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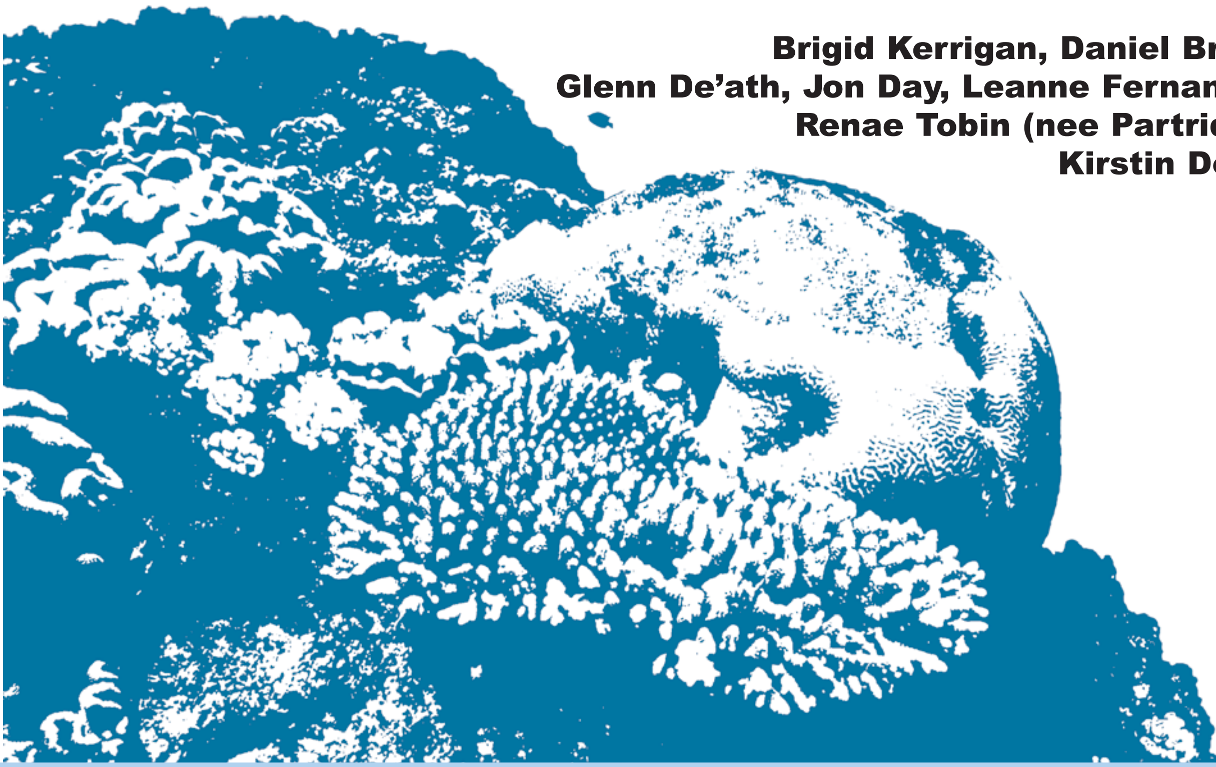

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Classifying the Biodiversity of the Great Barrier Reef World Heritage Area

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CONTENTS

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EXECUTIVE SUMMARY

This technical report outlines the methods that the Great Barrier Reef Marine Park Authority used to classify the biodiversity of the marine environs of the Great Barrier Reef World Heritage Area for the Representative Areas Program. Classification was the first step in the multiphase Representative Areas Program that eventuated in a new network of no-take areas, free from extractive activities, in the Great Barrier Reef Marine Park.

The main objectives of the Representative Areas Program were to:

- Maintain biological diversity at the ecosystem, habitat, species, population and genetic levels
- Allow species to evolve and function undisturbed
- Provide an ecological safety margin against human-induced and natural disasters
- Provide a solid ecological base from which threatened species or habitats can recover or repair themselves and
- Maintain ecological processes.

The objectives were to be achieved through implementing a comprehensive, adequate and representative network of no-take areas throughout the Great Barrier Reef Marine Park.

The Classification Phase (Phase I) of the program had two main purposes:

1) To collate the available data and information on spatial patterns of species distributions, patterns in habitat and species diversity
2) To describe the biological patterns of the Great Barrier Reef World Heritage Area by drawing on available data, existing classifications of species distributions and patterns in biodiversity (including the Interim Marine and Coastal Regionalisation of Australia), numerical classifications of the more spatially comprehensive data sets and expert knowledge.

The subsequent phases of the program were**:**

- *Review* - determine the extent to which the existing zoning protects the biodiversity of the Great Barrier Reef Marine Park
- *Identification* - identify networks of areas that fulfil the biological objectives of the program
- *Selection* – select from amongst the identified networks those that also minimise negative and maximise positive impacts on socio-economic and cultural values
- *Draft Zoning Plan* - for the Great Barrier Reef Marine Park that incorporates stakeholders' comments on networks of candidate areas from the Selection Phase
- *Final zoning plan* - to Federal Government for approval.

The requisite data for the Classification Phase were scattered through published and unpublished material dating back 50 years or so. Over 70 scientists and experts were surveyed to identify the information and data on spatial patterns in the distribution and diversity of both biota and physical parameters. The respondents were from relevant disciplines in private industry, academia, research, and management institutions. Over 60 datasets were collated.

Spatial patterns of diversity were further described using multivariate regression tree (MRT) analysis on the most comprehensive datasets (soft corals, hard corals, reef macroalgae, reef fishes, epibenthos, algae, sediments, benthos and deepwater seagrasses). The analyses spatially clustered reef and non-reef components of the Great Barrier Reef World Heritage Area, which were then mapped to reflect the results of the MRT analyses.

The second component of the Classification Phase – describing the biological patterns of the Great Barrier Reef World Heritage Area – drew upon the classification and regression tree (CART) analyses, other existing regionalisations and the data gathered in the scientific surveys. In a series of workshops, the experts combined these analyses and data with their detailed knowledge to produce bioregionalisations for the Great Barrier Reef World Heritage Area. The workshops aimed to:

(i) Produce a biophysical bioregionalisation of the reefs, coastal regions, Great Barrier Reef lagoon and inter-reef, continental shelf and pelagic systems based on mapped distributions of biophysical parameters and the general knowledge of the Great Barrier Reef marine ecosystem

(ii) Produce informative and self-explanatory descriptions of the bioregions
(iii) Classify the bioregion boundaries in terms of the degree of 'fuzziness'
(iv) Produce a list of ‘Special Areas’ that were biophysically unique in terms of assemblage composition, represented key nesting/spawning sites, or supported rare and threatened taxa/habitats to assist in the selection of a network of no-take areas
(v) Produce a comprehensive set of biophysical operational principles to assist in the identification and selection of a network of no-take areas.

Outputs (i) to (iii) were part of the Classification Phase and are described in this report. Outputs (iv), the ‘Special Areas’, and (v), the biophysical operational principles, are described separately (Fernandes et al. 2005, 2009, 2010).

Thirty Reef and 40 non-reef bioregions were identified.

- reef bioregions six data sets were the main basis of the bioregionalisation: reef fish (2 datasets); soft corals; hard corals; reef biota; and macroalgae. Other information which was used to clarify bioregion boundaries included reef geomorphology, bathymetry, mean tidal range, broad-scale currents and existing regionalisations.
- non-reef bioregions bioregion boundaries were drawn largely from the distributions of seagrasses, epibenthos, algae, sponges, sediment changes, broad-scale currents and bathymetry. Again, much other data were used to refine and review the boundaries.

The bioregionalisation of the Great Barrier Reef World Heritage Area highlighted data gaps. Despite more than 30 years of underwater research on reefs, there were few empirical data on the biota of large sections of reefs, particularly in the previously termed Far Northern Section of the Great Barrier Reef Marine Park and the deepwater (greater than 50 m) reefs; spatially comprehensive data on the biota of non-reef regions are limited to the shallow inter-reef within the Great Barrier Reef lagoon; there were few datasets on spatial patterns in biodiversity within the pelagic habitat, continental slope and abyssal plain. In particular, there is an urgent need for more information on the distribution of non-reef fauna (infauna and epifauna) and flora.

The bioregions described in this report were the main descriptions of biodiversity in the Great Barrier Reef Marine Park that were the basis of the Representative Areas Program. Prior to the production of this report, the overall process and outputs of the Classification Phase were independently and favourably peer reviewed. The review found that “*the classification of spatial patterns in biodiversity in the Great Barrier Reef World Heritage area is of very high quality and has produced a robust regionalisation*”.

INTRODUCTION

The Great Barrier Reef World Heritage Area contains the largest continuous coral reef system in the world as well as one of the world's most ecologically diverse ecosystems (figure 1). At 348 000km^2, it is five times the size of Tasmania. The *Great Barrier Reef Marine Park Act 1975* established the Great Barrier Reef Marine Park Authority 't*o provide for the protection, wise use, understanding and enjoyment of the Great Barrier Reef in perpetuity through the care and development of the Great Barrier Reef Marine Park*'. Protecting the natural values of the Marine Park is a primary aim of the Great Barrier Reef Marine Park Authority. The Great Barrier Reef Marine Park constitutes 99 per cent of the Great Barrier Reef World Heritage Area. As a signatory to the Convention on Biological Diversity (United Nations Environment Program 1994), Australia recognises the importance of conserving biodiversity. These facts, combined with Australia's geographic location and socio-economic climate, have given it a major role as a storehouse of diversity for tropical marine ecosystems, including coral reefs.

Protection of marine areas by creating no-take zones is one of the means by which marine area managers can help maintain biodiversity (Roberts and Hawkins 2000, National Research Council 2000). No-take zones are areas where all extractive activities are prohibited. Under the previous zoning system only 4.6 per cent of the Great Barrier Reef Marine Park was given this high level of protection: Marine National Park B, National Park or Preservation Zones. Twenty-one per cent of coral reef area was in these highly protected zones while equally important coastal fringing habitats, inter-reefal areas, lagoon and continental slope habitats were largely unrepresented. Only 3.6 per cent of non-reef areas were in no-take zones. This bias towards protection of reefs is not surprising in view of their high profile with the public and scientists, their perceived fragility and immediately recognisable aesthetic values. However, under-representation of the inter-reefal habitats in no-take areas needed to be redressed in order to conserve the spectrum of biodiversity in the Great Barrier Reef World Heritage Area.

The Australian and New Zealand Environment and Conservation Council (1999) concurred with this view. They recommended that Australia could better protect its marine biodiversity, in part, by establishing a national representative system of marine protected areas (NRSMPA). Five years earlier, over 60 Great Barrier Reef World Heritage Area stakeholders recommended to 'protect representative biological communities throughout the [World Heritage Area] to act as source areas, reference areas and reservoirs of biodiversity and species abundance'. This was part of the *25 Year Strategic Plan for the Great Barrier Reef World Heritage Area* (Great Barrier Reef Marine Park Authority, 1994). Both recommendations are in accordance with a global initiative to establish a worldwide network of representative marine no-take areas (Kelleher et al.1995).

In 1996, the Great Barrier Reef Marine Park Authority began implementing these recommendations by establishing a Representative Areas Program. A "representative area" is an area that is typical of the surrounding habitats or communities with similar physical features, oceanographic processes and ecological patterns. If such an area becomes a no-take zone, it protects a sample of the habitats and communities that it typifies.

Objectives of the Representative Areas Program

The main objectives were to:

1. Maintain biological diversity at the ecosystem, habitat, species, population and genetic levels
2. Allow species to evolve and function undisturbed
3. Provide an ecological safety margin against human-induced disasters
4. Provide a solid ecological base from which threatened species or habitats can recover or repair themselves
5. Maintain ecological processes.

Development of a comprehensive, adequate and representative network of no-take areas through the Representative Areas Program would contribute to achieving this objective. Other Great Barrier Reef Marine Park Authority programs, outside the scope of this report, also contribute to achieving protection of biodiversity by addressing, for example, sustainable use, water quality and coastal development issues.

Comprehensiveness, adequacy and representativeness (CAR) are the principles identified as appropriate by the Australian and New Zealand Environment and Conservation Council Task Force on Marine Protected Areas (Australian and New Zealand Environment and Conservation Council 1998, 1999). These principles were the foundation of the approach used by the Great Barrier Reef Marine Park Authority for the Representative Areas Program; they are discussed in more detail in the Australian and New Zealand Environment and Conservation Council documents and the technical report on the Identification Phase of the Representative Areas Program (Lewis et al. 2003). Although debate continues over the definition of the CAR principles, the following definitions were adopted for the purposes of implementing the Representative Areas Program (Great Barrier Reef Marine Park Authority 1999a):

- Comprehensiveness: refers to the inclusion of the full range of habitats and taxa recognised within and across regions making up the Great Barrier Reef World Heritage Area; information about special or unique communities, habitats or species, should be used to capture the complete range of diversity
- Adequacy: refers to having a sufficient amount and degree of protection of communities, species and populations
- Representativeness: the areas included within a network of no-take areas should reflect (that is, represent) the diversity of the habitats from which they derive.

The Representative Areas Program conformed with the NRSMPA directive mentioned above (Australian and New Zealand Environment and Conservation Council 1999). The Australian and New Zealand Environment and Conservation Council framework recognised that marine systems are interconnected, which necessitates coordinating marine protected areas that cross jurisdictional boundaries. Thus, the Great Barrier Reef Marine Park Authority coordinated with Queensland management agencies to establish the network of no-take areas for the Great Barrier Reef World Heritage Area.

Process for developing a network of representative areas

A multi-phase process was developed to establish a comprehensive, adequate and representative network of no-take areas within the Great Barrier Reef World Heritage Area (Great Barrier Reef Marine Park Authority 1999a). The phases of this program were:

- **Classification** of the spectrum of biological diversity within the marine environs of the Great Barrier Reef World Heritage Area. Spatial analysis and expert opinion was used to identify and describe bioregions, based on their biophysical characteristics.
- **Review** of the existing network of no-take areas as representative of the bioregions that describe the diversity of the Great Barrier Reef World Heritage Area.
- **Identification** of the many spatially different networks of candidate areas[1] in the Great Barrier Reef Marine Park that could be considered for inclusion in no-take zones. These networks were identified using all available biophysical data to achieve the biological objectives of the program.
- **Selection** from amongst the identified networks in the Great Barrier Reef Marine Park those that are comprehensive, adequate and representative and that also minimise negative and maximise positive impacts on socio-economic and cultural values.
- **Preparation of a draft Zoning Plan** for the Great Barrier Reef Marine Park that incorporates stakeholders' comments on networks of candidate areas from the Selection Phase, and includes notes and/or displays explaining the plan to the public.
- **Preparation of a final Zoning Plan** for the Great Barrier Reef Marine Park that incorporates stakeholders' comments on networks of candidate areas from the draft Zoning Plan.

Aims of this Report

This report details the first phase of the Representative Areas Program - classifying the biological diversity of the marine environs of the entire Great Barrier Reef World Heritage Area, including areas that are not in the Great Barrier Reef Marine Park but are within the Great Barrier Reef World Heritage Area. While the classification of biodiversity encompassed the entire marine portions of the Great Barrier Reef World Heritage Area, the rest of the Representative Areas Program was limited to the boundaries of the Great Barrier Reef Marine Park.

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[1] A *candidate area* is an area within a bioregion identified as suitable for inclusion in a comprehensive, adequate and representative network of no-take areas.

Despite some 30 years of underwater research on coral reefs, knowledge was spatially limited and far from complete. Imperfect scientific knowledge about species and community distributions and spatial patterns of diversity was not a reason for delaying decisions on management of the Marine Park. The Representative Areas Program adopted the precautionary principle[2], as recommended by Australian and New Zealand Environment and Conservation Council. To move forward the Great Barrier Reef Marine Park Authority classified the diversity of the Great Barrier Reef World Heritage Area using existing information as discussed in this report (Australian and New Zealand Environment and Conservation Council 1998, 1999).

Figure 1. The Great Barrier Reef Region.

[2] At the time of the Representative Areas Program, the 'precautionary principle' in the *Great Barrier Reef Marine Park Act 1975* adopted the definition of the Intergovernmental Agreement on the Environment (1992), which states that in the application of the precautionary principle, public and private decisions should be guided by:

(i) careful evaluation to avoid, wherever practicable, serious or irreversible damage to the environment; and,
(ii) an assessment of the risk-weighted consequences of various options.

METHODS

Biophysical data used in the bioregionalisation

Phase One of the Representative Areas Program required classification of the spectrum of biological diversity within the marine environs of the Great Barrier Reef World Heritage Area. This section describes how data and information on spatial patterns in habitat and species diversity were collected and collated. These data included existing regionalisations. The role of the Scientific Steering Committee in the Classification Phase is also described.

Data Collection Methodology

At the time of the Representative Areas Program, existing ecological databases for the Great Barrier Reef World Heritage Area were spatially and taxonomically limited. It was essential, therefore, to use all available data (both physical and biological) to define habitats, assemblages and species distributions. These variables could be used as 'surrogates' for other known and unknown species groups. The addition of expert views meant that all existing data and the experts' personal knowledge could be used to maximise the probability of deriving an accurate and defensible description of biological diversity.

Biophysical Science Survey

To provide a framework for gathering biophysical data and advice on patterns of species distribution and environmental driving forces, a questionnaire (Appendix 1) was developed and used in interviews with more than 70 scientists and experts, from private industry and academic, research and management institutions. The participants were selected for their expertise in specialised fields, comprehensive general knowledge of the Great Barrier Reef ecosystem, and/or experience in establishing protected areas in either terrestrial or marine environments. All interviews were conducted from March to July 1999.

Survey information collected was stored in a database comprised of three linked tables:

1. <u>Contacts</u> - full contact details for all scientists and experts involved in the Classification Phase of the Representative Areas Program; a summary of the type of information they contributed; and any further involvement through workshops, expert groups and advisory committees
2. <u>Survey</u> - answers to the questions outlined in the questionnaire (see Appendix 1); notes on distribution patterns and key environmental drivers, principal impacts and threats, protected area design parameters (shape, size, connectivity), and general comments on current zoning, enforcement and ecological theory in relation to reserve design
3. <u>Analysis</u> - a summary of the datasets held by the Great Barrier Reef Marine Park Authority's GIS library; location of datasets on the network; file type; type of analyses performed (if any); GIS status; and use in bioregionalisations.

Data were collected during the survey from many sources including agencies acting as custodians of Commonwealth-owned and other data (e.g. bathymetry from Australian Geological Survey Organisation).

Scientific Steering Committee

In addition to the expert advice sought through the survey of scientists, a Scientific Steering Committee was formed, its membership chosen on the advice of scientists. The Committee, which spanned a broad range of research disciplines, provided advice to the Representative Areas Program team on the process and outputs of the classification and identification phases. The Committee helped develop and guide the process and tasks discussed in this report.

The terms of reference of the Scientific Steering Committee were to:

1. Provide advice to the Great Barrier Reef Marine Park Authority on scientific issues, programming and priorities relating to the program
2. Identify datasets and provide advice on information gaps and the quality of data
3. Assist in an initial spatial description of the marine diversity of the Great Barrier Reef Marine Park
4. Review and comment on methods and outputs and assist the Great Barrier Reef Marine Park Authority to achieve the best possible outcomes for the Representative Areas Program consistent with the timetable and resource constraints.

Review of Biophysical Data

The biophysical data available was highly variable in spatial coverage, type and quality. Most datasets gave a very approximate, static picture of an environment that is highly dynamic spatially and temporally. For example, the spatially comprehensive sediment data is an amalgamation of multiple data sets compiled over 20 years using different techniques of variable quality and consistency to sample and analyse the sediments. The biological data ranges from collections that are spatially constrained yet of high taxonomic resolution (e.g. Queensland Museum database) to broad-scale surveys that focus on a select group of taxa (e.g. macroalgae or soft corals). Biological data were also highly variable in type, ranging from presence, presence/absence, relative abundance, to absolute abundance. Table 1 summarises the data sets that were available to the Classification Phase of the Representative Areas Program. Appendix 2 lists the source(s) and references for each data set used.

Table 1. Main datasets reviewed for use in Classification Phase.

Physical	Biological
BATHYMETRY • Depth and elevation model • Gridded bathymetry (15 and 30 arc second) • Maps of water depth, seafloor aspect, slope, Secchi depth, and benthic irradiance • Physiographic units and regional divisions SEDIMENT • Broad sediment size classes and facies • Sediments associated with *Halimeda* beds • Mud, carbonate, mineral and biological sediment facies • GIS coverage for Queensland coastline • GIS coverage for intertidal areas ESTUARIES • GIS coverage for coastal rivers • Australian drainage basin dataset ISLANDS • GIS coverage for islands • GIS coverage for cays • Island and reef inventory • Classification of islands REEFS • GIS coverage for reefs • GIS coverage for exposed reefs • Great Barrier Reef Marine Park Authority cover for named rocks • Island and reef inventory • Classification of reef morphology • Regionalisation of reef morphology • Numerical grid regionalisation of reef morphology OCEANOGRAPHY • Biological oceanography • Cyclones, flood plumes and water quality in Great Barrier Reef lagoon • Surface and oceanic currents • Regional seasonal ocean maps • Australian region oceanography dataset • Exposure to wind SEA TEMPERATURE • 10 year mean fields • Sea surface temps effects on coral bleaching TIDES AND CURRENTS • Regional hydrodynamics and dispersal project • Coral reef and mangroves: modelling and management project • Tidal ranges WAVES • Australian region wave dataset CYCLONES • Atlas of Great Barrier Reef reef region • Australian region cyclone dataset	PLANTS • Inter-reef algae • *Halimeda*-bed coverages • Inshore seagrasses • Deepwater seagrasses • Mangroves • Reef macro algae CORALS • Soft coral surveys • Hard coral surveys • Long-term monitoring reef surveys • Surveys of reef biota in Cairns section ECHINODERMS • Museum specimen data • Descriptions and characteristics of echinoderms from Cairns Section EPI-BENTHOS • Transects off Townsville • Far Northern section • Samples span entire Marine Park UROCHORDATES • Museum databases MOLLUSCS • Museum specimen data SPONGES • Northeast Australia surveys MISCELLANEOUS • Museum specimen data – fish and invertebrates FISHES • Baitfish • Pelagic fish • Reef fish surveys • Spawning sites • Pelagic fish - Billfish and Marlin REPTILES • Turtles • Snakes BIRDS • Seabird atlas MAMMALS • Whales REGIONALISATIONS • Interim Marine and Coastal Regionalisation of Australia • Australian coastal regionalisation • Delphic reef regionalisation

The main spatial patterns of distribution of each taxon or individual species for which data were available are described in Great Barrier Reef Marine Park Authority (1999b). Additional comments regarding distribution patterns were filed in the ‘Comments Report’ of the database at the Great Barrier Reef Marine Park Authority.

An important cautionary note: in reality, species distributions often reflect continua versus discrete disjuncts. Ecological studies can detect spatial discontinuities in distributions that are, in fact, simply artefacts of the sampling design; hence, management strategies need to deal with continua as well as apparently discrete distributions (A. Underwood personal communication). As a result, some of the biophysical region boundaries were classified as 'fuzzy' reflecting either incomplete data or predicted continua or both.

A number of highly valuable data sets were not accessed during the Classification Phase of the Representative Areas Program due to the Program's restricted timetable. These data included Heatwole's seasnake data, Limpus' crocodile data, some museum collection data on invertebrates, and some of Ayling's reef surveys in the Cairns Section. The Scientific Steering Committee advised that the data collected were, however, sufficient basis to proceed with describing the diversity of the Great Barrier Reef World Heritage Area.

In general, scientists described a strong cross-shelf component in the abundance and diversity of both reef and non-reef taxa. These cross-shelf patterns vary with latitude due to the variability in key physical factors:

- Current strength
- Depth
- Division between wet and dry tropics
- Exposure
- Light levels, turbidity
- Local hydrology around reefs (e.g. passages with high flow-through rates)
- Presence of islands and complex coastlines
- Prey availability
- Reef geomorphology
- Reef substrate type
- Salinity
- Sediments - offshore extent of terrigenous sediments
- Slope
- Strength and relative influence of East Australian Current
- Temperature
- Terrestrially-derived nutrients and pollutants
- Tidal range
- Vegetated or unvegetated non-reef sediments
- Water productivity
- Width of the shelf

Developing the Bioregionalisation

Review of Existing Regionalisations

Reef Biota Regionalisation: The first bioregionalisation of the Great Barrier Reef based on reef biota was completed in 1996 by Drs Tony Ayling (Sea Research, Consultant), Terry Done and David Williams (Australian Institute of Marine Science) (Wachenfeld 1996). With collectively more than 70 years knowledge of species distributions and marine ecosystem functioning, the three scientists identified some 18 bioregions based on distributions of reef fishes, hard corals and general reef biota (figure 2). This bioregionalisation provided an excellent initial spatial representation of patterns in reef biodiversity, albeit taxonomically limited. The reef expert panel used this bioregionalisation as a template for developing the final bioregionalisation.

Interim Marine and Coastal Regionalisation for Australia: Interim Marine and Coastal Regionalisation of Australia is a broad-scale ecosystem-based bioregionalisation for the entire Australian coastal and marine environment (Interim Marine and Coastal Regionalisation of Australia Technical Group 1998). This bioregionalisation was based on a limited set of physical parameters: reef morphology, tidal ranges, rainfall, cyclone incidence, sedimentary basins, bathymetry, and mud and carbonate distributions; and only three biological parameters: mangroves and saltmarsh, hermatypic corals and littoral crabs. Nine regions were identified in the Great Barrier Reef World Heritage Area (figure 3).

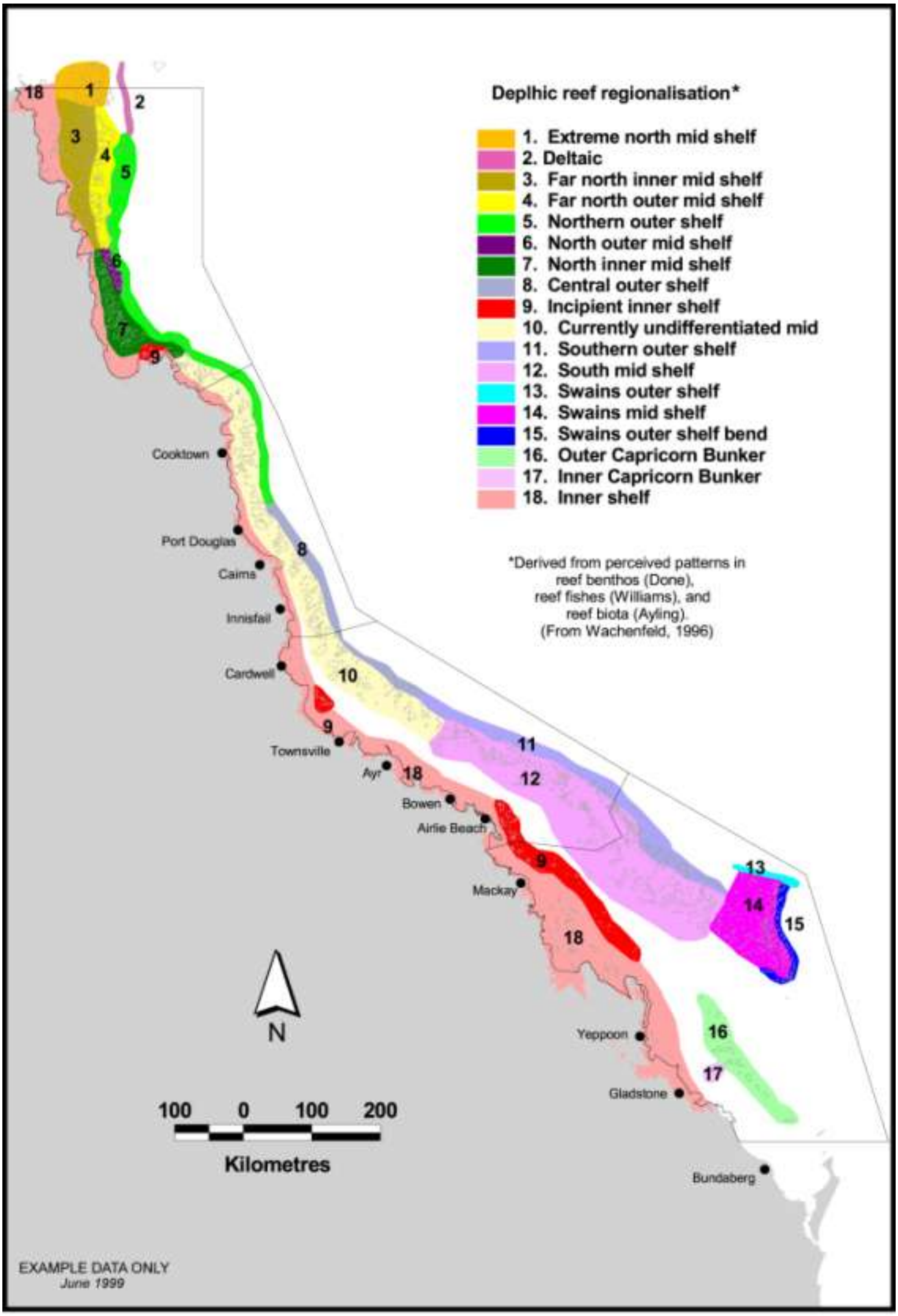

Figure 2. A delphic reef regionalisation for the Great Barrier Reef.

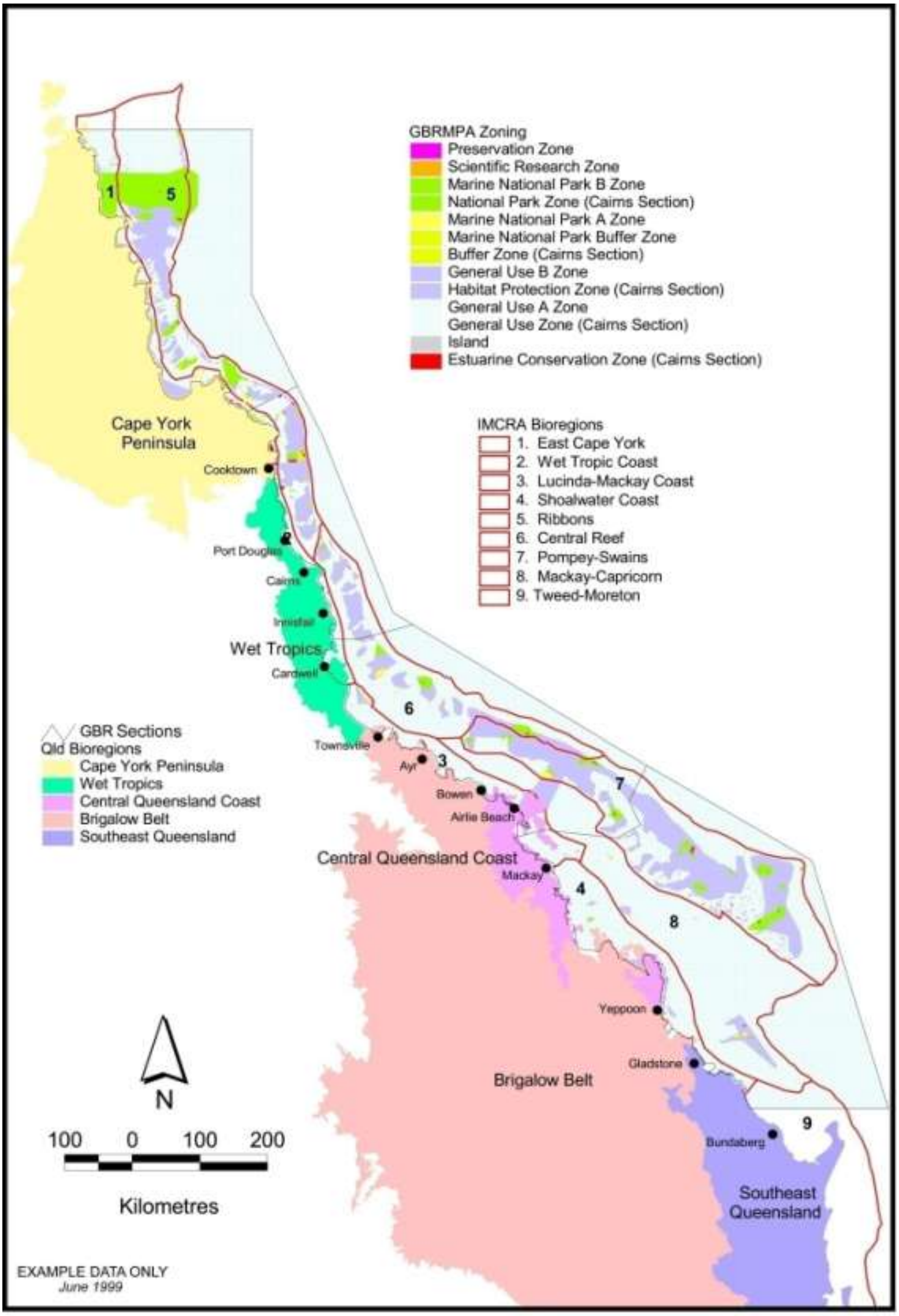

Figure 3. A 1998 Interim marine and coastal regionalisation of Australia adjoining bioregions of Queensland and Great Barrier Reef Marine Park zoning areas.

The meso-scale (greater than 100s km) spatial resolution of the Interim Marine and Coastal Regionalisation of Australia bioregions was broader than the level of knowledge that existed for the Great Barrier Reef region and was too broad to enable selection of an effective network of no-take areas within the Great Barrier Reef Marine Park. A finer scale regionalisation (10's to 100 km) was required to establish a system of no-take areas in the Great Barrier Reef Marine Park.

Surrogates for Biodiversity

In the absence of complete knowledge of all species and habitats, some level of surrogacy is necessary; for example, physical factors can be used to predict patterns in biota, or known species patterns used to predict patterns of other species.

Choosing datasets of physical and/or biological features for use in the Representative Areas Program is a *de facto* recognition that these features will be used as surrogates for other forms of biodiversity where data are weak, and for biodiversity that is as yet uncatalogued or unknown. The ecological literature abounds with studies on the issue of surrogacy; for example, there are many studies of taxonomic sufficiency—the level of taxonomic detail that is required to resolve ecological patterns and processes in polluted environments (e.g. Vanderklift et al. 1996). However, few models of surrogacy appear to be robust across scales of space, time and taxonomy in undisturbed marine (or terrestrial) ecosystems (for example see Vanderklift et al.1998; Ward et al.1999; Andelman and Fagan 2000; Olsgard and Somerfield 2000).

The main difficulty in identifying useful surrogates for biodiversity is the dynamic and broad nature of the concept of biodiversity itself (for example see Gaston 1996; Hawkesworth 1995; Lister 1998; Garcia-Charton and Perez-Ruzafa 1999). Given the spatial, temporal and taxonomic scales on which biodiversity must be measured, as well as the diversity of processes that create and maintain biodiversity, it is unlikely that precise surrogates will ever be found for many aspects of marine biodiversity.

Nonetheless, at broad scales, there are correlates of marine biodiversity that are useful for representing the broad-scale patterns of biodiversity. Such correlates are most robust for the shallow-water environments, because many species and assemblages have been well studied in near-shore waters and on reefs in shallow water. For example, depth and substrate type are commonly cited as environmental correlates of the distributions of soft-sediment fauna and flora (e.g. Cohen et al.2000). Also, taking a seascape view of biodiversity (sensu Garcia-Charton and Perez-Ruzafa 1999), biophysical habitats that are broadly defined and mapped show promise as surrogates and are increasingly being proposed as a means of improving marine ecosystem management (Ward et al.1999; Appeldoorn and Recksiek 1998; Mumby and Harborne 1999; Done and Reichelt 1998; Ray 1999).

Biological knowledge about the Great Barrier Reef World Heritage Area is limited, as is knowledge of the way in which the physical systems of the Great Barrier Reef World Heritage Area control and maintain the biodiversity, but on a more general level there is considerable knowledge of how communities and species relate to physical attributes such as bathymetry. Therefore, in the absence of complete data on most of the biodiversity of the Great Barrier Reef World Heritage Area, the Representative Areas Program used the available knowledge of bathymetry, substrate, and other physical characteristics as surrogates for biodiversity to supplement the available biological datasets.

Great Barrier Reef experts used data on reef fishes, macroalgae, and hard and soft corals as well as physical data as surrogates for other reef fauna and flora. The assumption is that the spatial patterns in reef attributes of which was known reflect patterns in species for which there is little or no quantitative data.

There are two points of caution in relation to surrogacy in the marine environment:

1) The relationships among biota and key physical factors are highly variable on both spatial and temporal scales. For example, in the Central Section [now termed Townsville / Whitsunday Management Area] of the Great Barrier Reef Marine Park there is a strong relationship between the type of coral community and the assemblage of reef fishes. Therefore, the general assemblage of fishes can be predicted from the coral community. In the Far Northern Management Area, however, this relationship breaks down: the mid-shelf

reefs support mid-shelf corals yet the fish assemblages are typically inshore. This spatial variability highlights the point that relationships are correlative, not causative, and that multiple factors act synergistically to determine observed distribution patterns.

2) Generally, only a subset of the epibenthic or infauna species and taxa among those sampled at any one time show a significant relationship with physical variables (e.g. sediment type: maximum r^2 of ~30 per cent). For many species no significant relationship has been found.

The uncertainty associated with using such data, together with the other forms of biological surrogacy (such as representing hard-coral biodiversity by using the distribution of hard-coral community types), means that the candidate areas produced from the identification and selection phases of the Representative Areas Program may not fully represent the biodiversity of the Great Barrier Reef World Heritage Area. This lack of certainty highlights the vital importance of replication of protected areas to capture unknown or undescribed diversity, of continued research, and of the incorporation of results into management strategies. The Great Barrier Reef Marine Park Authority will continue to review and monitor the network of no-take areas as new information becomes available.

Distinguishing reef from non-reef habitats

Reefs are relatively physically distinct habitats when compared to the habitats that comprise the non-reef parts of the Great Barrier Reef Marine Park. In the non-reef areas there can be muddy seabed communities, seagrass beds, sandy seabed communities, sponge gardens, algal communities and more. Because coral reefs were better known and structurally relatively distinct compared with non-reef communities, the description of the biodiversity of the Great Barrier Reef World Heritage Area was divided into two components: reef and non-reef. In doing this, the Great Barrier Reef Marine Park Authority made the assumption that ecological processes and functioning can be maintained, to some degree, by protecting examples of biophysically distinct bioregions. The available data on ecological processes and functioning were not of sufficient detail to enable descriptions, and hence protection, of biodiversity on these bases alone.

Statistical analyses

The biophysical data available varied in terms of latitudinal spread and quality. Several data sets were, however, sufficiently comprehensive for analysis. Classification and multivariate regression tree analyses described below were used to detect spatial patterns separately in reef and non-reef species or taxa (Coles et al. 2000, De'ath and Fabricius 2000). These spatial patterns were a significant input to the workshops in which experts developed the bioregions.

- For the reef bioregionalisation, six key data sets were used, which were sufficiently reliable and comprehensive for analyses: soft corals; hard corals; macroalgae; reef benthos; and reef fishes [2 datasets]. All data were converted to presence/absence data for analysis.
- For the non-reef bioregionalisation analyses three main data sets were used: epibenthos, deepwater seagrasses and sediments.

Classification and Multivariate Regression Tree Analysis

Classification and regression trees (CART) explain variation of a single response variable by repeatedly splitting the data into more homogeneous groups. The splitting is done using one or more categorical and/or numeric explanatory variables. The response variable(s) may be categorical (classification trees), numeric (univariate or multi-variate regression trees) or both. Both classification and regression trees are ideally suited for the analysis of ecological data, which are often complex, involve non-linear relationships, high-order interactions and missing values (De'ath and Fabricius 2000). 'Trees' have the following advantages:

- Flexibility to handle a broad class of response types
- Invariance to transformations of the explanatory variables
- A statistically sound basis for model selection (namely cross-validation)
- Ease of interpretation
- Ability to handle missing values in both response and explanatory variables.

Although they can be used for exploration, description and prediction they are uncommon in ecological studies.

Illustrative examples of regression and classification trees are shown below, using the per centage cover and presence-absence of *Lemnalia*, a genus of soft coral (figure 4).

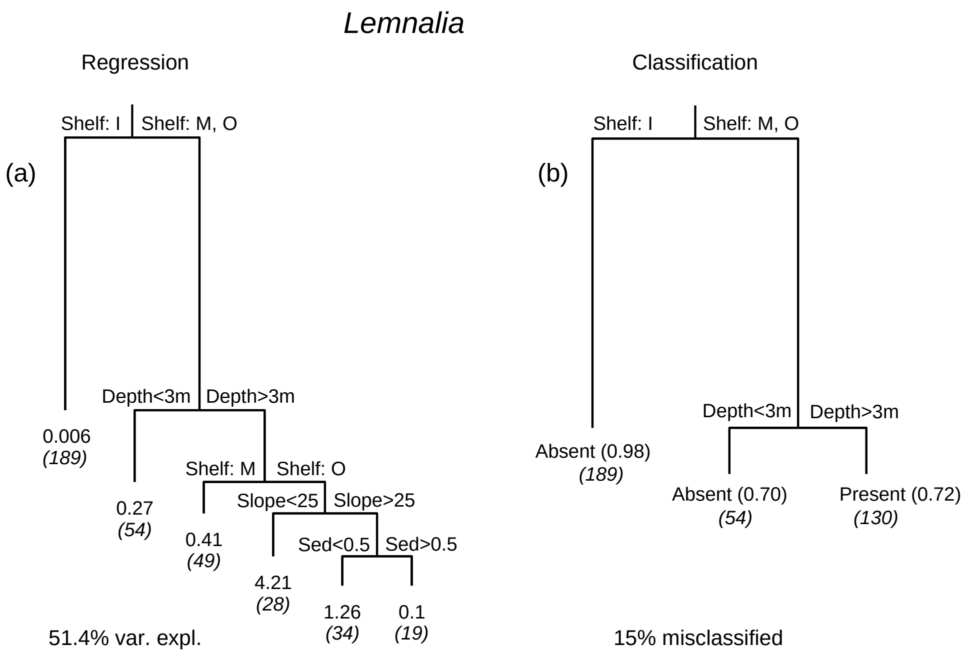

Figure 4. Regression trees of *Lemnalia* shelf position, location and depth explaining (a) per centage cover and (b) presence-absence.
I denotes inshore reefs, M denotes mid-shelf reefs, O denotes outer/offshore reefs.

Multivariate Regression Trees

Multivariate regression trees (MRT) (De'ath and Fabricius 2000) extend univariate regression trees by using a multivariate response, and forming the groups according to a chosen measure of species dissimilarity. Figure 5 shows how the species composition of three soft corals depends on their distance to rivers and coast, and sediment levels.

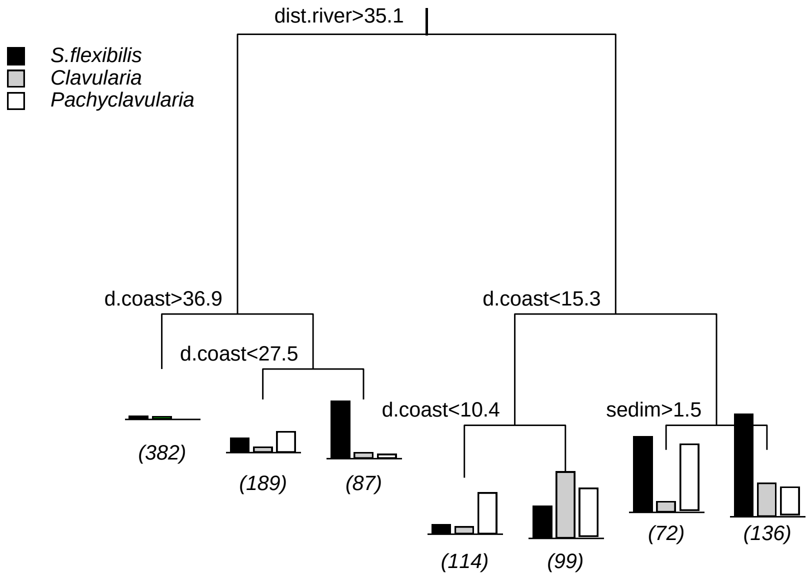

Figure 5. Regression tree analysis of three species of soft coral in terms of distance to rivers and the coast, and sediment levels.

Modelling Biodiversity using CART and MRT

Using MRT we can directly relate species composition to environmental data. The groups form constrained community types, with each type defined by a particular set of environmental conditions. The inclusion of explanatory spatial variables can lead to well-defined assemblages

that do not overlap spatially. This greatly assists in the determination of bioregions. For individual taxa of interest, their distributions and ecological niches can be efficiently uncovered by using univariate regression trees (De'ath and Fabricius 2000).

The predictive capability of the CART-MRT approach is maximised (and known) when using cross-validation to select the optimum number of groups. Thus we can precisely quantify the probability of individual taxa and assemblages occurring under various representative area schemes.

Traditional classification approaches, such as clustering, followed by discriminant analysis to relate cluster membership to environmental data, is more complex than the direct constrained clustering of MRT. Cluster analysis generates groups that may be internally homogenous, but group members are often scattered spatially and poorly explained by the environmental data. This aspect, together with the difficulty of quantifying the predictive capability of composite methods, limits their effectiveness for defining bioregions.

The plot of an MRT is simply interpretable (figure 6), both in terms of species composition, and environmental and spatial effects. It can be further enhanced by incorporating the MRT output into a GIS. The reef and non-reef CART analyses, which were most useful in developing the bioregions were those in which all the key datasets were used.

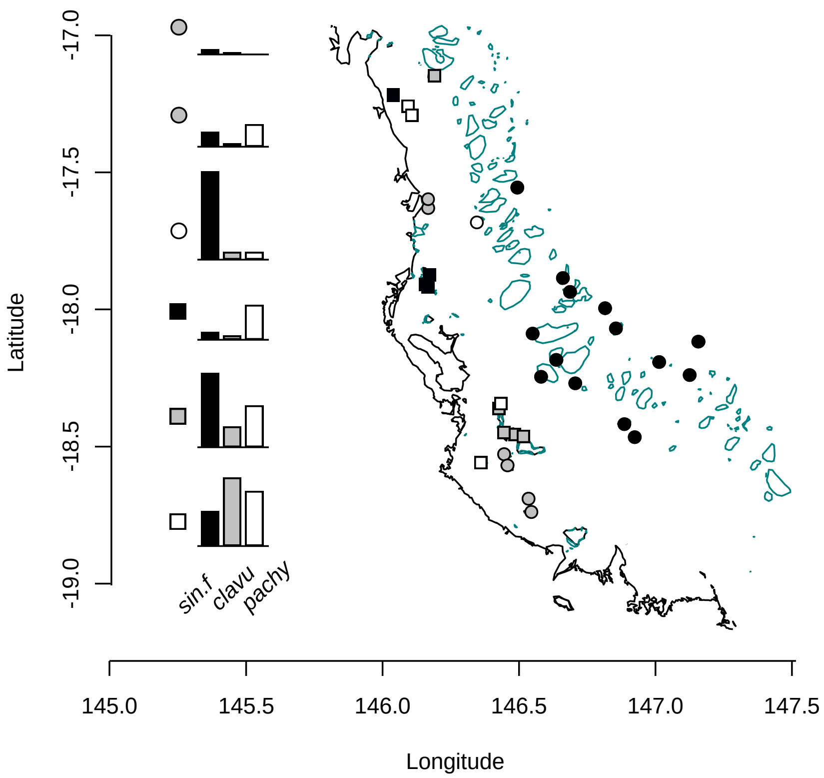

Figure 6. Regression tree analysis of three species of soft coral from Cairns to Townsville.

Regionalisation Workshops

Two panels of experts were formed to produce a biophysical description of the Great Barrier Reef World Heritage Area. Separate workshops on the reef and non-reef environs, followed by a Plenary session, were convened for four reasons:

1. Coral reefs are very distinct habitat units that have been the focus of extensive research for over 30 years (since the development of SCUBA). Hence, our knowledge of this system is far more comprehensive than, for example, knowledge of the soft bottom inter-reefal habitat.
2. Data and information on the reef areas were readily available for mapping and MRT analysis.

3. Combining reef and non-reef habitats in one description of diversity would have been an unnecessarily complex process, due to the varying spatial scales at which ecological processes function and the variable quality of available data.
4. Finally, panel members requested a plenary workshop to explore the potential for integrating the two descriptions.

Panel Selection

Potential workshop members were identified during the surveys of over 70 scientists and experts, and by the Scientific Steering Committee for the Representative Areas Program. The aim was to bring together a group of experts that maximised collective experience and diversity of disciplines. The Reef Panel drew upon over 120 combined years of knowledge and research in the Great Barrier Reef World Heritage Area and similar habitats, while the Non-Reef Panel drew upon over 100 combined years.

Workshop Methodology

Specific guidelines (below) were developed to ensure that the two workshops (Reef and Non-Reef) followed a similar process, and produced outputs that, as far as possible, were justifiable and of high scientific integrity. The guidelines outlined the principal objectives, expected outputs and the data available at the time of the workshops. These guidelines developed by the Scientific Steering Committee determined that the diversity of the Great Barrier Reef World Heritage Area should be described at the scale of 100s (sometimes 10s) of kilometres. This is the scale over which habitats can change, and also the scale of resolution of the data. This scale matched the taxonomy of levels of biodiversity classification discussed by Edyvane (1996).

A complete list of datasets (table 1), hard copies of data sets (paper maps and a Data Atlas, Great Barrier Reef Marine Park Authority 1999b) and notes describing data quality, source and key patterns were provided to the workshop participants.

Panel participants were briefed about the Representative Areas Program and their specific role in the program. It was explained that their input would be integral to the decision-making process in conjunction with subsequent social, economic and cultural analyses.

Workshop Objectives and Outputs

The key objectives of the workshops were:

A. To produce a biophysical descriptions of the reefs and coastal regions, Great Barrier Reef lagoon and inter-reef, continental shelf and pelagic systems, based on:
   - Mapped distributions of taxa including both abundance and patterns in diversity
   - Distributions of physical habitat descriptors such as sediment type, grain size, bathymetry, currents
   - Reef geomorphology, where applicable
   - Mapped distributions of critical habitats and sites for migration, spawning, nesting etc.
   - Mapped distributions of natural disturbances
   - General knowledge of the Great Barrier Reef marine ecosystem.

B. To produce informative and self-explanatory descriptions of the bioregions.

C. To classify the bioregion boundaries in terms of the degree of 'fuzziness' by attributing them to one of the following categories, where possible:
   1. Clearly defined on physical characteristics
   2. Clearly defined on biological characteristics
   3. Clearly defined on both physical and biological characteristics
   4. Fuzzy because in reality we are dealing with a continuum
   5. Fuzzy boundary because of a lack of data or knowledge.

The main expected outcomes from the workshops were:

- A list of bioregions based on the data provided and expert knowledge
- Clear descriptions of the bioregions and the boundaries.

Reef Workshop

Participants were provided with all the biophysical data, existing bioregionalisations and spatial analyses that were available at the time of the workshop (refer Appendix 2 for a list of the material available to the participants). Species distributions, physical data and results of the CART analysis were provided as a hardcopy and put into GIS (ArcView). Mapped distributions of taxa and results of analyses were projected onto a whiteboard through ArcView. Overall, GIS (ArcView) proved to be a powerful exploratory tool during the workshop as experts could access multiple layers of data and analytical results simultaneously or sequentially; new boundaries could be immediately entered into GIS; and new bioregions could be visually compared to existing ones and those derived from the CART analyses.

The following guidelines, developed by the Scientific Steering Committee, were considered during the workshop as bioregions were defined. The reefs included in candidate areas should include examples of all elements of reef biodiversity by:

- Incorporating all reef geomorphic types; habitat types; assemblages; taxa; and species
- Representing the species richness of the area surrounding any candidate area, whether of high or low taxonomic diversity, since low diversity does not necessarily indicate low-value environments
- Ensuring the maintenance of ecological processes (e.g. Recruitment)
- Incorporating a mosaic of habitats that would by default, encapsulate a suite of known and unknown species and assemblages
- Maximising cross-shelf extension to encapsulate documented variation in species diversity, abundances and life history characteristics
- Ensuring replication of candidate areas to spread the risk of damage from natural disturbances.

First, the results of the CART analyses on the six key reef data sets were assessed against the experts' general knowledge of spatial patterns in reef biota and then compared to the initial bioregionalisation based on reef biota (figures 2, 3). The experts decided to use the CART results as a template for developing the final biophysical regions. Four of the six scientists were either custodians, or had detailed knowledge, of all six key data sets used in the analysis.

The CART spatial clusters were projected onto the whiteboard over maps of the coast, reefs and islands. The length of the Great Barrier Reef World Heritage Area was divided into ten sections of roughly equal size. The experts then defined the bioregion boundaries in sections from the far northern Great Barrier Reef World Heritage Area to the south. The boundaries drawn on the whiteboard were digitised immediately in ArcView. The initial positions of the boundaries were based on general knowledge of spatial patterns in taxa but individual data sets were referred to refine the positions. The general morphology of the Great Barrier Reef Region - continental shelf width and orientation; presence or absence of barrier reefs; reef size; and depth of surrounding water - were identified as the main physical structuring parameters. Broad-scale currents and tidal height were used to assist in defining boundaries where biological information was limited.

As the bioregion boundaries were drawn, the regions were labelled and described according to biophysical criteria. Justifications for the delineation of the regions were recorded during the workshops.

Non-Reef Workshop

The Non-Reef Panel followed a similar process to the Reef Panel; however it faced a number of unique challenges:

- It worked from a more limited database than the Reef Panel
- The members were unfamiliar with the range of non-reef data available
- There were no combined bioregionalisations published before the workshop. In contrast to the Reef Panel, the only published biogeographic analysis that existed was a Queensland-wide analysis of sponges (Hooper et al. 1999)
- The Non-Reef Panel dealt with a greater variety of systems - coastal, inter-reef, lagoon, continental slope, abyssal plane and pelagic.

Consequently, the Non-Reef Panel needed time to familiarise themselves with the data which consisted of: spatial patterns in diversity and species distributions of sponges and seagrasses; general epibenthos of the Far Northern cross-shelf transect; sediment distributions; pelagic fishes; and broad-scale currents of the Great Barrier Reef World Heritage Area (Appendix 2).

The same guidelines, developed by the Scientific Steering Committee, were considered during the Non-Reef workshop as were considered during the Reef workshop, with the exception of reef-specific guidelines.

The first step in the bioregionalisation was to differentiate the coastal zone based on the offshore extent of terrigenous sediments in relation to silica or calcium carbonate sand deposits. The panel decided to use the distribution of carbonate sediments and sediment size as base layers. Seagrass, algae and epibenthic fauna data were then overlaid, and regions identified principally on the biota. Region boundaries were to be evaluated against the distributions of sponges and pelagic fishes to ensure comprehensiveness.

Following assessment of the CART analysis of the key data sets (e.g. Queensland Department of Primary Industries – Northern Fisheries Centre deepwater seagrasses and epibenthos, and the AUSEABED sediments, Coles et al. 2000) and familiarisation with all of the available data, the panel divided the Great Barrier Reef Marine Park into nine sectors of equal scale. As with the reef bioregionalisation, coast, reefs and islands coverages formed the base maps projected onto a whiteboard using Arcview; the regions defined by the CART analyses of deepwater seagrasses and epibenthos were overlaid. The CART analyses of the sediment distributions and other physical data were displayed periodically to clarify boundary positions where there was limited biological information. Region boundaries were positioned largely on the distributions of seagrasses, epibenthos and sponges; major changes in sediments; broad-scale currents; and bathymetry.

Plenary Workshop

The reef and non-reef bioregionalisations were presented simultaneously to the Plenary Panel. The relative boundary positions were compared from north to south. Some common boundaries were identified; for example, cross-shelf divisions in the Far Northern Section and latitudinal breaks around Princess Charlotte Bay, north of Cairns and at ~20^{o}S. In addition, the area south of Princess Charlotte Bay to Lizard Island/Rocky Isles was identified as a biogeographic transition area.

Despite some level of concurrence, the Plenary Panel unanimously decided to keep the two bioregionalisations separate, as in each case differences in boundaries existed for specific reasons.

Public Review

Much information about the marine environment of the Great Barrier Reef World Heritage Area is not held in databases or confined to scientific expertise. Commercial and recreational users often have valuable knowledge about the areas they use. In September 2000, the Great Barrier Reef Marine Park Authority distributed 2000 brochures together with the draft bioregions to marine park users, stakeholders and community groups to ask their input. Their comments on the bioregions were specifically asked for and they were also asked them to send any information they had on the bioregions. They were invited to suggest (and justify) changes to the boundaries and descriptions of bioregions and were assured that the Reef and Non-Reef Panels would review their information. Suggestions that complemented the panel's knowledge were used to refine the bioregions.

Twenty-one suggestions for changes to the bioregions or their descriptions were received. Four gave detailed descriptions of biologically special or unique places which were used as such (Fernandes et al. 2010). Six conflicted with the information that the expert panels had provided. Nine were implemented, as they were clearly defined, well justified and complemented the existing body of information. Two were not sufficiently well defined to implement.

RESULTS

Biophysical Regions - Descriptions and Justifications

The Classification Phase resulted in the division of the 348 000 km ^{2} of the Great Barrier Reef World Heritage Area and the more then 2900 reefs into 70 bioregions: 30 in reef and 40 in non-reef areas (the latter includes eight less-known offshore areas)(see figures 7, 8 and tables 2 and 3 for descriptions). The bioregions ranged in area from 2.31 km^2 to 29 300 km^2. They reflect the huge diversity of habitats and communities within the Marine Park and the variation between reef and non-reef areas, north and south, and inshore and offshore.

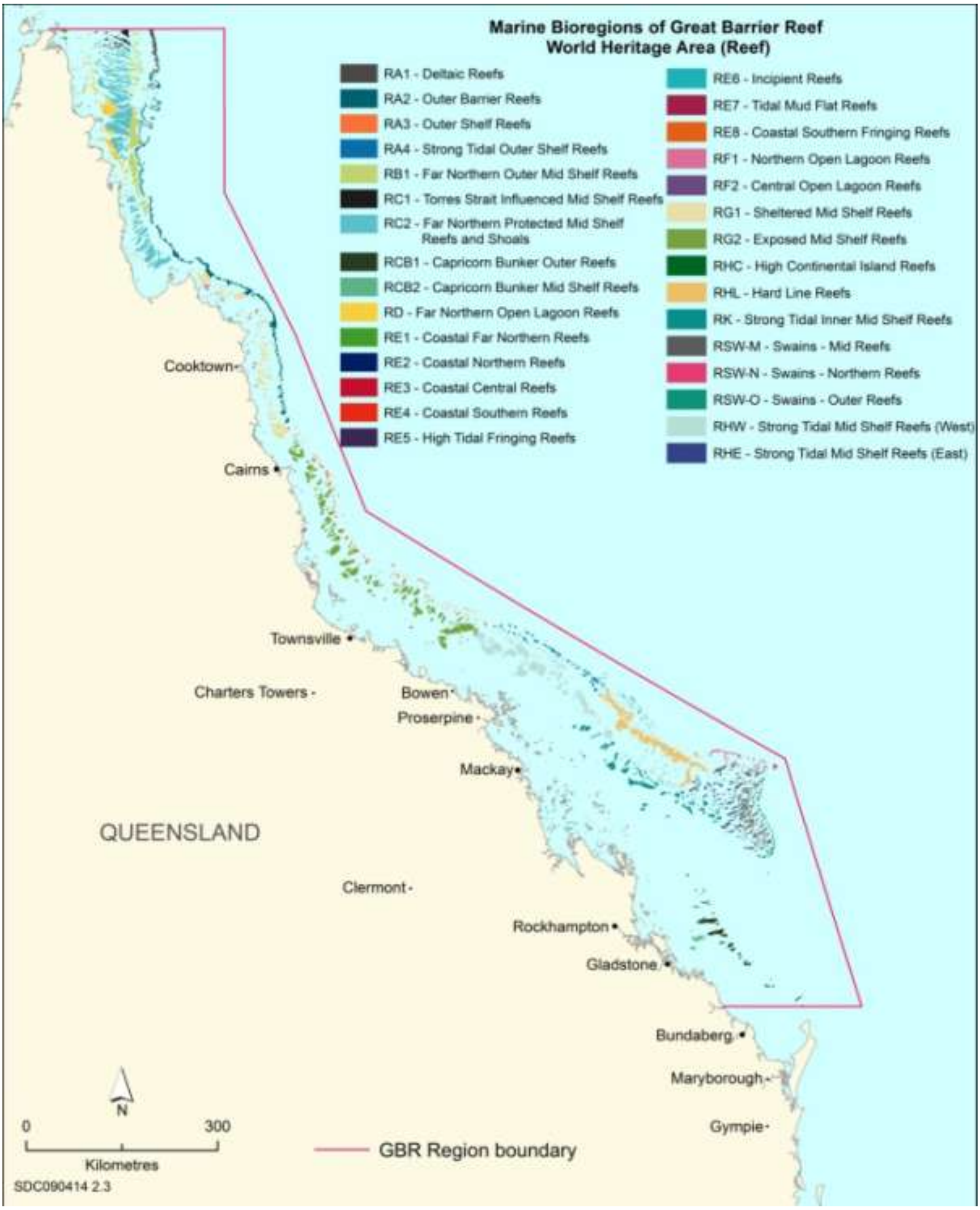

Figure 7. Reef bioregions of the Great Barrier Reef.

Figure 8. Non-reef bioregions of the Great Barrier Reef.

Table 2. Description of reef bioregions.
The table provides a Bioregion ID, Bioregion Name and Description/Justification. Biologically distinct refers to differences in absolute and relative abundances of species of hard and/or soft corals and/or fish and/or macroalgae.

RA1 Deltaic Reefs: Distinct geomorphology, coral and fish. Torres Strait influences (strong currents). Less exposed to Coral Sea than RA2 due to widening of continental shelf.
RA2 Outer Barrier Reefs: Distinct geomorphology, coral and fish. Coral Sea influence. Mosaic of steep, exposed high-energy fronts and current-swept channels. Leeward reef benthos has a mix of clear-water and coastal species.
RA3 Outer-Shelf Reefs: Distinct geomorphology, with more submerged reefs than elsewhere. Transition zone. Open matrix of reefs allows greater Coral Sea influence, little coastal influence.
RA4 Strong Tidal Outer-Shelf Reefs: Continental shelf protrudes widely but slopes gently. Small outer reefs set back from the edge. Strong tidal movement, high-energy area, biologically distinct.
RB1 Far Northern Outer Mid-Shelf Reefs: Distinct biologically from true outer-shelf or mid-shelf reefs. Species-rich benthos. Mostly smaller reefs, dominated by shoals.
RC1 Torres Strait influenced Mid-Shelf Reefs: Reefs small, and have Torres Strait influence. Biologically distinct from RC2.
RC2 Far Northern Protected Mid-Shelf Reefs and Shoals: RC2 and RD have highest species diversity of octocorals on the Great Barrier Reef. Rich hard coral communities. Larger shoals and reefs than RC1. Extensive reef flats and shoal terraces, separated by diverse channel system (some calm and sheltered, others with strong flow). Many turtle sightings.
RD Far Northern Open Lagoon Reefs: RC2 and RD have highest species diversity of octocorals on the Great Barrier Reef. Small islands and low vegetated isles with fringing reefs as well as near-shore platform reefs. Distinct and species rich coral communities. Species rich algal communities. Less fish diversity than RC2. Many turtle sightings.
RE1 Coastal Far Northern Reefs: Relatively rich in both hard and octocoral species. Sediment resuspension during south-east trade winds. Biologically distinct patches of reef.
RE2 Coastal Northern Reefs: Higher species richness, and more *Sargassum* than in RE3. Low soft coral cover, but higher richness than RE3. Silty in sheltered areas. Sediment resuspension during south-east trade winds. Biologically distinct patches of reef.
RE3 Coastal Central Reefs: Biologically distinct, patchy reefs; more exposed to prevailing winds than RE2. Very low soft coral diversity and cover, but rich in gorgonians on deeper reef slopes. Influenced by episodic Burdekin River plumes and other annual river plumes. Very muddy in sheltered areas and on deeper slopes. Sediment resuspension during south-east trade winds.
RE4 Coastal Southern Reefs: Moderate tidal ranges, moderate to high turbidity. Broad Sound mouth and Proserpine River influence on water quality. Varying exposure levels within the region, fairly high habitat diversity. Biologically distinct.
RE5 High Tidal Fringing Reefs: Very high turbidity, thus habitat for light-avoiding benthos at the base of the reefs. Strong coastal influence and unusually strong currents for inshore area, strong tidal movements and high tidal range. Well-developed fringing reefs, with poor hard and soft coral communities, but rich gorgonian and algal communities.
RE6 Incipient Reefs: Area has lots of algae and only incipient reefs. Very high turbidity and tidal movements. Strong southern influences on coral and algal species.
RE7 Tidal Mud Flat Reefs: Greatest tidal range and tidal movements on the Great Barrier Reef. Higher turbidity than RE5 and RE6. Very few reefs or corals, but distinct algal communities.
RE8 Coastal Southern Fringing Reefs: Dominated by episodic Fitzroy River flood plumes. Southern influence in algal species. Fringing reefs around high continental islands with high cover of hard and soft coral and algae, but low coral diversity.
RF1 Northern Open Lagoon Reefs: Small islands and low vegetated isles with fringing reefs. Muddy influence from wet tropical rivers. Distinct in terms of reef size and assemblages (soft coral, fish and algae).
RF2 Central Open Lagoon Reefs: Region dominated by episodic Burdekin flood plumes. Sea floor deeper and lagoon significantly wider, with more tidal movement than RF1. Few reefs and islands.

RG1 Sheltered Mid-Shelf Reefs: Sheltered by outer barrier reefs. Reefs may form lagoons. Distinct hard and soft corals, fish and algae. Octocoral assemblages diverse, mostly clear-water species and some coastal species.
RG2 Exposed Mid-Shelf Reefs: Fairly exposed to Coral Sea, with clear water and strong wave action on outer area. Reefs may form lagoons. Episodic Burdekin flood plumes may reach inner reefs adjacent to RF2, resulting in greater cross-shelf variation than in many other bioregions.
RHE Strong Tidal Mid Shelf Reefs (East): High energy/high tidal movement. Turbid water. East Australian Current splits to make an eddy in the open area where there are small well-spaced reefs. Many smaller fish - possibly high-recruitment area. High water-column productivity. Biologically distinct (fish). Leeward parts of reefs dominated by filter-feeders. Fuzzy boundary with RSWM.
RHW Strong Tidal Mid-Shelf Reefs (West): High energy/high tidal movement. Turbid water. High water-column productivity. Biologically distinct (fish). Leeward parts of reefs dominated by filter-feeders.
RHC High Continental Island Reefs: *Palm Islands*: Geomorphologically unique, with high diversity (habitat and benthos) due to exposure to clear water by the Palm Passage on the eastern sides - very sheltered and muddy coastal habitats on the protected sides, and current-swept channels between the islands. *Whitsunday Islands*: Geomorphologically unique. Both cross-shelf and north/south gradient in benthic communities. Species-poor, muddy reefs close to the Proserpine River. Unique and very fragile hard and soft coral communities in the inlets.
RHL Hard Line Reefs: Geomorphologically distinct. Extensive outer barrier, set well back from edge of continental slope. Fish communities less diverse, but similar to Swain Reefs and Whitsundays. Strong influence from Broad Sound, high tidal energy. Current-swept channels with steep walls, sheltered leeward-reef communities with low diversity but high abundances of selected species.
RK Strong Tidal Inner Mid-Shelf Reefs: High turbidity and very high water column productivity. Distinct from RHW and RHE. Rich bivalve, sponge and ascidian (sea squirt) dominated communities on leeward reef slopes. Distinct fish communities (including baitfish) with lower diversity. Strongly influenced by Broad Sound tidal node.
RCB1 Capricorn Bunker Outer Reefs: RCB1 and RCB2 oceanographically isolated, may be biologically distinct from the rest of Great Barrier Reef. Set back from edge of continental shelf but very exposed due to local currents. Distinct differences in coral trout populations compared with the Swain Reefs and elsewhere on the Great Barrier Reef. High soft coral diversity.
RCB2 Capricorn Bunker Mid-Shelf Reefs: RCB1 and RCB2 oceanographically isolated, may be biologically distinct from rest of Great Barrier Reef. More turbid, more protected and more algae than RCB1, characteristic of mid-shelf area. Good turtle-feeding habitat.
RSWM Swains Mid Reefs: Very sheltered. Biologically distinct communities from Swains Outer Reefs (RSWO). Many cays. Fuzzy boundary with RHE.
RSWN Coral Sea Swains-Northern Reefs: Near edge of continental slope. Northerly aspect. Biologically distinct with strong influence of Coral Sea fauna and some similarities to northern outer-shelf reefs, but lower diversity of hard and soft coral species.
RSWO Swains Outer Reefs: Set back from shelf edge. Easterly aspect. Lower influence of Coral Sea fauna than RSWN. Biologically distinct from Mid Swains (RSWM), more similar to Capricorn Bunker Outer Reefs (RCB1). Communities on flanks and leeward sides dominated by xeniids, a large and very characteristic group of soft corals, unique in their ecology and biology.

Table 3. Descriptions of non-reef bioregions.
The table provides a Bioregion ID, Bioregion Name and Description/Justification. Biologically distinct refers to differences in absolute and relative abundances of seagrasses and/or sponges and/or general epibenthos and/or pelagic fishes.

NA1 Coastal Strip: Sand rather than mud, low carbonate and low nutrient. Dry tropic influence from land. Very dense seagrass in places – some areas important for dugong and turtle feeding. Boundaries of bioregion along the coast match changes in shoreline type.
NA3 High Nutrients Coastal Strip: Terrigenous mud and high levels of nutrients from the adjoining land. Seagrass in sheltered sites only. Good turtle and dugong feeding habitat. Wet tropic influence for much of the coast.
NA4 Inshore Terrigenous Sands: Strong Broad Sound tidal influence. Very mobile sands, little algae or seagrass.

NB1 Inshore Muddy Lagoon: High carbonate sand, prawn habitat. Rich soft-sediment sponge fauna, 24 per cent not yet recorded elsewhere.
NB3 Inner Shelf Seagrass: Very sandy area with distinct invertebrate and fish communities. Seasonal seagrass in patches. Distinct gorgonian fauna, associated with low wooded islands. Boundary for sponges and gorgonians extends south to Cape Grafton only.
NB5 Inner Mid-Shelf Lagoon: Coarse sediment from land influences (medium-high land input). Sparse seagrass.
NB6 Inner Shelf Lagoon Continental Islands : Strong currents, gravel and hydroids around Pine Peak Island. Some gorgonians and low reef sites, water very turbid. Seagrass meadows in some bays.
NB7 Mid-Shelf Lagoon: Muds dominate, minimal algae or seagrass. Leeward parts of Hook and Bait Reefs are geomorphologically different. Very steep, extensive benthos, gravel, low sponge diversity but only 21 per cent of species are similar to those in southern lagoonal reefs. Mobile sand dunes influenced by strong East Australian Current.
NB8 Capricorn Bunker Lagoon: *Halimeda* and seagrass up to 50 per cent cover. Mixing of southern inshore and tropical inshore sponge species, 28 per cent not yet found elsewhere.
NC Mid-Shelf Inter-Reef - Seagrass : Fine sediments, high carbonate content between a large number of reefs. Contains deep water shoals.
ND Mid-Shelf Inter-Reef: Shelly sands, almost no fine sediments. Very little seagrass. Abundant crinoids (feather stars).
NE Outer Shelf Lagoon: *Halimeda* Banks. *Caulerpa* goes only as far as the inner edge of the shelf edge. Eastern boundary follows the inner boundary of the Ribbon Reefs.
NF *Halimeda* Banks – some coral: *Halimeda* and *Caulerpa* banks with deep rubble reef or sparse coral patches. NE/NF boundary follows Pollard Channel.
NH Mid-Shelf Sandy Inter-Reef: Sandy, low-density seagrass beds, known turtle-foraging sites.
NI *Halimeda* Banks: Dense *Halimeda*, almost no coral, some seagrass.
NJ Princess Charlotte Bay Outer Shelf: Sandy, change to carbonate sediments. Red-spot king prawn grounds.
NK Princess Charlotte Bay: Muddy bay, surrounded by silica sand deposits with low nutrient levels. Some seagrass.
NL1 Outer Shelf Algae and Seagrass: Areas of medium-density seagrass and medium density algae, diverse solitary corals. High diversity of sponge species at Lizard Island and North and South Direction Groups, 28 per cent not yet recorded elsewhere on the Great Barrier Reef.
NL2 Outer Shelf Seagrass: Shelly sands (very coarse) with smaller areas of seagrass and algal gardens (low density).
NL3 Outer Shelf Inter Reef - Central: Shelly sands with very sparse algae and seagrasses.
NL4 Outer Shelf Inter Reef - Southern: High currents. Coarse sediments. Available data indicates low biomass and high diversity of biota.
NL5 Swains Inter Reef: Rich sponge fauna, 26 per cent not yet recorded elsewhere on Great Barrier Reef, and only 31 per cent of species occurring in both Swain and Capricorn Bunker regions. Complex and rocky in places, with lower tidal current than in NL4. Fuzzy boundary with NL4. Some *Halimeda*, and some seagrass in patches in middle Swains.
NM Mid Shelf Seagrass: Dense seagrass beds. Very muddy area with distinct invertebrate and fish communities. High diversity of sponges near Turtle Islands group with 36 per cent not yet recorded elsewhere in Great Barrier Reef region.
NN Capricorn Bunker Banks: Pre-reef *Halimeda* deposits around Capricorn Bunker reefs. Diverse sponge fauna (187 species), mostly different from southern fauna (NB8), slightly more similar to northern island-group faunas (NL5).
NO Capricorn Trough: Deep oceanic influence. Mix of pelagic (e.g. foraminifera) and *Halimeda* seabed deposits. Very fuzzy boundary between NO and NB7.
NP Eastern Plateau: Based on depth, region broadens towards Eastern Plateau; mostly fine pelagic sediments.
NQ Steep Slope: Very steep slope dropping off to depths below 2500m; slopes prone to slippages.
NR Queensland Trough: More moderate slope than NQ; mostly fine pelagic sediments.
NS Intermediate Broad Slope: Widening of slope with lower gradient; mostly fine pelagic sediments.

NTW Western Pelagic Platform: Gentle, broad slope; number of sediment drifts (mobile sand banks formed under East Australian Current); mostly fine pelagic sediments punctuated by many coral shoals. Oceanic sharks and large bluespot trout present.
NTE Eastern Pelagic Platform: Gentle, broad slope. Mostly fine pelagic sediments with several long (30 n.mile) E-W shoals of extensive plate corals to 5-10 m depth. A number of mobile sand banks have formed under East Australian Current.
NU Terraces: Characterised by hard substrate seafloor terraces at depths of 90-300 m; terraces punctuated by shoals to depths of around 10 m.
X1 Far Northern Offshelf; X2 Offshelf Queensland Trough; X3 Outer Far Northern Inter Reef; X4 Capricorn Bunker Inter Reef; X5 Outer Central Inter-Reef; X6 Central Offshelf; X7 Central Inter Reef; X8 Southern Embayment: These deepwater, offshore areas extend from the edge of the continental shelf to the eastern border of the Great Barrier Reef World Heritage Area. They were described largely from physical information. For the purposes of the Representative Areas Program, and until further information is gained, they are treated as separate bioregions.

The fuzziness of boundaries between bioregions was decided by the expert panels. Most of the boundaries between the reef and non-reef bioregions were classified as 'fuzzy' (table 4), due in part to the connectivity of the regions and in part to incomplete knowledge. The fuzziness of other boundaries was classified as indicated in table 5.

Table 4. Fuzziness of bioregion boundaries.

	Number of bioregion boundaries	
Fuzziness class	**reef**	**non-reef**
1. Clearly defined physically	9	6
2. Clearly defined biologically	4	2
3. Clearly defined both physically and biologically	9	6
4. Fuzzy boundary due to continua in environment	3	14
5. Fuzzy boundary due to the limited data	25	2
Combination 4/5		36
Total	50	66

A number of points of caution were raised by the Non-Reef Panel, including:

- Their limited familiarity with the available data and information
- The lack of broad-scale data, with the exception of the queensland department of primary industries and fisheries epibenthic (seagrass) surveys
- Difficulties in spatial extrapolation of data and the use of physical and biological surrogates. In terms of physical surrogates, the relationships among key factors and distribution of biota are highly variable both temporally and spatially. Generally, only a subset of the species/taxa among those sampled at any one time show significant relationship with physical variables (e.g. sediment type: maximum r^2 of ~30 per cent); for many species there is no apparent significant relationship.

The following caveat made by both the Reef and Non-Reef Panels applies to all the bioregions:

- The bioregions shown on both maps (figures 7, 8) were defined by a panel of experts in the Great Barrier Reef region, using the best data and regional analysis available to Great Barrier Reef Marine Park Authority in 1999. The maps represent consensus among the experts on the delineation of 'bioregions' within the Great Barrier Reef World Heritage Area.
- The experts considered that areas within each bioregion should be protected in a comprehensive, adequate and representative manner to protect the WHA's biological diversity.
- In some cases the boundaries of the bioregions are not precise, due to the lack of information or the gradation between the communities.
- The attributes for each bioregion were distinguished by the experts, based on the direct observations of locations within the bioregions and extrapolation from the understanding of how habitats relate to location and the environment. This was supplemented by analytical methods (spatial cluster analysis), using the appropriate available data. The bioregions will need to be reviewed as new data and information become available.

Table 5. Summary of the boundary descriptions of reef and non-reef bioregions.
1 = Clearly defined on physical characteristics; 2 = Clearly defined on biological characteristics; 3 = Clearly defined on both physical / biological characteristics; 4 = Fuzzy boundary because that in reality there is a series of continua; 5 = Fuzzy boundary because of the lack of data/knowledge. All reef boundaries not classified explicitly were treated as category 5; all non-reef boundaries not classified explicitly were treated as category 4 to 5.

Boundary	**Category**	**Boundary**	**Category**	**Boundary**	**Category**
RC1:RC2	1	RG2:RF2	1	RK:RHW	3
RD:RC2	1	RG2:RHW	2	RHW:RHL	1
RC2:RB1	4	RA3:RA4	2	RHL:RA4	1
RA1:RA2	1	RA4:RHW	4	RHL:RSW-M	3
RA2:RB1	3	RHC:RE5	3	RSW-M:RSW-N	3
RD:RG1	3	RE4:RE5	3	RHE:RSW-M	5
RF1:RG1	1	RE5:RE6	5	RSW-M:RSW-O	3
RA2:RA3	1	RE5:RE8	5	RCB2:RF3	3
RA3:RG2	4				
NA1:NB1	3	NM:NL1	4/5	NS:X6	1
NA1:NM	3	NL1:NQ	1	NB5:NB7	5
NB1:NC	3	NM:NA1	1	NB6:NB8	4
NB1:NH	4	NM:NB3	4	NB7:NO	4
NB1:NJ	4	NL1:NL2	4	NL4:NL5	3
NC:ND	5	NL2:NL3	4	NB8:NB7	4
NC:NH	4	NB3:NB5	4	NU:X8	1
NH:NJ	2	NR:X2	1	NB8:X8	1
NE:NF	4	X4:NB8	3	NN:X4	3
NL3:NL4	4			NJ:NQ	4

Independent review of the classification process and outputs

The then Chief Executive Officer of the Cooperative Research Centre for Reef Research, Dr Russell Reichelt, reviewed the process and outputs of the Classification Phase. He was not involved in this work but was a senior scientist who had researched for many years in the Great Barrier Reef World Heritage Area and was familiar with the work of other scientists in the region. The two main terms of reference of the review were:

1. Review the scientific and technical aspects used by Great Barrier Reef Marine Park Authority in the Representative Areas Program from November 1998, with specific review of the Classification Phase.
2. Assess the quality of the scientific and technical work/methods carried out for the Classification Phase of the RAP and report whether the Classification Phase was:
   (a) conducted in the most efficient and effective manner considering the existing resource, time and data limitations; and
   (b) an acceptable basis upon which to further develop the RAP.

The full terms of reference are given in Appendix 3.

Dr Reichelt concluded that: "*the classification of spatial patterns in biodiversity in the Great Barrier Reef World Heritage Area is of very high quality and has produced a robust regionalisation*". Furthermore, "*At the scale of the undertaking, this work is exceptional internationally in that it has assessed all of the marine habitat types in the WHA, rather than focussing only on shallow coral reefs and coastlines*".

Significantly, Dr Reichelt considered that "*the Authority has sufficient information in terms of regionalisation on which to base its next phase(s), the identification and selection of candidate areas*".

The full report can be obtained by contacting the Great Barrier Reef Marine Park Authority.

DISCUSSION

In the past, management has focussed on remote, so-called “pristine”, areas and higher-profile and better-known species or habitats (Margules and Pressey 2000). The implicit assumption was that the lower-profile, lesser known species and habitats are less important or less valuable. As more information is gathered, the more we learn that lower profile taxa and habitats do matter (e.g. the role of coralline algae in building coral reefs, the role of mangroves as nursery areas and for shoreline protection). Both national and international management agencies have moved towards a more comprehensive view – one that classifies entire natural systems either hierarchically or through describing bioregions at some scale (Kelleher et al.1995, Thackway 1996, Australian and New Zealand Environment and Conservation Council 1999, Sattler and Williams 1999, Day and Roff 2000).

The Classification Phase of the Great Barrier Reef Marine Park Authority’s Representative Areas Program, as comprehensively as possible, delivered a description of the biological diversity of the entire Great Barrier Reef World Heritage Area. While not based on complete knowledge, the description was based on the best knowledge available and provided the most comprehensive and defensible basis for a Reef-wide approach to management available to date.

Uncertainty associated with the regionalisations was addressed in two ways: explicit descriptions of the fuzziness of the bioregion boundaries, and a caveat that recognises that improvement in data or analytical techniques will refine the bioregionalisations.

The regionalisation of the Great Barrier Reef World Heritage Area has highlighted data gaps. Despite over 30 years of underwater research on reefs, limited empirical data are available on biota for large sections of reefs, particularly in the Far Northern areas of the Great Barrier Reef Marine Park, and for most Great Barrier Reef deepwater (>50 m) reefs. In addition, spatial patterns in biodiversity within the pelagic habitat, continental slope and abyssal plain are even more limited but have been considered, as far as possible, in this study. There is an urgent need for more information on the distributions of inter-reefal fauna (infauna and epifauna) and flora. The Great Barrier Reef Marine Park Authority is working together with key scientific institutions to address these data gaps.

The regionalisation of the Great Barrier Reef World Heritage Area facilitated the Representative Areas Program in fulfilling its biodiversity protection objectives. Representation of bioregions in no-take areas offers the best way to protect examples of every kind of habitat and community type in the Marine Park; the Great Barrier Reef Marine Park Authority used the bioregions as one of several principles (see Fernandes et al. 2005) to implement the comprehensive, adequate and representative network of no-take areas throughout the Marine Park.

The Great Barrier Reef Marine Park Authority acknowledges that the Representative Areas Program, while important, is one of several tools needed to protect biodiversity in the Marine Park. Other Great Barrier Reef Marine Park Authority programs, in collaboration with Australian and the Queensland Government and private industry, are addressing issues relating to sustainable use including the sustainability of commercial fisheries, tourism and recreational use, water quality and coastal development.

The *classification* of spatial patterns in biodiversity within the Great Barrier Reef World Heritage Area led to the *Review* and *Identification* phases of the Representative Areas Program. The review phase required assessment of the existing network of no-take areas against the bioregions, e.g. how well the existing no-take areas protect the bioregions and habitats identified within the Great Barrier Reef Marine Park. The identification phase produced spatially different networks of no-take areas that could achieve the biological objectives of the program (Lewis et al. 2003). The areas finally *selected*, in the selection phase, as new no-take areas were those that satisfied the ecological objectives (Fernandes et al. 2005, 2009, 2010; Dobbs et al. 2007, 2008) while maximising complementarities with social, economic, cultural and management values and uses (e.g. Chadwick et al. 2004).

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GLOSSARY

assemblages – groups of plants and animals

AUSEABED – is an information handling structure for seabed data about Australia's EEZ and accessible through the Ocean Sciences Institute at University of Sydney.

benthos – animals and plants living on the sea floor

biodiversity (biological diversity) –variety of life forms at the level of ecosystems, species and gene pools

biomass – the weight of all the plants and animals (of an area)

bioregion – an area of land and/or water whose limits are defined by the geographical distribution of biophysical attributes and ecological systems; the groups of animals and plants, and the physical features, are relatively distinct from the surroundings

bioregionalisation - the process by which bioregions are derived

biota – plants and animals of a region

bivalve – animal (mollusc) with two plates (valves) to its shell

candidate area – an area within a bioregion identified as suitable for inclusion in a comprehensive, adequate and representative network of no-take areas

carbonate – white chalky mineral formed from fragments of animal skeletons (e.g. coral, shells) and some seaweeds

Caulerpa – a group of green fleshy seaweeds

communities – groups of different plants and animals that live together in an area

diversity – variety in the number of plant and animal types in an area

epibenthos – animals and plants living on the sea floor at depths between the low water mark and the 200-metre line

episodic – occurring irregularly

filter-feeder – animal that feeds on small animals or plants by straining them out of the surrounding water

foraminifera – tiny oceanic animal with a chalky shell, which contributes to reef building

geomorphology – physical features of the earth's surface

gorgonian – horny coral or fan coral

habitat – the place or type of site in which an organism (or group of organisms) naturally occurs

Halimeda – tropical seaweed made up of chains of chalky segments; an important reef builder that grows in dense gardens

highly protected area – an area of land and/or sea where extractive uses are prohibited, and which is protected as far as possible from structures and from activities that pollute or damage habitats.

Hydroids – small colonial animals forming tuft-like growths on seaweeds etc.

incipient – beginning, in an initial stage

Marine Protected Area – an area of sea especially dedicated to the protection and maintenance of biological diversity and of natural and associated cultural resources, and managed through legal or other effective means

octocorals – group of corals with eight tentacles (includes fan corals and whip corals)

pelagic – living in the open sea or near the surface of the open sea

protected area – an area of land and/or sea that is managed in some way to maintain natural, social and/or cultural values (akin to any of the IUCN categories)

region – an area of land and/or water whose limits are defined by the geographical distribution of physical attributes

representative area – an area that is typical of its surroundings at some chosen spatial scale, having similar physical features, oceanographic processes and ecological patterns, and hence likely to have similar biological communities and/or species

representative protected area – an area of land and/or sea specifically designed to maximise ecological representation; when given appropriate protection, it will help to maintain biodiversity and sustain ecological processes over the long term

sediment – material that settles to the seafloor (e.g. mud, sand, broken shell)

solitary corals – free-living corals, generally a single large animal (polyp)

species – group of interbreeding animals or plants

terrestrial – referring to land

terrigenous – derived from the land via rivers or beaches (e.g. terrigenous deposits)

turbidity – cloudy, muddy water

water-column productivity – quantity of microscopic plants and animals in the water at a particular location

Appendix 1. Biophysical Science Survey - Questionnaire

Survey of reserve habitat requirements for adequate representation and protection of biological diversity in the Great Barrier Reef Region

As part of the Representative Areas Program, we are surveying a select group of experts researching different groups of organisms in the Great Barrier Reef Region.

Our aims are to describe:

- The prime habitat requirements of different groups of organisms
- The main causes and patterns of diversity for those groups
- Appropriate reserve designs for these organisms
- Additional sources of data and expertise
- Any areas of special importance for the maintenance of marine ecosystem diversity and function.

While we realise that information may be incomplete, we urge you to use your expert opinion and judgement in answering this survey as best you can. If you would like to qualify your response or are unable to complete the survey please give reasons in the spaces below or on the spare sheets provided.

Please consider the following questions in the context of choosing representative areas of habitat to be protected by Marine Park zoning. This relates particularly to the scale of information you provide. For practical reasons protected areas are likely to range in size from a few km to 100s of kms. For example zoning decisions are more likely to be influenced by environmental variation among different reefs than variation within a single reef.

You may wish to fill out the electronic version of this form by typing responses in the shaded yellow boxes and drawing lines and labels on the maps with the drawing tools provided, or you may wish to print out this form and write and draw on the paper copies.

More detailed maps of each section of the Marine Park are attached to this e-mail if you require them.

1. Your name?
2. Your position?
3. Your organisation?

4. Which groups (e.g. populations, taxa, or communities) of organisms are you most familiar with (e.g. southern Dugong, butterfly fishes, soft bottom infauna) in the Great Barrier Reef region?

Group 1

Group 2

Group 3

Group 4

Group 5

For **one of these groups** please attempt to answer the following questions. (Feel free to provide information for **additional groups** on separate copies of this survey.)

5. Organism group (e.g. algae)

6. What environmental **factors** (or even approximate surrogate variables) and **categories** would best define the most distinct **spatial patterns in diversity and abundance** for this group?

		Categories				
	Factor	**1**	**2**	**3**	**4**	**5**
Example 1	*salinity*	*0-5 o/oo*	*5-20 o/oo*	*20-30 o/oo*	*>30 o/oo*	
Example 2	*slope*	*flat*	*moderate*	*steep*		
Factor 1						
Factor 2						
Factor 3						
Factor 4						
Factor 5						
Factor 6						

Please answer the following questions with regard to maintaining representative diversity in the organism group described, while allowing for reasonable use.

(To allow for uncertainty feel free to provide a range of values e.g. "between 20-30 per cent")

7. Is any particular shape, orientation or configuration of reserve of value in preserving the organism group?

8. Is any particular shape, orientation or configuration of reserve to be avoided?

9. If several reserves are used, what distance apart should they be to maintain connectivity among organisms?

10. Are there any environmental boundaries that need to be considered when siting protected areas?

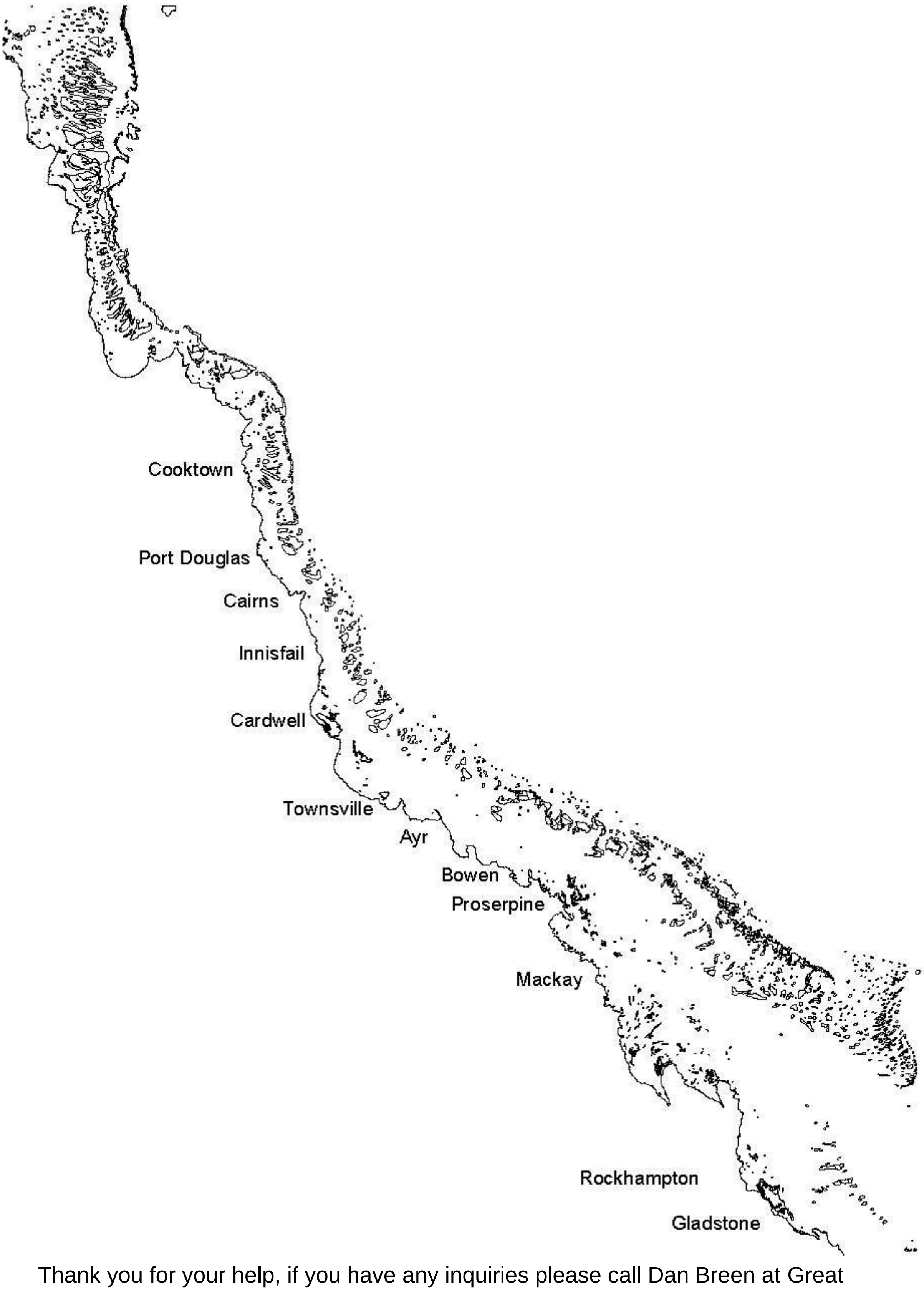
11. What major threats need to be considered for the conservation of this group of organisms?

12. Assuming zoning is effective what other strategies are required to protect these organisms?

13. Can you provide any other relevant data, information or references to other sources? (see attached contact list)

14. Would you like to provide additional information during the selection of Representative Protected Areas and the subsequent rezoning process?

Please turn over to the map below or if required use the more detailed section maps in the attached .exe files.



Thank you for your help, if you have any inquiries please call Dan Breen at Great Barrier Reef Marine Park Authority at (07) 4750 0700

Appendix 2. References to datasets used in developing the bioregionalisation for the Great Barrier Reef and used in the Representative Areas Program

Soft Corals

Source

- Soft coral surveys of Dr Katharina Fabricius, AIMS and Cooperative Research Centre for the Great Barrier Reef.

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Hard Corals

Source

- Hard coral surveys of Drs Terry Done and Lyndon Devantier, Australian Institute of Marine Science.

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- Dr Lester Cannon, Queensland Museum, Brisbane.
- Dr Rob Coles, Warren Lee Long and Len McKenzie, Queensland Department of Primary Industries –Northern Fisheries Centre.
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  - Ocean Mapping Group, University of New Brunswick, Canada
  - Lamont Doherty Geophysical Observatory
  - Australian Hydrographic Office
  - Royal Australian Navy
  - Great Barrier Reef Marine Park Authority
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Appendix 3. Terms of reference for an independent review of the process and outputs of the Classification Phase of the Representative Areas Program

AN EVALUATION OF THE SCIENTIFIC AND TECHNICAL ASPECTS OF THE GREAT BARRIER REEF MARINE PARK AUTHORITY'S REPRESENTATIVE AREAS PROGRAM
(ie. SPECIFICALLY THE CLASSIFICATION PHASE)

TERMS OF REFERENCE

1. Review the scientific and technical aspects used by Great Barrier Reef Marine Park Authority in the Representative Areas Program (RAP) from November 1998, with specific review of the Classification Phase.
2. Assess the quality of the scientific and technical work/methods carried out for the Classification Phase of the RAP and report whether the Classification Phase was:
   (a) conducted in the most efficient and effective manner considering the existing resource, time and data limitations; and
   (b) an acceptable basis upon which to further develop the RAP.
3. Provide advice as to how subsequent phases of RAP might best build upon the Classification Phase.
4. If the answer(s) to (2b) is in the negative, make recommendations for improving Great Barrier Reef Marine Park Authority's Representative Areas Program and to recommend priorities and/or additional resources required to satisfactorily meet the program's objectives.
5. To advise on the value of the Classification Phase of the Representative Areas Program to other agencies and recommend potential uses and applications of the outputs for other projects (e.g. Long-term Monitoring Program or Cooperative Research Centre research projects).
6. Considering the answer to (5), to advise on whether the future work priorities of the following three agencies/organisations should be adjusted in forward planning to more effectively address the objectives of the Representative Areas Program:
   - Great Barrier Reef Marine Park Authority
   - Australian Institute of Marine Science
   - Cooperative Research Centre for the Great Barrier Reef

In pursuance of the main Terms of Reference defined above, the review is requested to give particular attention to the relevance, scope and objectives of the Representative Areas Program with respect to:

- i) The various international and national commitments and programs regarding the protection of biodiversity.
- ii) The priorities of Great Barrier Reef Marine Park Authority and the 25 Year Strategic Plan for the Great Barrier Reef World Heritage Area.
- iii) The content and quality of relevant scientific work related to the protection of biodiversity.
- iv) The broad environment within which the program is currently being undertaken.

The review should be completed and submitted to the Chair of Great Barrier Reef Marine Park Authority as soon as practicable.