cairns/Port Douglas region to determine the proportion of total regional expenditure that can be ‘attributed’ to the dive-boat trip.
- 3) It uses responses to questions about the relative importance of different species of marine wildlife in the decision to go on dive-boat trip to determine how much of the ‘attributable’ dive-boat expenditure can be ‘attributed’ to individual marine species.

NB: Step (3) implicitly assumes that all attributable dive-boat expenditure can be attributed to individual species. It thus neglects the fact that some at least some dive-boat expenditure may be attributable to non-marine attributes of the dive trip (the dive experience itself, the time with friends, the boat trip itself, etc). Consequently, this will tend to *overestimate* the total expenditure attributable to each species.

However, estimates that are generated from this process do not include the value of sightings of iconic wildlife species by other types of tour operators (e.g. sightseeing cruises, sunset cruises etc). And this will tend to *underestimate* the total regional expenditure that is attributable to each species.

Since the biases work in opposite directions, and since one cannot tell, *a priori*, which bias is stronger, one cannot tell whether final estimates will over or under estimates of regional economic impact of individual species. Readers are thus encouraged to think of these final estimates as providing information about the *relative* importance of different species in

attracting tourist expenditure (rather than as a means of generating estimate of absolute value of individual species).

Estimates of the regional economic impact of dive boat trips (based on estimates of the proportion of total expenditure that is directly attributable to the dive boat) are more robust.

Preliminary results

The following results represent preliminary analyses of the pilot passenger survey conducted from October to December 2006. Further in-depth analyses are continuing through 2007 for subsequent reporting and peer-reviewed publication.

Sample demographics

Of the total sample, 56% were male. The mean age of respondents was 44.7 years (range 20-68 years). Respondents originated from fourteen countries, with the largest groups coming from the United States (29 respondents), followed by Australia (22), Germany (9), the United Kingdom and the Netherlands (7 each). First time visitors to the GBR represented 58% of the sample, and first time visitors to the Far Northern Section of the GBR represented 88% of the sample.

The majority of respondents were highly experienced SCUBA divers, with 87% of the sample holding Advanced Open Water (PADI) certification or higher. The mean number of years of SCUBA experience for the sample was 13.2 years (ranging from 1-39 years of experience), and the median total number of dives conducted by respondents (in their lifetime) was 266 dives (ranging from 29 to 3,000 dives).

For 58% of the sample, taking this dive trip to the Far Northern GBR was the main purpose of their trip away from home. For 36%, the dive trip was one of several activities and/or destinations on their trip away from home.

Importance of seeing particular marine wildlife groups and species

Respondents were asked: "How important was it for you to see these marine wildlife when choosing this Far Northern GBR dive trip" and were provided with a ten-point semantic differential scale (where 1 = 'Not at all important' and 10 = 'Very important') for a list of key marine wildlife groups, including marine turtles, sharks, fishes, sea birds and 'other wildlife' (Q.13, Appendix 1). Respondents were also asked to list 'any species in particular' for each group, and were provided the option to tick a box if they 'would not have chosen this dive trip if there were no chance of seeing this wildlife group'.

The mean rating scores (out of ten) for each wildlife group were:

- Marine turtles: 8.4
- Sharks: 8.4
- Fishes: 8.5
- Sea Birds: 4.1

Particular species of marine turtle listed by respondents were green turtles (n=4) and hawksbill (n=1). The small number of respondents indicating a particular species suggests that while seeing marine turtles was an important consideration when choosing the trip, there was limited consideration of any particular species. Nineteen respondents (22%) indicated that they would not have chosen this dive trip if there was no chance of seeing marine turtles.

Particular species of sharks listed by respondents included: tiger sharks (n=13), grey reef sharks (n=4), silvertip whalers (n=3), leopard sharks (n=2), hammerheads (n=2) and white tip reef sharks (n=1). Twenty-two respondents (25%) indicated that they would not have chosen this dive trip if there was no chance of seeing sharks.

Particular species of fish listed by respondents included: barracuda (n=2), trevally (n=2), wrasses, stingrays, mackerel, tuna, nudibranchs, bat fish, 'bumpheads' and 'other pelagics' (all n=1). Additional responses were 'large variety more important', 'all' and 'schools of fish'. Fifteen respondents (17%) indicated that they would not have chosen this dive trip if there was no chance of seeing the particular species of fish that they had nominated.

Only one respondent listed a particular sea bird ('boobies') and another respondent indicated 'life on cays' in general. Only two respondents indicated that they would not have chosen this dive trip if there was no chance of seeing sea birds.

Other wildlife species that were listed by respondents as important considerations when choosing their dive trip included: nudibranchs (n=6), manta rays (n=5), corals (n=5), soft corals (n=2), coral spawning, dugongs, turtles, cetaceans, whales, dolphins, octopus, cuttlefish, sponges, shells, jellyfish, parrot fish, marine invertebrates, flat worms, frog fish, pipe fish and crocodiles (all n=1). Six respondents (7%) indicated that they would not have chosen this dive trip if there was no chance of seeing the particular species they had listed.

Satisfaction and perceptions of the far northern GBR

Respondents were asked to rate their overall satisfaction with their Far Northern GBR diving trip (Q.15, Appendix 1), as well as their wildlife experiences on the dive trip (Q. 16), on separate ten-point scales (ranging from 1 = Very Poor to 10 = Excellent. Mean scores for these questions were 8.7 and 8.8 respectively. The mean rating for the follow up question asking "Overall, how well did this Far Northern GBR diving trip meet your expectations?" (3.5 out of 5) indicates that on average passengers' expectations of the trip were slightly exceeded by their actual experience (Q.17). Fifty-two of the respondents (60%) indicated that they would very likely return, or definitely return to visit the Far Northern GBR again in future (Q.19).

Respondents were asked to rate the 'environmental quality' of the sites they visited in the Far Northern GBR on their dive trip (Q.20). 'Environmental quality' was defined as "how healthy you perceive the reefs and wildlife populations to be in the region" and a ten-point rating scale (1 = Very poor environmental quality, 10 = Excellent environmental quality) was provided. The mean rating for this question was 8.0. The mean rating for a follow up question asking "Did the environmental quality of the sites you visited meet your expectations?" (3.2 out of 5) indicates that on average respondents expectations were met or slightly exceeded (Q.21).

Wildlife species/groups contributing to satisfaction

Respondents were asked: "How much did your interactions with each of the following types of marine wildlife contribute to your overall satisfaction with your trip" (Q. 22) and were provided with a ten-point semantic differential scale (where 1 = 'Didn't contribute at all to my satisfaction' and 10 = 'Contributed a great deal to my satisfaction') for the same list of key marine wildlife groups provided earlier in Question 13. Respondents were again asked to list 'any species in particular' for each group, and were provided the option to tick a box if they did not see these wildlife.

The mean rating scores (out of ten) for each wildlife group were:+

- Marine turtles: 8.8

- Sharks: 8.4
- Fishes: 8.5
- Sea Birds: 4.7

Respondents listed particular wildlife species they encountered and in some cases the locations at which they were seen. Marine turtle species reported to have been encountered during the trips were green, loggerhead and hawksbill turtles. Shark species reported to have been encountered were grey reef, silvertip whalers, tiger, wobbegong, epaulette, leopard, hammerhead, white tip reef and tawny reef sharks. Fish species that were listed by respondents as having been encountered were Maori wrasse, barracuda, potato cod, snapper, moray eels, red bass and leafy scorpion fish. Sea bird species reported to have been encountered were brown boobies, night herons and frigate birds. Other marine wildlife groups/species listed by respondents were: dugong (from a single sighting on one trip), nautilus, nudibranchs, manta rays, cetaceans, dolphins, corals and 'marine invertebrates'. No respondents indicated that they had not seen any marine turtles, and only two respondents indicated that they had not seen sharks on their trip.

Preliminary analysis of economic values of wildlife groups/species

As noted earlier, this study attempts to attribute visitor expenditure to individual species in a three-step procedure. In the first place, we used survey data to estimate the total regional expenditure of each visitor. Specifically, respondents were asked to indicate the approximate amount that they had spent per day on different categories of goods.

When estimating total expenditure on each category of good, we used the mid-point of each (e.g. \$35 for the range \$21-\$50; \$75 for the range \$51-\$100, etc.) – although the lowest amount (e.g. \$300) was used for the top category, giving an unambiguous downward bias to final estimates. These mid-points were then added together to arrive at an estimate of daily regional expenditures across all items *except* the dive-boat. Preliminary estimates indicate that the average visitor spent \$328 per day while in the region. These daily expenditure estimates were then multiplied by the total number of days spent in the region, to generate an estimate of total regional non-boat spending. Preliminary estimates indicate that the average visitor spent \$1,737 in the region – approximately 23% in the Port Douglas area and the rest in and around Cairns. This roughly accords with the proportion of time spent in the different regions (approximately 27% in Port Douglas).

Estimates of the *total* regional per-visitor expenditure (including dive boat expenditures) were then generated by adding the total regional expenditure estimates to

- The cost of the dive boat trip (mean preliminary estimate = \$3,943 per person); and
- Extra expenditures from the dive boat trip (mean preliminary estimate = \$272 per person).

Mean preliminary estimates indicate that each respondent spent close to \$6,000 in the region (\$5,952 per person).

1. We then used responses to questions about the importance of the dive-boat trip to the overall decision to travel to the Cairns/Port Douglas region to determine the proportion of total regional expenditure that can be 'attributed' to the dive-boat trip. The figure below (Figure 1) provides details on how that was done, listing the questions (and responses) that were used, and identifying the number of respondents falling within each category.

It seems that *most* regional expenditure is directly attributable to the dive-boat trip (i.e. visitors would not have come to the region if they could not go on the trip). Specifically,

preliminary estimates indicate that the dive boats are directly responsible for almost 90% of respondent expenditure within the region (approximately \$5,321 per person³).

2. We then used responses to questions about the relative importance of different species of marine wildlife in the decision to go on dive-boat trip to determine how much of the 'attributable' dive-boat expenditure can be 'attributed' to individual marine species. For example, the proportion of attributable dive boat expenditure that was attributed to sea turtles, was calculated by dividing each visitor's response to the question 13 on the "importance" of sea turtles by the *total* "importance" of all species (i.e. the sum of all importance scores). Preliminary estimates of the per-visitor regional expenditure that is attributable to each marine species considered in this questionnaire are as follows:

- Marine turtles: \$1,360
- Sharks: \$1,375
- Fishes: \$1,354
- Sea Birds: \$589
- Other wildlife: \$643

Update on the progress of the GBR tourism operator Business Expenditure Survey and Key Informant Interview

Survey design

In order to establish the direct and indirect economic contributions of GBR dive tourism operators to their local economy, a Business Expenditure Survey (Appendix 2) and Key Informant Interview (Appendix 3) were designed by the research team and sampling began in mid-April 2007. A strict agreement of confidentiality of data from this survey was undertaken with each respondent, ensuring that no operators or individuals will be identifiable from the results.

In order to encourage participation by GBR tourism operators, a promotional 'Information Sheet' (Appendix 6) was developed and distributed to operators via email, accompanying requests for their participation.

It is important to note that prior to the commencement of this Project, members of the research team (Birtles, Valentine, Curnock, Mangott) had established a strong collaborative relationship with many of the Cairns and Port Douglas dive tourism operators included in the target sample, over a twelve-year period, via the Minke Whale Project (led by Birtles). The confidence of the tourism industry in this research project and their trust of the research team have proven invaluable in achieving industry support for the Project and high levels of participation in the surveys.

Sampling progress

After introducing the Project and presenting an outline of objectives and methods to swim-with-minke whales permitted tourism operators, GBRMPA and QPWS managers at the 2006 Post-Season Minke Whale Tourism Monitoring Workshop (15 December 2006; extract of Minutes attached as Appendix 4), a total of seventeen Cairns and Port Douglas-based Reef tourism operators were contacted via telephone and/or email and asked to participate in early April 2007. An MS-Word copy of the Business Expenditure Survey was emailed to participants, with instructions for it to be completed in their own time, by a person with sufficient detailed financial knowledge of the company. Over 16-18 April 2007, Research Assistants A. Mangott and M. Curnock visited the offices of participating GBR tourism

³ Not all respondents answered all questions. So these figures vary somewhat depending upon the way in which missing data is handled.

operators in Cairns and Port Douglas to conduct Key Informant Interviews with owners/managers of participating operators.

At the time of writing this Report, sampling of these operators is continuing, with KI interviews conducted with ten of the 17 operators over 16-18 April and remaining interviews with Cairns and Port Douglas-based operators planned over June-August 2007. Completed Business Expenditure Surveys have so far been received from four operators. Further completed Business Expenditure Surveys are expected to be returned by remaining operators over June-August 2007. Our approach to sampling of the Business Expenditure Surveys has been to allow operators to 'take their time' in completing this long and very detailed Survey as we recognise that they are very busy with the day to day management of their operations. We have had assurances from many of the operators that they are supportive of the Project and are completing the Survey in gradual stages when time is available. We have received only one refusal to participate from a single operator.

Sampling of Cairns and Port Douglas-based operators is continuing over June to August 2007 and sampling of Townsville and Whitsundays-based GBR tourism operators is planned for August to December 2007.

Project 4.8.7 Forecasting Risk of Exposure to Irukandji

Project Leader and Host Organisation: Professor Mike Kingsford, JCU.

Rationale and Objectives

The purpose is to minimise risk to swimmers through knowledge of the sources of jellyfishes and changes in their abundance. Although anecdotally there is no link between abundance of *Carukia barnesi* and proximity to estuaries, this has never been tested critically. The inshore zone is the area of highest use by the public and forecasting the risk of envenomation is critical. The approach involves sampling near-shore waters near to and away from estuaries in an area of north Queensland that has high usage by tourists and locals. The coastal zone between the Daintree River and Mackay has the highest frequency of envenomation and is our area of focus. Samples of *C. barnesi* and *Chironex fleckeri* will be used for genetics and elemental fingerprints to determine population structure.

Key Objectives

- (a) Develop a microsatellite DNA marker library to assess spatial structure in *C. barnesi*.
- (b) Use elemental chemistry and microsatellites to test for differences in the population structure of *C. barnesi* and *C. fleckeri* among locations. Initially, sampling will be done at two sites near Palm Cove to obtain samples for preliminary work on elemental chemistry and genetics. Variation in elemental chemistry and genetics within a site will be used to make final decisions on numbers of replicates. These samples will also be critical for the development of a DNA marker library.

Progress – Outputs

Some 40-50 samples of *C. fleckeri* were collected for genetics and statolith chemistry from Weipa. Some 100 samples of *C. barnesi* were collected from Low Isles, Double Island, Hamilton Island and Airlie Beach for venom extraction, genetics and statolith chemistry. DNA and statoliths of an additional 300 *Carukia barnesi* collected in 2005 are being examined. A microsatellite library is in progress for both *Chironex* and *Carukia*. The first set of sequences indicates that some contain microsatellites, and initially 384 clones will be sequenced from

each of the two libraries, after which primers will be designed to test for specificity and polymorphism.

Project 4.8.8 Communication, Community Engagement and Enhanced Delivery for Program 8

Project Leader and Host Organisation: Dr Colin Simpfendorfer, JCU.

Rationale and Objectives

The science projects in Program 8 have a strong interplay with community engagement to ensure the successful conduct and delivery of the research. In addition, they have a need to be conducted in the context of an engagement system like that developed for the CRC Reef's Fishing and Fisheries Team. The previous system involved a communications officer to facilitate researcher engagement with industry, public and indigenous sectors, and coordinating communications between researchers and stakeholders.

This schedule describes the principal communication activities and products for Program 8 related activities based on the previous communication model described above. It is anticipated that the communication activities identified in the schedule (Project 4.8.8) link to other communication activities within the MTSRF program, in particular Program 4 (Threatened Species).

Key Objectives:

- (a) Coordinate communication activities and products to enhance the delivery of research activities and findings of Program 8 in 2006/2007.
- (b) Develop linkages with other communication activities within the MTSRF Program.

Progress – Outputs

A newsletter template for the Fishing and Fisheries Research Centre has been developed, as well as presentation (Microsoft PowerPoint) templates. Three newsletters have been produced and two have been distributed. A newsletter discussing three MTSRF Program 8 projects has been distributed. An article in the most recent Fishing and Fisheries Newsletter (Issue 31, December 2006) discussed the new MTSRF projects being undertaken by the team. This was distributed to around 2000 recipients throughout Queensland and steps have also been made for digital delivery of newsletters, media releases and other communication documents such as technical reports with the development of a mailman news-list site. This will allow for more cost effective delivery of communication products as well as making them available in full colour. Development has begun for Program 8 project WebPages to be linked to host institutions (e.g. JCU, RRRC and DEH). These pages will include information about research projects, and will be updated as results become available. Downloadable PDFs of various communication products will also be made available.

Project posters (Projects 4.8.3, 4.8.4 and 4.8.5) for use in public displays such as the Fishing and Outdoor Expo have been produced. Edition 2 of the Program 8 newsletter is currently being produced and newsletter articles have already been submitted. A final draft of this newsletter is awaiting one more article for completion. The Fishing and Fisheries mailman list is in operation and has more than ninety subscribers and is constantly increasing. This list is used to distribute MTSRF Program 8 newsletters. Draft versions of the Fishing and Fisheries Research Centre website have been developed. Once operational, this website will contain links to Program 8 projects, RRRC, QDPI&F, FRDC, CSIRO and DEW. It will become an important communications avenue for a wide variety of projects.

Further Information

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