Title: Designing effective protected area networks - integration of the tropical cyclone disturbance regime in the Great Barrier Reef Representative Area Program : a GIS application

Author: Sophie Debort

Year: 2006

Designing effective protected area networks - integration of the tropical cyclone disturbance regime in the Great Barrier Reef Representative Area Program : a GIS application

Sophie Debort
University of Wollongong

School of Earth and Environmental Sciences

Designing effective protected area networks – integration of the tropical cyclone disturbance regime in the Great Barrier Reef Representative Area Program: a GIS application.

By

Sophie Debort

A thesis submitted in partial fulfilment of the requirements of the award of the Masters of Earth and Environmental Sciences (research) from the University of Wollongong, Australia

November 2006

Certification

The information in this thesis is entirely the result of investigations conducted by the author, unless otherwise acknowledged and referenced, and has not been submitted in part, or otherwise, for any other degree or qualifications.

Sophie Debort

01 / 11 /2006

STATEMENT OF ACCESS

I, the undersigned, the author of this thesis, understand that the University of Wollongong will make it available for use within the University Library and, by digital copy or other means, allow access to users in other approved libraries.

All users consulting this thesis will have to sign the following statement:

In consulting this thesis, I agree not to copy or closely paraphrase it in whole or in part without the written consent of the author; and to make proper public written acknowledgment for any assistance which I have obtained from it.

Beyond this, I do not wish to place any restriction on access to this thesis.

____

Signature

1 \ 11 \ 2006

Date

ABSTRACT

In recognition of the scenic, ecological, and scientific values of the marine environment, attempts at conservation are increasingly recognized. In a world progressively modified by human activities, the conservation of biodiversity is essential as insurance to maintain resilient ecosystems and ensure a sustainable flow of ecosystems goods and services to society. Unfamiliarity with large disturbances that rarely occur has resulted in the neglect of this kind of event in reserve management. Cyclones are extremely powerful events that can damage coastal and marine environments like coral reefs by generating large wave forces, sediment re-suspension and subsequent smothering, influx of large volumes of freshwater and terrestrial sediment due to heavy rains, and winds and storm surge. For example, in the Great Barrier Reef (GBR), a lack of knowledge about large natural disturbances like cyclones and their effect on the marine environment has prevented managers of the Marine Park from explicitly considering such perturbations in planning.

The goal of this study was to place what is known about widespread natural disturbances (tropical cyclones) into the context of marine reserve design requirements and management decision for the conservation of the GBR, Australia. To do so, the newly implemented Representative Area Program (RAP) of the GBR Marine Park (GBRMP) was evaluated against the recently characterised tropical cyclone disturbance regime across the region (Puotinen, 2005a). Recruitment to reefs by settlement of distant larvae via a series of short steps within and between reefs is a key process towards reef recovery. It was then assumed that the reefs that are highly protected (HPR) from human activities should also be relatively cyclone-free, to allow them to act as ‘sources’ of larvae to enable recovery of less protected adjacent reefs after disturbances. The level of cyclone disturbances at HPR was characterised based on its frequency and timing, and its influence on connectivity between HPR (source) and non-HPR (sink) reefs across the GBR.

Even though most HPRs have had time to recover fully between tropical cyclone events at least once over the last 35 years, they typically had a short time to recover between subsequent cyclone events (short recovery periods). Thus, they may

not always be available as 'sources' of larvae in a given year, which reduces the effective connectivity between sources and sink reefs in that cyclone disturbance regime. Under such scenario, the RAP may not adequately protect the GBR. This is the case because HPR (potentially representing the best source for support and replenishment of adjacent areas) have not been placed to ensure infrequent exposure to cyclone damage. Because reserves are usually meant to be permanent, their design must be effective even under conditions that may be very different from current conditions. In this context, it is important to consider the history of disturbance in a region as it may determine the level of complexity or fragility that this region can develop between disturbance events. The RAP was developed with the best information available at the time, but the characterisation of the GBR cyclone disturbance regime now available (Poutinen, 2005a) suggests that the timing of the most recent cyclone event is not typical of the 1969-2003 time series. Thus, an 'insurance' factor based on Allison *et al.* (2003) was complied to identify how much additional reef area would need to be set aside to allow for the creation of a new framework accommodating the reality of cyclone disturbance in marine reserve planning. Overall, only for short recovery times (5-10 years) and ecosystem level connectivity between source and sink reefs can a sufficient additional insurance reserve be realistically set aside to provide a buffer against cyclone disturbance. One solution to this may be to create temporary dynamic reserves as needed after severe cyclones. The effectiveness of such measures over the long-term will depend not only on the occurrence and magnitude of other disturbances that may develop synergistically to create more dramatic effects on reefs but also on global climate change. Predicting effects of directional climate change will facilitate the evaluation of the long-term success of a reserve.

ACRONYMS

AML: Arc Macro Language
BOM: Bureau Of Meteorology
GBR: Great Barrier Reef
GBRMP: Great Barrier Reef Marine Park
GBRMPA: Great Barrier Reef Marine Park Authority
GIS: Geographic Information System
HPR: Highly Protected Reefs
MPA: Marine Protected Areas
RAP: Representative Areas Programme

ACKNOWLEDGEMENTS

Data was kindly provided by the Great Barrier Reef Marine Park Authority (basic GBR datasets), and Dr. Marji Puotinen (tropical cyclone disturbance data and GIS layers).

Completing my masters has often seemed like a process of learning how not to do research. Despite this, I would firstly like to acknowledge the continual support of my supervisor, Dr. Marji Puotinen who remained approachable throughout the year at times and days I needed and also provided insightful, constructive criticism enabling a better progress.

This project was conducted at the Spatial Analysis Laboratories at the University of Wollongong where access to GIS software was provided. The GIS component would have been impossible without the technical assistance of the following: Heidi Brown (spatial data handling), and Andrew Smith (for the so numerous, inexplicable and random computer bugs). Thanks guys for the hours of endless brain turmoil you saved me and the after hours that kept me from going insane.

I will never be grateful enough to my sponsor for proving the funding and support necessary to get throughout those last 4 years of overseas studies. Thanks Mum and Dad. Merci de votre support et de votre assistance aussi bien sentimentale que morale malgrés la distance et le accrochages en cours de route. Merci de m'avoir supporté et d'avoir été a l'écoute quoiqu'il arrive et à n'importe quelle heure de la journée ou de la nuit pour me permettre de rester dans le droit chemin afin d'en arriver là. Promis papa, c'est le dernier diplome sur lequel je fais mes dents.

I would also like to thank my sister, Caroline, for her support and guidance when it was hard to be far from home and for the fantastic project we're looking forward to together. Merci Caro d'avoir toujours eut le temps et d'y croire assez pour te lancer avec moi dans ce tour du monde. Ca aura été ma motivation pour pouvoir arriver au bout de cette année et un projet grandiose à realiser.

Finally I'd like to thank my wonderful friends, the ever smiling faces of those around me and the long distance laughs and jetlagged / out-of-schedule extensive phone calls with those further away. Much thanks go specifically to Arnaud, Christophe, Carolina, Mishi, my two amazing flatmates Monica and Claudia, Carlos (Mexicain bien sûr) and the South American crew for assisting me with the recreational side of life at any times. You've made those last 4 years being a real blast. Thanks for the comfort you gave me, that extra boost when I needed, for listening to my winging (and swearing), for making me feel we all where in the same "mouise" and for convincing me I could get through it … because I did!

TABLE OF CONTENTS

CHAPTER 3: GBR cyclone disturbance history - rationale for assessing the RAP

CHAPTER 4: Evaluating the RAP network – a HPR perspective

CHAPTER 5: Summary and conclusions

LIST OF FIGURES

CHAPTER 1

CHAPTER 2

CHAPTER 3

LIST OF TABLES

Chapter 1: Introduction

1.1 Introduction

Marine reserves have gained much attention in recent years as a powerful tool for marine conservation and resource management. A network of no-take areas implemented within a dynamic adaptive larger seascape management approach has been put forward as the best solution to ensure long-term protection of marine communities (Lubchenco *et al.*, 2003; Murray *et al.*, 1999; Ogden, 1997). Designing marine reserves or a network of marine no-take areas is a complicated process because a range of factors must be considered and our knowledge of what constitutes a perfect design is far from complete. Maintaining the ecological structure and functioning of a reserve is dependent upon processes and events occurring both within and external to it.

Since its declaration in 1975 as the world's largest marine park, the Great Barrier Reef (GBR) has provided different degrees of protection for different habitats within its boundaries. In order to better protect its biodiversity, the GBR Marine Park Authority (GBRMPA) recently developed the Representative Areas Program (RAP), a multiple-use zoning approach aimed at providing high levels of protection for specific areas whilst allowing other uses, including certain extractive activities, such as fishing, to continue in others. The upgrading of the GBR zoning reflects a new awareness of the importance of interconnected habitats and ecosystem-approach for reserve management in the marine environment (Day *et al.*, 2002). However, of concern is that existing reserves and national parks are unlikely to provide for the long-term large scale dynamics of ecosystems if they do not account for the wide range of disturbances that occur. Although GBRMPA strived to develop an effective network of 'no-take' areas representative of the entire range of associated habitats in the GBR with the best information available at the time, the lack of knowledge about large natural disturbances and their effects on the marine environment prevented the new management plan from accounting for such perturbations. Puotinen (2005a,c) recently developed the first broad-scale synthesis of cyclone disturbance regime across the entire GBR region (over a 35 year period), therefore offering an opportunity to test if the new network of highly protected areas provided by the RAP adequately addresses the reefs ability to recover from episodic perturbation by cyclones over time.

Large scale disturbances, while rare, can essentially prevent a reserve from fulfilling its goals. Tropical cyclones are extremely powerful natural events, and as part of the general environment that many marine ecosystems experience, cannot be prevented. The improved understanding of how the timing and frequency of cyclones affects the GBR (Puotinen, 2005a) can help determine how well the RAP will accommodate such effects over time. This thesis investigates the degree to which the new network of highly protected areas provided by the RAP takes into account spatial and temporal patterns of episodic perturbation by a large natural disturbance (tropical cyclone waves as modelled across the whole GBR over the past three decades - 1969-2003).

1.2 Aims and objectives

The fundamental aim of this research is to evaluate the capacity of the RAP to adequately absorb cyclone disturbance over time given the distribution of its highly protected zones.

Every environment exposes organisms to stresses (e.g.: cyclone disturbances) that reduces their capacity to reproduce. The impact of these disturbances will depend on their magnitude, duration and frequency. Reserves will grant no protection against such unpredictable natural disturbances and so areas with frequent episodic catastrophes are least attractive as reserves (Roberts et al., 2003).
The magnitude and variation in connectivity and therefore recruitment of coral at different spatial and temporal scales is poorly documented (Nyström & Folke, 2001). Recruitment by settlement of distant larvae has been suggested to be the main contributor to reef recovery after an intense disturbance (Van Woesik, 1992). Ayres and Hughes (2004) reported that estimated rates of gene flow for five coral species in the

GBR are high at the local scale (< 5kms) but moderate among distant regions. Their study also indicated relatively high estimates of gene flow among reefs up to 1200kms apart within the GBR though it involves a multi-generational sequence of ‘steps’ (Ayre & Hughes, 2004). While the structure of the GBR, which forms a series of stepping stones, ensures that at least some proportions of long-distance migration occurs via a series of short steps between sites within a reef and adjacent reefs (Ayre & Hughes, 2000), recruitment to reefs is strongly correlated with local larval production.
Given this, if they are to provide an indication of potential for larval supply after a disturbance, only reefs that fall within the highly protected zones (where human disturbance is prevented) and experience a minimum of natural disturbance would be able to facilitate the transport of larvae to damaged reefs via a stepping stone process.

Therefore, it is assumed for this project that reefs within highly protected zones and relatively cyclone-free are best able to act as sources of corals larvae to enable episodic recovery of the remaining reefs. To enable this, ideally the highly protected reefs (HPR) in the RAP should be selected such that a minimum of natural disturbance occurs. The newly implemented management plan of the GBR (applying essential marine reserve criteria to the design of its protective zoning) was thus evaluated against the recently characterised tropical cyclone disturbance regime in order to investigate its effectiveness at inadvertently selecting HPR across the GBR that experience low levels of cyclone damage. The objectives that must be met to achieve this aim included:

- Review the relevant scientific literature in each of several key areas (as presented in the next chapter – Fig. 2.1).

- Provide a rationale for assessing the new RAP network based on the tropical cyclone history over the GBR (Chapter 3)

- Evaluate the efficacy of the new RAP network from the perspective of tropical cyclone disturbance and explore techniques to accommodate the reality of cyclone disturbance in the GBR reserve planning (Chapter 4)

- Assess the limitations and discuss the outcomes of the proposed approach (Chapter 5)

- Develop recommendations for further research to support improved conservation of the GBR (Chapter 5).

Chapter 2: Marine reserves and the context of large natural disturbances

2.1 Introduction

This chapter presents a review of the literature relevant to the aim of this project covering: (i) landscape ecology, (ii) conservation biology, and (iii) management of the GBR, with an emphasis on the design of effective protective area networks, the need for ecosystem management integrating large disturbance regimes, and the utility of GIS as an operating platform (Figure 2.1).

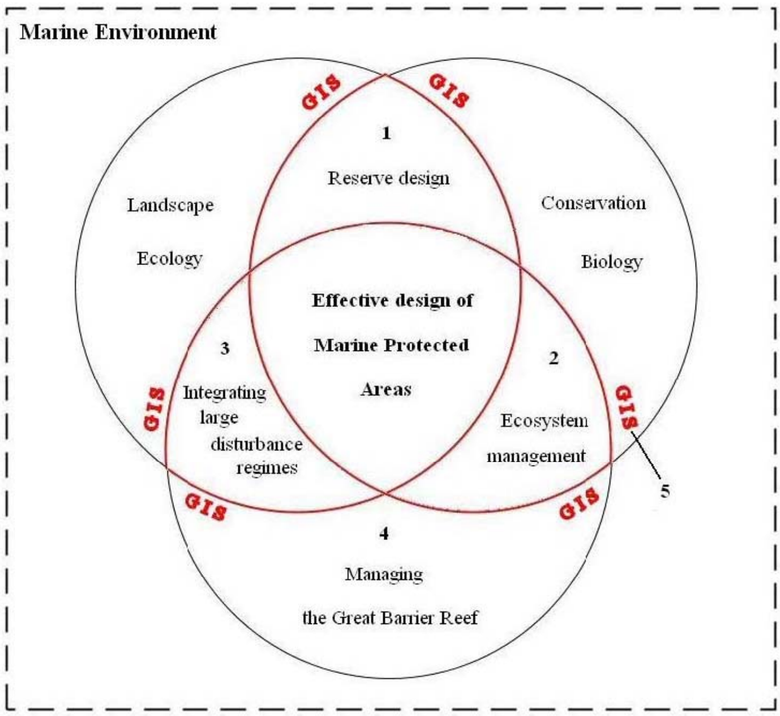


Figure 2.1. Overview diagram of the relevant fields of literature involved in this research and their relationships.

Reserve design theory (1) is primarily based on principles applied in conservation biology and landscape ecology for terrestrial systems. Their adaptation to the marine environment is evolving rapidly towards ecosystem management (2), with recent understanding of the uniqueness of marine ecosystems and processes such as large disturbance regimes (3). The role of disturbance is important for maintaining structure at the species, ecosystem, and landscape scale and protecting marine reserve communities such as the coral reefs of the GBR effectively (4). Integration of such criteria into the design of Marine Protected Areas (MPA) is now increasingly facilitated by the development of reserve selection tools built into GIS-based analytical frameworks (5).

2.2 Reserve design in the marine environment

The marine environment encompasses a broad array of ecosystems and covers much (70.8%) of the Earth's surface (Hixon *et al*., 2001). So little is known about all aspects of marine biodiversity and species richness that immediate conservation action to preserve this diversity is needed before we can afford the time for such an assessment (Hixon *et al*., 2001). The most prudent precautionary measure is to set aside areas of the marine environment for protection from all disturbances, natural or anthropogenic. Ecosystems are subject to pulse disturbances at various spatial and temporal scales. Establishing substantial networks of no-take marine reserves in an adaptive management framework is the most effective conservation action (Murray *et al.*, 1999; Bengtsson *et al.*, 2003).

2.2.1 Marine vs. terrestrial reserve design

Reserve design theory has been developed primarily with terrestrial systems and species in mind, and most applications of reserve design theory have also been terrestrial (Soulé and Terborgh, 1999). However, marine reserves are now strongly advocated by many managers, policy makers and biologists because reserves may both enhance the conservation of marine biodiversity and improve fishery management (Botsford *et al.*, 2003; Carr *et al.*, 2003; Allison *et al.*, 1998), and may also offer types of protection not provided by other management strategies (e.g. specific protection of critical areas) (Allison *et al.*, 1998).

Because the implementation of marine reserves is relatively new and the theoretical and empirical framework for their design is still in its infancy, it may be tempting to draw heavily from reserve experiences in the terrestrial realm (Allison *et al.*, 1998). However, marine systems differ fundamentally from terrestrial systems in the scale and variability of processes. Although it may be useful to equate marine protected areas with their counterparts on land to base reserve design on shared principles (e.g. the concept of 'minimum critical population size (Ogden, 1997)), key characteristics of ocean environments mean there are important differences in how they can be designed and administered effectively (Table. 2.1).

Table 2.1. Implications of relative differences between terrestrial and marine ecosystems for the objective and design of reserve networks. From Carr *et al*., 2003.

Please see print copy for Table 2.1

The relevance of terrestrial-based approaches in determining specific design criteria and prioritising sites for effective management in marine systems requires an understanding of both the nature and degree of the differences between marine and terrestrial systems. These may include ecological, genetic, and evolutionary patterns and processes, the nature and scale of contemporary threatening processes, and the way we manage biotic resources on land and in the sea (Carr *et al.*, 2003). For example, the prevalence of ocean waves and currents in the marine realm extends the spatial scale of many processes, leading to greater magnitude and higher rates of import and export (Carr *et al.*, 2003). On land, only a few species range over great distances, while many marine species have large ranges or migrate great distances. Pronounced differences in dispersal modes and the openness of populations among trophic levels also have critical implications for the design of marine reserves (Carr *et al.*, 2003). Ecological connectivity, temporal and spatial response to large-scale environmental variability, directional flows affecting populations and recruits, specific life-histories, and the state of relevant-knowledge are typically dominant ecological issues in reserve design for marine systems that differ from those in terrestrial systems, thus implying that marine reserve design requires approaches that consider the uniqueness of marine ecosystems (Day *et al.*, 2002).

2.2.2 Design principles for marine reserves

The strategic objectives for terrestrial reserve network design have been to efficiently include the full spectrum of regional-scale biodiversity within a system of protected areas, and to ensure long-term persistence of biological diversity in a changing world (Carr *et al.*, 2003). These representation and persistence objectives seem equally appropriate for marine reserve networks. Most studies of reserve design have been oriented towards fisheries and have involved designing reserves to achieve the goal of maximizing yield. Reserves for fishery management and preservation of biodiversity share the goal of maintaining persistence of the target population(s) (Botsford *et al.*, 2003). Scientists (see for example Roberts *et al.*, 2003a,b; Leslie *et al.* 2003) have developed design principals that take into account special characteristics of the ocean and the management objectives of a particular marine protected area. These include:

- definition of the marine reserve,
- its goals,

- the location, size and coverage of the reserve,
- whether a single site or a network,
- the connectivity patterns observed for the reserve, and
- basics for the reserve selection design.

2.2.2.1 Defining marine reserves

Marine space can be designated and protected in different ways depending on the management goals of a particular area and the population or communities it strives to preserve: marine protected areas (MPAs), parks, reserves, harvest refugia, and sanctuaries are some of the commonly used terms. These areas have a range of potential functions including conservation of biodiversity, tourism, protecting sensitive habitats, providing refuge for intensively fished species, improving fish yields, providing a management framework for sustainable multiple use or a combination of these goals (Allison *et al.*, 1998). The World Conservation Union provides the following definition for a Marine Protected Area: 'any area of the intertidal or subtidal terrain, together with its overlying water and associated flora, fauna, historical and cultural features, which has been reserved by law or other effective means to protect part or all of the enclosed environment' (Kelleher & Kenchington, 1991). This rather generic definition can be supplemented by schemes that designate protected areas according to their wide variety of habitats and regions, their wide variety of designs, conservation goals, and levels of protection (Allison *et al.*, 1998). Research is currently demonstrating that marine reserves are powerful management and conservation tools. For example, fully protected marine reserves are an emerging tool for marine conservation and management (Lubchenco, *et al.*, 2003; Murray *et al.*, 1999). It is argued that the best element of a marine reserve management plan is 'no-take' marine reserves, in which all extractive and destructive activities are banned (Hughes *et al.*, 2003; Ogden, 1997).

2.2.2.2 Determining goals

Evaluating a reserve's effectiveness is essential to ensuring conservation potential and requires the goals to be explicit. This may seem obvious, but some existing reserve systems thought of as 'conservation' reserves were not chosen to meet specific biodiversity objectives. For example, a large proportion of currently established marine reserves are found in places that are unsuitable for other purposes or were chosen for cultural or scenic reasons (Possingham *et al.*, 2000). Beck & Odaya (2001) define a conservation goal as the amount of the target (species and habitat) that must be preserved to protect the full range of diversity within an ecoregion. Before anything else, the goal of a marine reserve together with the species or communities to protect are the first concern managers need to define for any design to be effectively implemented (Allison *et al.*, 1998; Dale *et al.*, 1998). In fact, marine reserves are often intended to meet several objectives that can be conservational, economical or social. A popular strategy to achieve multiple objectives is zoning (Day *et al.*, 2003; Ogden, 1997), whereby a reserve can be very large and then zoned for various objectives and uses. For example, Australia's Great Barrier Reef Marine Park spans an area of over 348,000km^2 , and is subdivided into sections zoned to separate incompatible activities, such as marine ecotourism and commercial fishing. This zoning system includes a highly protected core area surrounded by a buffer zone.

2.2.2.3 Location, size and coverage

Although from the perspective of nature conservation alone, one would attempt to have the largest reserve possible, in reality the extent of any reserve system will be limited by social and economical constraints (Gerner & Bryan, 2003; Baker, 1992). The optimum size, number and distribution of reserves are still very uncertain. Selection of the location of reserves and the management of areas located around them must consider oceanographic patterns (e.g. currents) as well as biological patterns (e.g. life histories, dispersal ranges) and social factors (Allison *et al.*, 1998). For example, for reserves designed to protect coral reefs to interact effectively to maintain biodiversity, they need to be located close enough together such that larvae can be delivered from upstream reserves to downstream reserves (Roberts, 1997). Upstream reef area provides an indication of potential larval supply, as many coral reefs depend on larval sources outside their own boundaries. They also rely on community interactions with other reefs and other ecosystems in the larger seascape to support their ability to recover and/or adapt to disturbance (Nyström *et al.*, 2000). Some reefs or reef patches are more likely to receive larvae than others due to variation in patterns of current flow (Ayre & Hughes, 2000). As a result, marine reserves may have to encompass a greater habitat diversity to ensure that all habitats and associated resources needed over the lifetime of an individual are included (Carr *et al.*, 2003). A positive species-area relationship, that is an increase in species diversity with increasing habitat diversity as a function of area (Carr *et al.*, 2003), underscores the importance of larger marine reserves that encompass a greater diversity of habitats types (Knowlton, 2001). The proportion of a given habitat or ecosystem that the no-take reserve covers is crucial to its success. For example, previous reef studies revealed a significant relationship between biodiversity and either distance from the equator or mean temperature (Knowlton, 2001). However, a recent study by Bellwood and Hughes (2001) noted that habitat size matters more to biodiversity than latitude and longitude, as the more suitable the habitat for corals that exists surrounding a reef (area of suitable depth within 600kms), the greater its biodiversity. Indeed, for example, the recruitment rate in coral reef communities has been observed to increase with the amount of free space available on Heron Reef, in the southern GBR (Connell *et al.*, 1997). The dependence of diversity on habitat area has important implications for conservation (Knowlton, 2001). Not only do coral reefs need to be protected now in order to prevent future species extinction, but substantial associated habitats and processes near those reefs also need protection.

2.2.2.4 <u>Single site or network</u>

Whether many small reserves or a few large ones will protect more species has been rarely addressed for marine systems. Most of the discussion on goals in marine environments has centred on the area that should be placed in marine reserves to aid fisheries management. Previous studies suggest that reserves may need to cover at least 20% of the area of concern or 20% of the fish stock of concern to be effective as a tool in biodiversity conservation and fisheries management respectively (Beck & Odaya, 2001, Hixon *et al.*, 2001). Reserve selection approaches such as the aforementioned seek to identify minimum sets of areas (minimum total area or minimum number of sites) that represent a percentage of the original target species extent in the region of interest. Cabeza *et al.* (2004) highlighted alternative approaches that aim at (i) identifying reserve networks that increase representation of biodiversity for a given cost or area, (ii) using the local probability of occurrence of target species as a surrogate for species local persistence, and (iii) considering the spatial location of the reserve, implicitly acknowledging the role of spatial population dynamics on species persistence. Researchers propose that properly designed networks of reserves could provide several replicate source populations, reduce region-wide risk of anomalous effects on a single reserve and increase the potential benefits to non-reserve areas by increasing the connectivity between protected and unprotected areas (Allison *et al.*, 1998). A network approach is considered superior to the creation of isolated individual reserves for it can provide meaningful spatial relationships among sites for the maintenance of ecosystem linkages and connectivity, as well as off-setting effects from localized catastrophes (Allison *et al.*, 2003; Hughes *et al.*, 2003; Lubchenco *et al.*, 2003; Roberts *et al.*, 2003a; Nyström & Folke, 2001). Indeed, a network of reserves could potentially separate reserves sufficiently across space to spread the risk of a single reserve being affected by a local or even a larger scale perturbation.

2.2.2.5 Connectivity

In the sea, the need for connectivity stems from the openness of populations. For coral reefs for example, the most important advantage of networks has to do with larval transport. Identification of sources (areas from which locally-produced larvae are exported) and sinks (areas dependent on the import of larvae from other locations) of marine larvae is critical for the placement of marine reserves (Ogden, 1997). Connectivity is therefore an important consideration in reserve network design for coral reef ecosystems (Carr *et al.*, 2003). The magnitude and variation in connectivity and therefore recruitment of coral at different spatial and temporal scales is poorly documented (Nyström & Folke, 2001). Most marine populations are thought to be well connected via long-distance dispersal of larval stages given the spatial and temporal scales of ocean currents (Cowen *et al.*, 2000; Roberts, 1997). However, marine populations may not be as open over ecological time scales (years to decades) as envisaged. Innovative research on larval connectivity deduced from observations of oceanic circulations patterns suggest that coral reefs may be less spatially connected than previously thought (Andréfouët *et al.*, 2002; Cowen *et al.*, 2000). Simple advection models (Cowen *et al.*, 2000) and genetic studies (Ayre & Hughes, 2000) have reported that larval exchange may currently be overestimated. For instance, a study by Cowen *et al.* (2000) indicated that mesoscale oceanic circulations may minimise long-distance dispersal by concentrating larvae locally near their source locations, and that estimated transport success decreases when distance from the source increases, indicating additional dispersion of larvae over an ever increasing area. The argument that larvae can be transported regularly between distant and local populations is questioned as coastal and surface currents have been shown to enhance local replenishment of the source population, further reducing the number of larvae available for 'downstream' transport (Cowen *et al.*, 2000). Similarly, Ayre & Hughes (2000) observed coral reefs to depend primarily upon self-seeding (whereby recruits are produced locally) for the maintenance of populations while long-distance gene flow apparently prevents the accumulation of fixed genetic differences in populations along the GBR. The structure of the GBR, which forms a series of stepping stones at scales ranging from meters to thousands of kilometres, ensures that ecologically important patterns of dispersal must be complex and that at least some proportions of long-distance migration could occur via a series of relatively short steps between sites within a reef and between adjacent reefs (Ayre & Hughes, 2000). In the GBR, long-distance dispersal has been shown to be very important over evolutionary time scales, even if most recruitment appears to be local. Larval retention near local populations may be of great importance in the maintenance of local population structures (especially those that benefit little from 'upstream' reef sources) and local management of marine resources. Even with the simplistic assumption that larvae are dispersed passively by currents, interaction distances among reefs have been observed to be generally relatively short (100-250 kms) (Roberts, 1997). This would imply that marine reserves need to be established in dense networks and in the case of reserves where local retention is enhanced by active dispersal, reserves will need to be even more closely spaced as effective interaction distances will become smaller (Roberts, 1997). Further knowledge of larval exchange among populations of marine organisms is vital to the study of marine reserve designs as management decisions based on open population models might overestimate the level of population exchange (Cowen *et al.*, 2000). Patterns of interconnection among marine resources have long been recognised as an important management concern (Carr *et al.*, 2003; Andréfouët *et al.*, 2002; Roberts, 1997) and would allow an assessment of the potential for recovery from disturbance.

2.2.2.6 Reserve siting

Approaches to ensuring comprehensive representation of biological diversity in terrestrial reserves have focused primarily on contemporary patterns of distribution and abundance (Carr *et al.*, 2003). In terrestrial systems, reserve selection methods are used to identify efficient reserve networks that represent all or most biodiversity at the ecosystem or landscape level. These approaches integrate spatially explicit data on measures of biodiversity and land management to prioritise potential sites for conservation. These spatial analyses are becoming increasingly sophisticated, and when coupled with heuristics or linear programming algorithms, can identify nearly optimal reserve networks, as long as the necessary data is available (Cabeza *et al.*, 2004). Only recently have similar approaches been applied to marine systems (see for example, Leslie *et al.*, 2003; McDonnell *et al.*, 2002; Beck & Odaya, 2001). This is partly due to the fact that the necessary data at the spatial scale applicable to reserve design are far less organized and available for most marine environments than for many terrestrial environments (Carr *et al.*, 2003).

2.2.3 Ecosystem management: designing effective protected areas

There have been efforts to develop quantitative criteria and rules on which to base reserve siting (see for example, Cabeza *et al.*, 2004; Leslie *et al.*, 2003; McDonnell *et al.*, 2002). These include criteria such as maximizing biogeographic representations within reserves, including areas of rare and endemic species, and avoiding areas subject to frequent human and natural disturbances (Botsford *et al.*, 2003). Reserves are necessary for sustainability of marine ecosystems and biodiversity from the local to global scale. Design criteria should depend on the characteristics of species, populations, communities and ecosystems and relationships between the spatial and temporal scales of physical processes (Carr *et al.*, 2003). Reserves are essential for conservation efforts because they can provide: unique protection for critical areas, a spatial escape for intensively exploited species, and a buffer action against management miscalculations, uncertainty and unforseen or unusual conditions (Allison *et al.*, 1998).

An increasing awareness about the value of a conservation approach at geographical scales including both resident species and their biophysical environments and the level of connectivity between a wide range of habitats, species, communities and processes supporting them has led to an ecosystem-approach to management, away from the traditional focus on single species conservation (Day *et al.*, 2003, Lubchenco *et al.*, 2003). The importance of geographic range in determining the area over which reserves should be distributed is also influenced by the degree of variability in long-term environmental conditions (Carr *et al.*, 2003). For instance, large, infrequent disturbances can have significant impacts on the areas protected by marine reserves, but have seldom been included in management plans (Bengtsson *et al.*, 2003; Nyström & Folke, 2001; Turner & Dale, 1998). Dale *et al.* (1998) observed that ecosystem management of systems that may experience large disturbances needs to include the potential for such disturbance to occur and thus presents a variety of challenges to resource managers and ecologists.

2.3 <u>The context of large disturbances</u>

A disturbance is defined as a discrete event in time: a punctuated killing, displacement, or damaging of one or more individuals (or colonies) on a site (Connell *et al.*, 1997) that disrupt ecosystem, community, or population structure and changes resources, substrate availability or the physical environment (White & Pickett, 1985). Attributes of disturbances, such as intensity and duration, are ecologically important (Roberts *et al.*, 2003a; Baker, 1992). Natural and human-induced disturbances disrupt equilibrium processes inside reserves and make them less effective at meeting management goals (Freidlander *et al.*, 2003; Poiani *et al*, 2000; Dale *et al*., 1998). Despite the long-term stability of reefs in the face of many disturbances (Pandolfi, 2002), there is concern that recent human induced environmental changes enhancing the effects of natural disturbances may exceed the limits of tolerance of reef organisms (McClanahan *et al.*, 2002; Nyström & Folke, 2001). Many studies worldwide have recently emphasized that reserve coverage needs to be scaled up to account for large-scale ecological disasters (Dale *et al.*, 1998; Allison *et al.*, 2003; Bengtsson *et al.*, 2003; Freidlander *et al.*, 2003). Control of some external events and processes is possible (e.g. regulations specifying quality or quantity of inputs from upstream catchments). However, as is the case for natural disturbances such as wave damage from tropical cyclones, many factors are typically beyond the control of reserve management. The success of reserves may be seriously compromised unless allowance is made for the frequency, timing and extent of these externalities (Allison *et al.*, 1998).

2.3.1 Role of disturbance

Conservation approaches in landscape ecology are moving toward broader scales as environmental problems become more complex, interactive, and global in extent (Baker, 1992). The role of disturbance in maintaining structure at the species, ecosystem, and landscape scale is being increasingly appreciated. Large disturbances such as tropical cyclones may alter the structure of landscapes in nature reserves. Landscape structure may in turn alter the viability of species and the functioning of ecosystems. When viewed across long temporal and broad spatial scales, severe disturbances in marine ecosystems are not uncommon. Events such as oils spills, cyclones, disease outbreaks, hypoxic events, harmful algal blooms, and coral bleaching can cause massive mortality and dramatic habitat effects, or disruption of ecosystem functioning on local or even regional scales (Allison *et al.*, 2003; Van Woesik, 1992). Although designers of marine reserves might assume low risk from such events over the short term, severe disturbance is quite probable over the long term and must be considered for successful implementation of reserves. Ecosystem level conservation requires that the form of the ecosystem, including community composition and diversity, as well as the processes that maintain that form, be perpetuated (Baker, 1992).

Past reserve design and management strategies have not explicitly considered the variation in the disturbance regime that may be an important source of both spatial and temporal variation in landscapes (Bengtsson *et al.*, 2003). Reserve designers that strive to set aside areas of sufficient size to maintain populations and ecosystem functioning are likely to underdesign a reserve network if they ignore large-scale disturbance events that will further reduce the effective contribution of a reserve (Allison *et al.*, 2003; Nyström & Folke, 2001; Baker, 1992). Given this however, although disturbance is detrimental to individual reef organisms, new substratum becomes available at various temporal and spatial scales; this opens up patches of opportunity for renewal, development of the reef and for evolution (Dale *et al.*, 1998; Connell, 1978). Nyström *et al.* (2000) observed that disturbance regimes have been important for the development of species diversity, community structure and dynamics of coral reefs. To date, very few attempts have been made to model disturbance regimes for large marine ecosystems until Puotinen (2005a) produced the first broad-scale synthesis of the tropical cyclone disturbance regime across the entire GBR over 35 years (1969-2003). With this information on the dynamics of tropical cyclone disturbance across the GBR, it is now possible to investigate how the incorporation of such a regime into planning could facilitate effective management of the GBR.

2.3.2 Disturbance, connectivity, resilience and recovery

Ecosystem resilience is defined as the magnitude of a disturbance or of an array of disturbances acting together, that can be absorbed by a system before it shifts from one stable state to another (Gunderson & Pritchard, 2002). The concept of ecosystem resilience thus captures the ability of an ecosystem to resist, reorganise and re-establish from disturbance, as well as maintaining a diversity of options for development, evolution and adaptation to change (Nyström *et al.*, 2000). The capacity of ecosystems to cope with disturbance is determined by characteristics such as genetic variability within populations, diversity within and among functional groups, and variability and connectedness of habitats (Nyström *et al.*, 2000). For example, disturbances not only damage coral reefs but also can directly or indirectly affect their physical (alteration of the substrate, current patterns, local topography, and incident light levels) and biological (abundance, distribution of associated organisms or plants, reducing refuges or food supplies) environment (Connell *et al.*, 1997). In spite of the partial or total destruction of individual coral reefs, and their negative long-term impacts as chronic disturbances, short-term climatic variations such as cyclones can also create the potential for long-range dispersal to occur (Cowen *et al.*, 2000; Harmelin-Vivien, 1994). Ayre & Hughes (2000) reported that large-scale genetic structures are determined by historic patterns of gene flow and chance long-distance dispersal events. Indeed, after an intense disturbance affecting both individual populations and their biophysical environment, recruitment by settlement of distant larvae is the main contributor to reef recovery (Van Woesik, 1992). The abundance and recovery of coral reefs varies with the type, intensity, and spatial scale of disturbances and the associated amount of damage (Connell *et al.*, 1997). Where a disturbance damages some individuals but does not remove them or alter the physical environment permanently, rapid recovery may occur from local interaction between coral colonies. In contrast, where most individuals are killed or the physical substrate directly altered by a disturbance, recovery will depend almost entirely upon arrival of propagules from elsewhere and is likely to happen at a slower rate (Connell *et al.*, 1997). Therefore, managing seascape resilience to increase the chances of reefs reorganising after disturbance is greatly dependent on connectivity as it contributes to the rate and extent of recovery. Acute/pulse disturbances are short-term, whereas episodic/chronic ones are long-term. A series of acute disturbances that occur so frequently that there is little time between them for recovery is regarded as an episodic disturbance (Connell *et al.*, 1997). Natural disturbances tend to be pulse disturbances (Nyström *et al.*, 2000), but human activities transform these acute disturbances into more persistent ones which reduces resilience (Bengtsson *et al.*, 2003).

2.3.3 Disturbances affecting the GBR

Occupying less than 1% of the world's ocean surface, coral reefs can be considered the tropical rainforests of the seas in terms of both high biodiversity and threatened status, with 50-70% of reefs under direct threat from human activities (Wilkinson, 1999). Human-induced disturbances on reefs range from localised events such as shipwrecks, increased tourist and recreational activities, increased nutrient levels, point source pollution (e.g. sewage discharge, oil spills), coastal developments and destructive fishing methods; to more persistent large-scale events such as chronic pollution, long-term overfishing, and even global climate change (Van Woesik, 1992).

However, human impacts on reefs do not occur in isolation. Reefs are also affected by natural disturbances, such as predation by crown-of-thorns starfish, physical damage from tropical cyclone waves and subsequent intense flooding, and coral bleaching (Van Woesik, 1992). Disturbances of either natural or anthropogenic origin, each with its own characteristics, can also interact synergistically to produce different post-disturbance conditions (Dale *et al.*, 1998). For example, it is unclear how the ongoing warming of the planet will translate into changes in the frequency and intensity of extreme events such as tropical cyclones in specific regions. However, the effects of anthropogenic disturbance such as enhanced habitat degradation will likely increase the overall negative influence of cyclones through synergistic effects. Ecosystem management in systems experiencing disturbances requires that we understand both natural disturbances and the role of humans in creating or altering large-disturbance effects and in managing the post-disturbance landscape.

It is generally recognised that the timing, spatial location and intensity of natural disturbances such as tropical cyclones are beyond human control, and that attempting to preserve a given state of an ecosystem is less appropriate than maintaining the ecosystem elements and processes of self perpetuation (Baker, 1992). Therefore, effective conservation of the GBR requires understanding the temporal and spatial patterns of these disturbances as well as working within those patterns to achieve the best possible outcome for the protected area network. There are many processes, as well as other issues and concerns, that must be addressed in designing and managing marine reserves, but natural disturbance, particularly large disturbances such as those generated by tropical cyclones, have received little attention. Large-scale disturbances such as cyclones tend to alter currents, reef topography and substratum availability (Nyström *et al.*, 2000) and will destroy reserves that are smaller than the combined area of the disturbance and the necessary ecological memory for reorganisation (Bengtsson *et al.*, 2003). Ecological memory is the composition and distribution of organisms and their interactions in space and time and includes the life-history experience with environmental fluctuations (Nyström & Folke, 2001) that make ecosystem reorganisation possible. Recovery intervals are likely to be a function of the size and patchiness of disturbance events as well as regional differences based on the cyclone disturbance history. Indeed, recolonisation into a disturbed area will be dependent on the life histories of the reef participants, their biological and physical structures, their connectivity and the degree of diversity within functional groups (Allison *et al.*, 2003; Nyström & Folke, 2001). The latter is important to the ability of an ecosystem to buffer disturbance and maintain functions under changing environmental conditions. As diversity within and between functional groups in the seascape is reduced, resilience is also reduced, and disturbance effects are likely to become more severe (Nyström & Folke, 2001). Cyclones are amongst the most severe physical disturbance to affect coral reefs (Van Woesik, 1992), and one of the large scale natural unpredictable disturbances that are known to periodically affect the GBR. Given that management planning has seldom included large disturbances (Nyström & Folke, 2001; Dale *et al.*, 1998) and that most of the relevant disturbance regimes affecting the GBR are poorly understood, it is unlikely that it was possible to explicitly consider natural disturbances in the design process of the new GBR management plan. However, the recently characterised tropical cyclone regime provided by Puotinen (2005a) across the entire GBR region now offers an opportunity to test if the new network of highly protected areas provided by the RAP allows for a safety margin to take episodic cyclone perturbation over time into account.

2.3.4 Integrating disturbance regimes in marine reserve design

Very few studies have examined ways of integrating disturbance regimes into marine reserve design. A notable exception is the Allison *et al.* (2003) study, which suggests a simple way to increase the performance of a reserve network by incorporating an 'insurance factor' into the reserve design. This insurance factor represents the additional reserve area necessary to buffer the reserve against effects of catastrophes (such as oil spills and hurricanes) and thus ensure that the functional goals of the reserve will still be met despite a given catastrophe regime. While the insurance factor builds into the planning process the expectation of some loss of component reserves and sets aside a compensatory amount of area within the reserve needed for a given catastrophe regime, it does not indicate where reserves should be placed or how far apart they should be spaced within a region (Allison *et al.*, 2003). Other studies have documented the spacing of disturbance-prone reserves (Allison *et al.*, 1998; Bengtsson *et al.*, 2003). They recommend that present temporally static reserves should be complemented with temporally and spatially dynamic reserves placed both in human-dominated landscapes and in more pristine ecosystems. Many of these new types of reserves would exist only temporarily and would need to be part of a larger-scale landscape management approach (Bengtsson *et al.*, 2003).

2.4 Managing the GBR Marine Park

2.4.1 The Great Barrier Reef: introduction

The GBR, an Australian and international icon, forms the world's largest, most diverse and healthiest coral reef system. It stretches more than 2,000 kms from 10°S to 25°S off the southeast coast of Queensland, Australia (Fig. 2.2).

Please see print copy for Figure 2.2

Figure 2.2. The GBR region. Reefs are represented by black polygons, and the extent of the GBR is delineated by the red boundary. (*Source*: http://www.gbrmpa.gov.au)

Nearly 3,000 reefs, ranging in size from 1ha to over 100 km^2, are scattered throughout the vast GBR, along with 618 continental islands and 300 sandy cays (CRC Reef Research Centre, 2002). The GBR Marine Park (GBRMP) is comprised of more than just corals. The GBR is diverse and complex, with 500 species of seaweeds, 15 species of seagrass beds, mangroves, sponge gardens, 4,000 species of molluscs, 1500 species of fish, 20 species of sea snakes, six of the world's seven breeding species of turtles, over 200 species of birds, some of the largest population of dugongs in the world and 30 visiting species of whales, dolphins and porpoises (CRC, 2002). It also encloses a high-level of inter-connectivity between its various marine habitats. The GBR and its catchment are also an economic 'powerhouse'. Commercial and recreational fisheries, shipping, tourism and ports operate in the GBRMP. These industries constitute some of the major threats to the persistence of the rich biodiversity of the GBR as they put it under pressure from a range of disturbances. Such anthropogenic disturbances include:

- Downstream effect of land use: water quality issues,
- Coral bleaching,
- Coastal developments,
- Increasing fishing effort and impacts,
- Shipping and pollution incidents, and
- Increasing tourism and recreation.

Besides human-induced impacts, biological (crown-of-thorns starfish predation) and natural disturbances (cyclones) also affect the coral communities of the GBR (Van Woesik, 1992). Because anthropogenic and natural disturbances affect the entire region, management needs to take them both into account. Managing the GBR effectively is important for the preservation of its remarkable biodiversity while ensuring reasonable use.

2.4.2 The zoning of the GBR

In recognition of its outstanding natural beauty and biodiversity, the GBR has been classified as a multiple use Marine Park since 1975, and is managed by the Great Barrier Reef Marine Park Authority (GBRMPA). It has also been protected within a World Heritage Area since 1981, obliging Australia to ensure its preservation (Van Woesik, 1992).

The government response to the need to protect the GBR has been to strive to improve water quality, promote sustainable fisheries, inform national and international policy on climate change effects on reefs and protect biodiversity using a differential use zoning (GBRMPA, 2004). For the latter, each type of zone provides a different level of protection, with ‘no-take’ as the most restrictive, within the Marine Park. A multiple-use approach to zoning provides an effective model to conservation from an ecological (recognising that marine ecosystems operate at temporal and spatial scales), practical (easier to manage, potentially buffering and diluting impacts of various nature) and social (help resolve and manage conflicts) perspective (Day *et al.*, 2002). However, one of the issues facing GBRMPA is the need to better protect biodiversity. Until recently (2004) only 4.7% of the Marine Park was protected in Marine National Park Zones (known locally as Green Zones or “no-take” zones) (Fig. 2.3). In response to suggestions that this level of protection was insufficient to adequately protect the biodiversity and ensure the long-term survival of the Reef (Jago *et al.*, 2005; Day *et al.*, 2002), GBRMPA recently rezoned the Marine Park through the establishment of the Representative Areas Programme (RAP) (GBRMPA, 2003; details on the review phases involved in the implementation of the RAP are described in Appendix 1).

To protect biodiversity within no-take areas requires information on the composition and spatial distribution of representative and crucial ecosystems. Therefore, areas of relative homogeneity were identified to build the RAP, dividing the GBR into 30 reef and 40 non-reef bioregions (i.e. areas within which habitats, communities and physical features would be more similar to each other that to similar habitats occurring in other bioregions – Appendix 1) using detailed GIS assessments (Day *et al.*, 2002). Green zones were established to protect a representative sample of each bioregion. The new zoning plan, accepted by the Australian Parliament on July 2004, builds upon the existing network of Green Zones to protect 'representative' examples of all the different habitats and communities in the GBR and to preserve the amazing plant and animal life throughout the Marine Park.

Please see print copy for Figure 2.3

Figure 2.3. Zoning of the GBR prior to 2004. Green, orange and pink zones show highly protected areas. (*Source*: *http://www.gbrmpa.gov.au*)

2.4.3 The RAP

The RAP attempted to establish a comprehensive, adequate and representative network of protected areas representative of all bioregions that will help to: (i) maintain biological diversity at the ecosystem, habitat, species, population and genetic levels, (ii) maintain ecological processes and systems, (iii) provide an ecological safety margin against human-induced and natural disturbances and if necessary enable species and habitat to recover, (iv) ensure viable and sustainable industries.

In addition to protecting 'representative' examples of the entire range of associated and interconnected habitats, the RAP also offers protection for other areas of high conservation value by assigning protective zoning to other important habitats, breeding and spawning areas as well as other special and unique sites. The new zoning plan increased protection of the GBRMP to 33.3%, offering a comprehensive network of no-take zones protecting marine areas (Jago *et al.*, 2005). The rezoning of the reef was based on the following key principles:

- 11 biophysical principles (Table. 2.2),
- A minimum of 20% per habitat type within no-take areas,
- Representation of the diversity of plants and animal across two key gradients:
    a) northern to southern reefs
    b) inshore to offshore, and
- Protection of biophysically special or unique places.

Table 2.2. Biophysical operational principles including recommendations for amounts of no-take areas for each bioregion and each known habitat type. *(Source: http://www.gbrmpa.gov.au)*

Please see print copy for Table 2.2

Please see print copy for Table 2.2

These biophysical operational principles were implemented to identify networks of areas that could meet the biodiversity objectives of the RAP. The resultant zoning maps show the location of zones, and each zone category specifies which activities can or cannot be undertaken and whether or not permission is required to undertake those activities (Table. 2.3).

Table 2.3. Description of the main zone categories designed for protection of habitats and ecosystems under the recently developed RAP zoning of the GBR. Starred items are those that afford a high level of protection. (*Source*: *http://www.gbrmpa.gov.au*)

Please see print copy for Table 2.3

Please see print copy for Table 2.3

The general use zones are the least restrictive and allow reasonable uses. On the other end of the spectrum, preservation zones require the preservation of the area in an undisturbed state. Between these two extremes, the remaining zones represent a graduation in the level of protection of the GBR. Identifying options for the new and effective network of 'no-take' areas representative of all generated bioregions took place through a combination of information gathering on the nature and uses of the areas, expert opinion, stakeholder involvement, and analytical approaches comprising marine software use and GIS-based analytical tools (GBRMPA, 2003).

While the new zoning plan was developed with the best information available at the time, data and knowledge being used to describe patterns in biodiversity are typically limited. For example, in creating the RAP, surrogates were used to describe, and hence protect, biodiversity where requisite data was not available to support the program (Day *et al.*, 2002). In their study, the latter authors further recommend that data about variability in the patterns of biodiversity in bioregions be collected and that the success of no-take areas in protecting biological diversity be assessed in order to improve the basis for management and decision-making.

2.5 Using GIS

As is true on land, substantial efforts at documenting marine biodiversity at the level of ecosystems and long-term monitoring of marine ecosystems at multiple spatial scales are imperatively needed (Hixon *et al.*, 2001). Allison *et al.* (1998) observed that while many strategies have been proposed for the protection of marine populations, reserves offer a fundamentally different type of protection: a spatially explicit form. Geographic Information Systems (GIS), used to organize the spatial and temporal information on marine biodiversity that is already available, will be especially valuable for the establishment of substantial networks of marine reserves. “Given the increasing demand for information on the status of biological diversity, many are realising the need for improved information systems” (Davis *et al.*, 1990). The value of GIS for managing this information and its use in conservation efforts is being increasingly recognised (Day *et al.*, 2003; Poiani *et al.*, 2000). With advancements in technology, especially in those of spatial analytical tools such as GIS, it is possible to more accurately delineate areas of under-represented, irreplaceable, threatened or rare ecosystems (Gerner & Bryan, 2003). Indeed, conservation efforts require detailed GIS that overlay different aspects of biodiversity at multiple scales, including species-area relationships (Hixon *et al.*, 2001). Combining this biological data with information about the nature, intensity, and urgency of threats to marine protected areas will enable policy makers and managers to choose and rank areas for immediate conservation efforts, as well as identify sites for long-term study and monitoring. Further, practical applications of marine reserve criteria integrating ecological theories make use of mathematical algorithms (Airamé *et al.*, 2003; Leslie *et al.*, 2003; Possingham *et al.*, 2000), coupled with GIS. Supporting this, the GIS platform has been shown to be effective at providing an explicit and transparent mechanism for identifying spatially explicit maps of alternative reserve network scenarios (Lubchenco *et al.*, 2003).

Few databases exist for research and analysis for management of and planning for the marine environment (Bryan *et al.*, 2003). One such example, the result of three years work assembling biophysical, economic and social information, provides the basis for establishing the new network of protected areas over the entire GBR region.

Identification of options for no-take area networks was conducted using a combination of expert opinion, stakeholder involvement and analytical approaches by adapting marine design software and applying a suite of GIS-based spatial analysis tools (Day *et al.*, 2003, Lewis *et al*., 2003). The reserve selection software MarXan (Ball & Possingham, 2000), applying a simulated annealing algorithm, was used as part of a complex GIS-based analytical framework to facilitate the design of the RAP for the GBR (Lewis *et al.*, 2003). The RAP program was developed at a broader scale than any previous zoning exercise on the GBR, as it was guided by a range of principles which implicitly required consideration of scores and datasets and hundreds of pieces of information, and it covered the entire $340{,}000^{+}$ km^2 of the Marine Park (Lewis *et al.*, 2003). Its inherent complexity stressed the importance of GIS and spatial analysis in terms of quality, quantity and time. Lewis *et al.* (2003) further emphasized the critical role that GIS played as a vital component of the RAP process by providing a smooth progression from automated reserve design to human decision making. Flexibility to explore alternative solutions is critically important for conservation planners as they need to evaluate a range of solutions valid from an ecological perspective in the context of other considerations (e.g. economic or politic) (Possingham *et al.*, 2000). This flexibility can largely be provided by an interactive GIS, enabling progressive updates as more knowledge and proposed changes are integrated into the original reserve network.

Chapter 3: GBR cyclone disturbance history – rationale for assessing the RAP

3.1 Introduction

The recent establishment of the first broad-scale synthesis of cyclone disturbance regime across the entire GBR region (Puotinen, 2005a) offers an opportunity to test how well the new network of highly protected areas provided by the RAP takes into account the dynamics of a characteristic large-scale natural disturbance. This chapter outlines how this recent knowledge will be used to select descriptors for assessing the local and regional impacts of tropical cyclones on the highly protected zones of the GBR. By recognising spatial and temporal patterns of cyclone disturbance from the viewpoint of the HPR, an index of change in connectivity under disturbance was developed and a protective multiplier defined for the GBR to allow the design of the HPR network to incorporate periodic cyclone disturbance.

3.2 Presentation of the tropical cyclone disturbance potential in the GBR

3.2.1 Cyclone distribution over the GBR

The cyclone season usually lasts from November to May in the GBR (Puotinen *et al.*, 1997). Whereas cyclones are short lived and constitute extreme physical phenomena, they are regular events at the scale of centuries and even more at a geological time scale although varying in frequency and intensity with location (Harmelin-Vivien, 1994). In the GBR, the majority of cyclones were distributed approximately between 9°S and 19°S from 1908-2003 (Puotinen, 2005c). Over the past 35 years, only three to eight cyclones tracked through the far north (north of 12° S) compared to an average of 18 for the rest of the GBR (Fig. 3.1). In contrast, up to ten times more cyclones (up to 32) tracked through the central GBR near Townsville (18°-19°S at 147°E). In general, a decreasing occurrence of cyclones was observed with direction north and south from this central 'hotspot' (Puotinen, 2004b). Such patterns in cyclone distribution have been used in previous studies to predict the potential damage to reefs based on their proximity to the cyclone path (Puotinen, 2004b; Woodley, 1992).

Please see print copy for Figure 3.1

Figure 3.1. The GBR divided into one degree latitude by one degree longitude boxes. The number of cyclones that tracked within each box from 1969 to 2003 is shown: white less than 10, light grey = 10-19, dark grey = 20-29, black = 30 or more. *Note: many cyclones passed through more than one box. Where a single cyclone track crossed the same box multiple times, it was only counted once*. Adapted from Puotinen (2004b).

3.2.2 Predicting cyclone damage to reefs

Patchiness in space and time is typical for reef damage from cyclone-generated waves, largely due to differences in cyclone characteristics, local bathymetry and community structure of the reefs (Harmelin-Vivien, 1994). Since most of the GBR is protected from long period swells (ocean waves forming outside the GBR capable of traveling 1000s of kms) almost completely by its outermost reefs (Young & Hardy, 1993), even when these are widely spaced, damage caused by cyclones within the GBR is largely dependent on the local wind-generated waves. These are spatially variable over small distances due to local bathymetry resulting in cyclone-induced damage varying with cyclone intensity and duration, location on the reef, and the reef degree of exposure to it (Van Woesik, 1992). A within- and between-reef shelter effect is also created as waves dissipate much of their energy when breaking at the leading edge of the first obstacle encountered (Puotinen, 2005b). As a consequence, the response of a reef to a cyclone is highly variable as different responses occur at both regional (100s of kms) and reef scale (10s of kms), and between and within zones on the same reef.

The characterization of the cyclone disturbance history in the GBR over the last 35 years involved the reconstruction of the distribution of the magnitude and duration of local wind-sea from each cyclone (Puotinen, in press), the development of a model that characterizes reef site exposure and vulnerability to damage from that energy (Puotinen, 2005b, 2003), and the interaction of these to generate a predictive model for reef damage (Puotinen, in press).
The spread and magnitude of tropical cyclone generated winds was hindcast using a model developed specifically for the Coral Sea (McConochie *et al.*, 1999), and implemented in GIS (Puotinen, in press) for each cyclone that passed through the GBR from 1969-2003. Over this 35 year period, relevant cyclone energy parameters were generated for the entire set of 85 cyclones. The intensity and duration of high wind energy capable of damaging reefs by potentially creating adequate conditions for the development of heavy local wind seas were typified in the form of the maximum wind speed generated at any time during each cyclone and the duration of gale force (17m.s-1) or higher winds (Puotinen, in press). Both of these energy parameters were consequently used in conjunction with measures of reef exposure and vulnerability in a model that predicted reef damage at each of 24,224 sites spread across the ~ 3,000 reefs for each of the 85 cyclones in the times series. Linkages between hindcasted cyclone energy, reef exposure, reef vulnerability and patterns in field observations of wave damage to reefs were identified by the model which effectively predicted the presence or absence of three types of damage: breakage, dislodgement, exfoliation, and for a combined category of widespread damage of any type (also refered to as “severe” damage of any type by Puotinen (2005a); these are equivalent terms in the context of this research). Based on the frequency, timing and spatial distribution of the predicted

damage, the cyclone disturbance regime was consequently characterized across the GBR region (Puotinen, 2005a).

Thus, while distribution of cyclone energy within the GBR was modeled at broad scales (100s of kms at a 1km resolution), reef vulnerability to damage was examined at local scales (individual sites within each reef (< 10s of m)) (Puotinen, 2005a). To enable the capture of this local scale variability in the numerous factors relating cyclone-induced damage to coral reef ecosystems, individual reef sites were placed 1km apart around the perimeter of each reef. For the 2,728 contiguous reefs forming the GBR, it produced a total of 24,224 sites at which to model the cyclone disturbance regime (Puotinen, 2005a) (Fig. 3.2). The distribution of reefs, and thus sites, varies across the GBR with the greatest concentration of reefs found in the far north (11˚S) and the least in the far south (24˚ S) (Fig. 3.3).

Please see print copy for Figure 3.2

Figure 3.2. The GBR divided into 1˚ latitude by 1˚ longitude boxes (blue quadrats) showing the level of organisation of the cyclone damage data at the scale of reefs (blue polygons) and reef sites (red circles). *Note: although each site is indicative of the local exposure conditions, it is not representative of the entire 1km area.*

Please see print copy for Figure 3.3

Figure 3.3. Number of reef sites within each 1˚ latitude by 1˚ longitude box: white = < 1,000, light grey = 1,000-2,000, dark grey = 2,000-3,000 and black = > 3,000. *Note: the more reef sites within a block, the more likely the presence of damage data by cyclones that pass through that area.* As presented by Puotinen (2005a).

3.2.3 Patterns in tropical cyclone disturbance of the GBR

The dynamics of the cyclone disturbance regime at the scale of the entire GBR were analyzed with regard to coral community structure by adapting the 'state-space' dynamics diagram presented by Turner *et al.* (1993) to the temporal and spatial parameters that define the tropical cyclone disturbance for the GBR as a whole and by describing the spatial patterns in the timing of the four damage types at reef sites averaged by 1˚ latitude by 1˚ longitude boxes as the spatial unit across the GBR. At the level of the entire GBR ecosystem, Puotinen (2005a) predicted cyclone disturbance was steady, allowing enough time for reefs to recover between successive disturbances. This observation is highly dependent on the estimated time for recovery. For example, for widespread damage of any type, cyclone disturbance was observed to be steady to unstable for increasing recovery time: 10 to 100 years respectively (Puotinen, 2005a, c). The reconstructed cyclone disturbance history was characterised for the GBR based on incidence and timing as illustrated by four parameters (number of disturbance-free intervals, mean length of disturbance-free periods (return interval, based on a geometric distribution, see Puotinen 2004b), maximum length of disturbance-free periods (in years), and the number of years since the last event) (Puotinen, 2005a, c). For example, for widespread damage of any type, the maximum return period averaged 10 years, and the number of years since the last event was never less than what was typical over the time series (Fig. 3.4). The number of years since the last event, as a measure of the timing of the most recent disturbance-free interval (derived by subtracting the mean disturbance interval from the number of years since the last disturbance) was used to indicate whether the level of disturbance seen at a particular reef was typical over the 35 year time series (see Puotinen, 2005a, c). In conjunction with patterns in the mean and maximum length of the return interval, the timing of the most recent disturbance-free interval can be used to evaluate whether current protection of reefs managed under the RAP may be sufficient in the future. For example, if reefs have recently experienced less disturbance than normal (over the last 35 years) they may be more disturbed in the future than they are now. In contrast, reefs that have experienced more disturbance recently than normal may provide the best insight of what their conditions typically resemble in the long-term. Puotinen's findings (2005a) suggest that reefs across most of the GBR were disturbed less frequently than normal in recent times and thus could be expected to have fully recovered. This provides valuable information for management. However, the degree to which this rationale is true depends on other disturbances that also potentially affect the GBR between successive cyclone disturbances (i.e. outbreaks of predators or diseases, pollution, and bleaching under intensified sea surface temperatures) and could synergistically influence the level of cyclone disturbance, as well as depending on routine ecological processes (e.g. competition, recruitment, recovery) that affect recovery (Puotinen, 2005a).

Please see print copy for Figure 3.4

Figure 3.4. Patterns in widespread damage of any type across the GBR from 1969-2003: A – mean length of damage-free periods, B – maximum length of damage-free periods, C – number of years since the last damage (as of 2003), and D – timing of the most recent damage-free period, averaged in each 1˚ latitude by 1˚ longitude box. The colours of each box indicate the relative number of years for A, B and C: white =< 10, light grey = 10-20 and whether the result was positive (white: disturbed less recently than normal), negative (black: disturbed more recently than normal) or zero (grey: disturbed at the median interval) for D. Adapted from Puotinen 2005a.

In the characterisation of the cyclone disturbance regime, Puotinen (2005a) used hindcast cyclone energy and reef vulnerability measures to determine how well these could predict reef damage. Temporal patterns of four cyclone-induced damage types (coral breakage, dislodgement, exfoliation, and widespread damage of any type) predicted from decision rules derived from classification and regression tree (CART) analysis (see Puotinen, 2005a) were then analysed across the GBR as a whole for the last 35 years. This helped classify the cyclone disturbance regime predicted as being steady to stable based on the timing of cyclone damage and estimated recovery time of coral communities (Table. 3.1).

Table 3.1. Summary of the predicted timing and dynamics of cyclone disturbance in the GBR from 1969-2003 for four measures of damage. *Note: the nature of the dynamics were derived from the 'state-space' diagram developed by Turner et al. (1993).* Adapted from Puotinen, 2005a,c.

Please see print copy for Table 3.1

Off these four cyclone damages, coral breakage and dislodgement were illustrated by a recovery time shorter than the return interval implying that reef sites had time to recover between successive disturbances within the time series (i.e. intermediate disturbance, or steady state). In contrast, exfoliation and widespread damage of any type by cyclone waves were observed to be frequent disturbances with recovery time longer than the return interval (sites didn't always have enough time to recover from one disturbance before the next one). However, these results represent worst-case scenarios due to modelling limitations, and it is unclear how the damage predictions would vary when including vulnerability factors (habitat: front vs. back, slope; actual presence and distribution of coral communities and structure) in the model (Puotinen, 2005a,b). Additionally, due to the unusual characteristics of the test cyclones on which the predictive model was based upon (the primary direction of approach for winds and thus wind-driven waves at surveyed reefs was incident to normally exposed, wave-hardened sites), the model was biased towards over-prediction of high-energy (dislodgement, exfoliation) rather than low-energy (breakage) types of damage. A damage survey of reefs affected by cyclone Ingrid (of severe intensity: category 4) recently undertaken in the far northern GBR (May 2005) could assist in remedying this. Regardless, it is probable that both exfoliation and widespread damage of any type are actually intermediate (steady) disturbances (Puotinen, 2005a, c).

When evaluating the RAP from the cyclone disturbance history perspective, widespread – or severe – damage of any type was chosen to characterize damage as it provides a summary of potential impacts of various types and represents a worst-case scenario.

3.3 Selecting a spatial unit

Processes investigated in the context of the GBR, such as cyclone damage, require a regional perspective. The nature of the requisite datasets itself poses a challenge due to the vast area that must be covered. Cyclones are one of the major natural disturbances on coral reefs as they affect coral reef structure and functioning at various spatial and temporal scales (Harmelin-Vivien, 1994) that differ from those of the patterns they produce. Indeed, damage to reefs is typically highly patchy at local scales while cyclones last for hours to days and cover hundreds of kilometres (broad scale) (Puotinen, in press). For this reason, Puotinen (2005a) modelled cyclone energy at broad scales (1km grid cells, as cyclone wind fields were reconstructed from relevant cyclone models that are only appropriate at that spatial resolution) and site exposure and vulnerability at fine scales (sites along each reef, because these are site-specific factors that vary at local scales). Predictions made at local scale were aggregated across 1˚ latitude by 1˚ longitude boxes for ease of presenting the data. Comparing the cyclone damage history to the zoning established by the RAP required defining an appropriate spatial unit capable of dealing with the aforementioned scale ranges. A sound spatial unit should enable a full examination of the cyclone damage data while also being convenient to use by managers. The most convenient spatial unit for managers to use is the reef. Consequently, a simple case study was conducted to estimate how much variability in damage prediction would be lost by generalising the site information by reef. As a representative sample of the range of cyclone disturbance that can occur across the GBR, two one-degree boxes were selected to represent the opposite ends of the spectrum of cyclone incidence (A= low cyclone incidence, B= high cyclone incidence) across the GBR (Fig. 3.5).

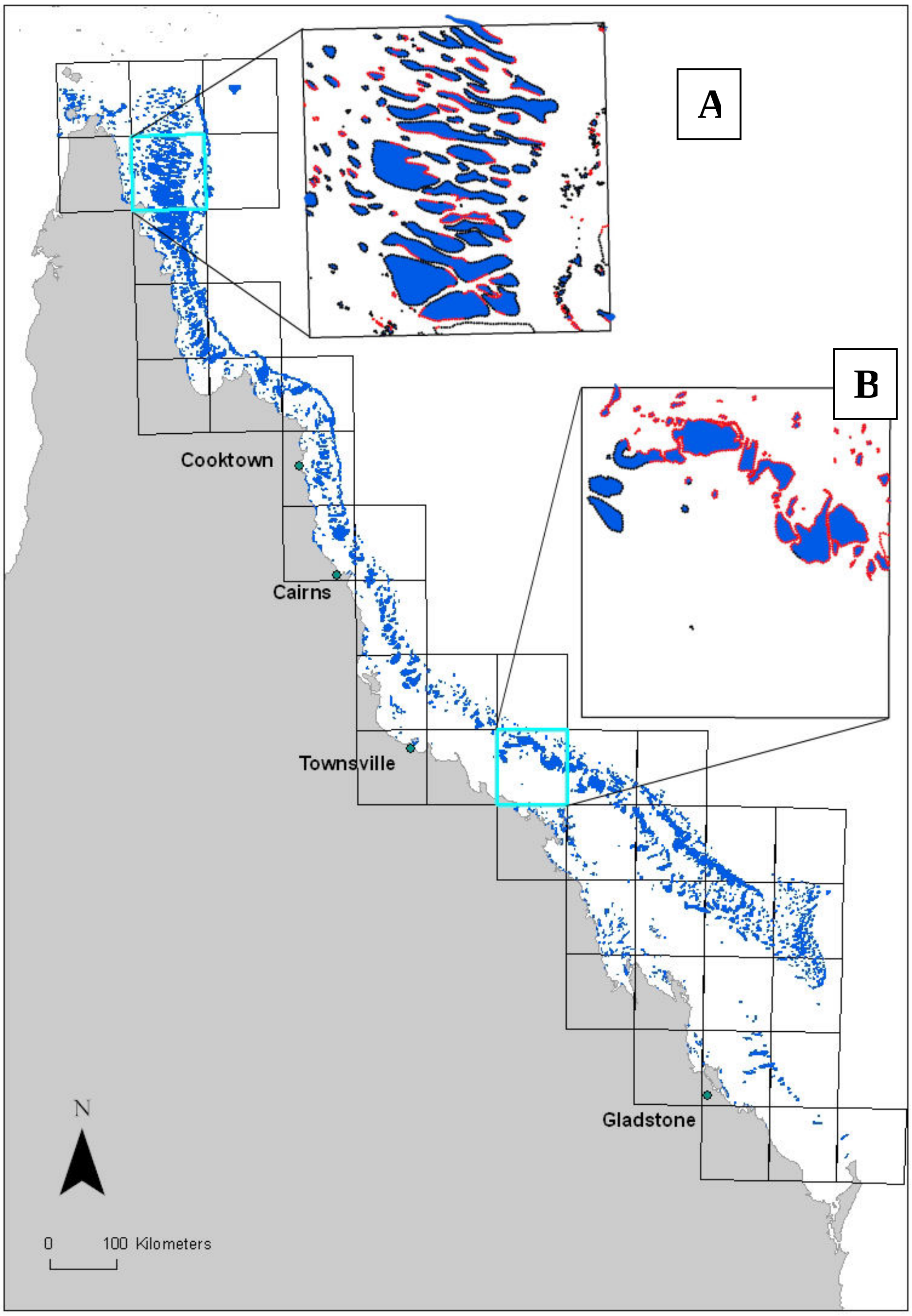


Figure 3.5. Location of 1˚ latitude by 1˚ longitude boxes used in the case study. Reefs are shown in blue, damaged sites in red, and undamaged sites in black. Example of widespread damage of any type occurrence is represented as predicted in 1993. Inset maps show A: the low cyclone-incidence box 5 (11°S, 143°E): far north Queensland, 8 cyclones over the 35 year period and B: the high cyclone-incidence box 22 (19°S, 148°E): Townsville-Whitsunday region, 23 cyclones over the 35 year period.

In Puotinen (2005c), predictions of damage at each site were stored as attributes attached to a GIS vector point coverage. Using the point coverage for widespread damage of any type, the damage frequency was recorded per year as the percentage of affected sites and compared to the percentage of affected reefs (as defined by showing damage occurrence for at least one of their sites) present within each of the two boxes. The mean and the standard deviation of the values of damage across a particular box for both spatial units was then calculated (Table. 3.2).

Table 3.2. Occurrence of widespread damage of any type at the site versus reef level for the entire time period (1969-2003) for box 5 (11°S, 143°E) and box 22 (19°S, 148°E). Mean and standard deviation (stdev) are shown in grey.

	box 5: 180 reefs, 2381 sites		box 22: 61 reefs, 841 sites	
Year	%affected sites	%affected reefs	%affected sites	%affected reefs
1969	0.0	0.0	0.0	0.0
1970	66.7	65.4	0.0	0.0
1971	100.0	100.0	100.0	100.0
1972	0.0	0.0	0.0	0.0
1973	0.0	0.0	21.5	26.2
1974	0.0	0.0	0.0	0.0
1975	0.0	0.0	0.0	0.0
1976	0.0	0.0	100.0	100.0
1977	0.0	0.0	74.1	68.9
1978	0.0	0.0	0.0	0.0
1979	100.0	100.0	0.0	0.0
1980	0.0	0.0	100.0	100.0
1981	0.0	0.0	0.0	0.0
1982	55.2	54.7	80.0	82.0
1983	0.0	0.0	0.0	0.0
1984	14.3	15.6	0.0	0.0
1985	0.0	0.0	21.3	34.4
1986	100.0	100.0	0.0	0.0
1987	0.0	0.0	0.0	0.0
1988	0.0	0.0	6.9	4.9
1989	0.0	0.0	54.2	47.5
1990	0.0	0.0	100.0	100.0
1991	100.0	100.0	0.0	0.0
1992	0.0	0.0	0.0	0.0
1993	74.4	87.7	0.0	0.0
1994	0.0	0.0	0.0	0.0
1995	0.0	0.0	0.0	0.0
1996	77.9	85.5	96.1	96.7
1997	0.0	0.0	37.8	36.1
1998	0.0	0.0	0.0	0.0
1999	0.0	0.0	0.0	0.0
2000	0.0	0.0	100.0	100.0
2001	0.0	0.0	0.0	0.0
2002	0.0	0.0	0.0	0.0
2003	0.0	0.0	0.0	0.0
mean	19.67	20.26	25.48	25.62
stdev	36.69	37.63	39.75	39.59

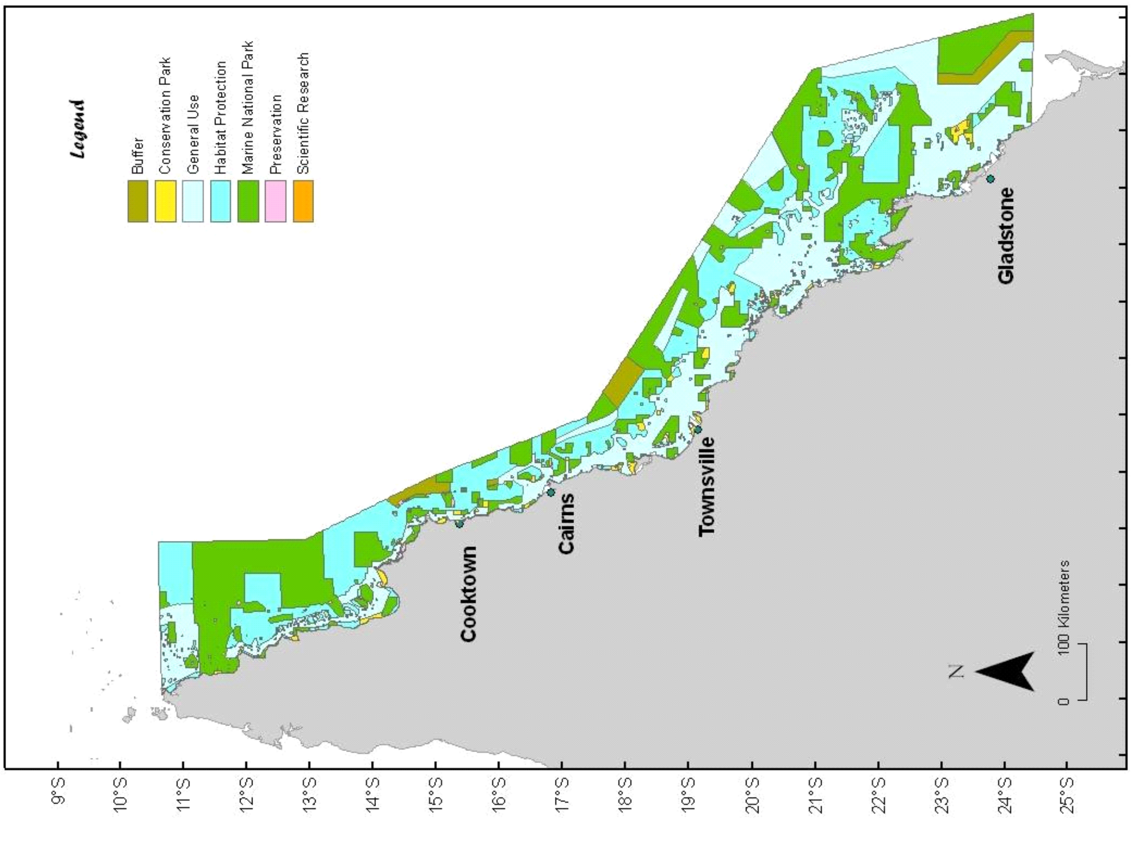
From this reef versus site comparison, the results proved not to be significantly different for either the low cyclone intensity box A (ANOVA, $F = 0.2568$, $P = 0.6157$) or the high cyclone intensity box B (ANOVA, $F = 0.2733$, $P = 0.6047$). It appears that not much information is lost by summarising the damage data by reefs. Because only 834 of the 2,728 reefs are highly protected (as defined in the next section of this chapter) and the damage data was readily accessible to the detail of the reef site level to be summarised, using the reef as the spatial unit was achievable within a reasonable amount of time for this study.

3.4 Determining levels of protection through the GBR

As mentioned in Chapter 2, each zone category in the RAP specifies which activities can or cannot be undertaken and whether or not permission is required to undertake those activities (Fig. 3.6).

Please see print copy for Figure 3.6

Figure 3.6. RAP zoning as of July 2004 presenting the location of the different zones and the guide to activities and uses allowed within them. Zones coloured orange, green and pink show highly protected areas. (*Source:* http://www.gbrmpa.gov.au).



Low-impact zones within the RAP (that require permanent high-level protection to minimise exposure to potentially threatening processes) correspond to the Marine National Park, Scientific Research and Preservation zones allowing non-extractive use and limited access (Fig. 3.6). In contrast, high-impact zones (low protection zones) allow greater levels of human use. These consist of: Buffer, Conservation Park, Habitat Protection and General Use zones where commercial, recreational, touristic, and fishing activities are allowed though regulated (Fig. 3.6). High protection zones (Fig. 3.7) are significant because they represent areas largely left in an undisturbed state (at least from human disturbances). These are thus best able to contribute to the stability and recovery of the ecosystem by limiting additional disturbances of anthropogenic origin and by acting as sources of larvae for transport to damaged reefs. Human activities, combined with natural disturbances, can transform a short pulse disturbance into a more persistent one (Nyström *et al.*, 2000; Hughes, 1994), which might affect coral reefs and their potential recovery in the long-term. Although natural disturbances can't be prevented, it is possible to limit the frequency with which they coincide with human disturbance. From a conservation viewpoint, this would suggest that areas experiencing high cyclone disturbance should be highly protected to avoid the permanent changes that can occur from the combination of natural and human disturbances (Nyström *et al.*, 2000; Hughes, 1994). However, this strategy could negate the ability of highly protected areas to act as sources of larvae. Thus it is assumed that the RAP's highly protected zones should be placed for minimal exposure to cyclone disturbance. Since GBRMPA has gone to great effort to increase high protected zones from 4.5% to 33.3% through the RAP, it is worthwhile investigating whether they have been placed in areas that would make the most difference: that is areas where natural disturbances such as cyclones are rare, so that they can fulfil their role as sources for recovery. To this end, the Marine, Scientific and preservation zones were combined into the high protection zones, and these areas were assumed to be most at risk from cyclone disturbance (Fig. 3.7). For the rest of this study, reefs across the GBR were overlayed in GIS with the high protection zones to form the base polygon coverage representing highly protected reefs (HPR) (Fig. 3.8).

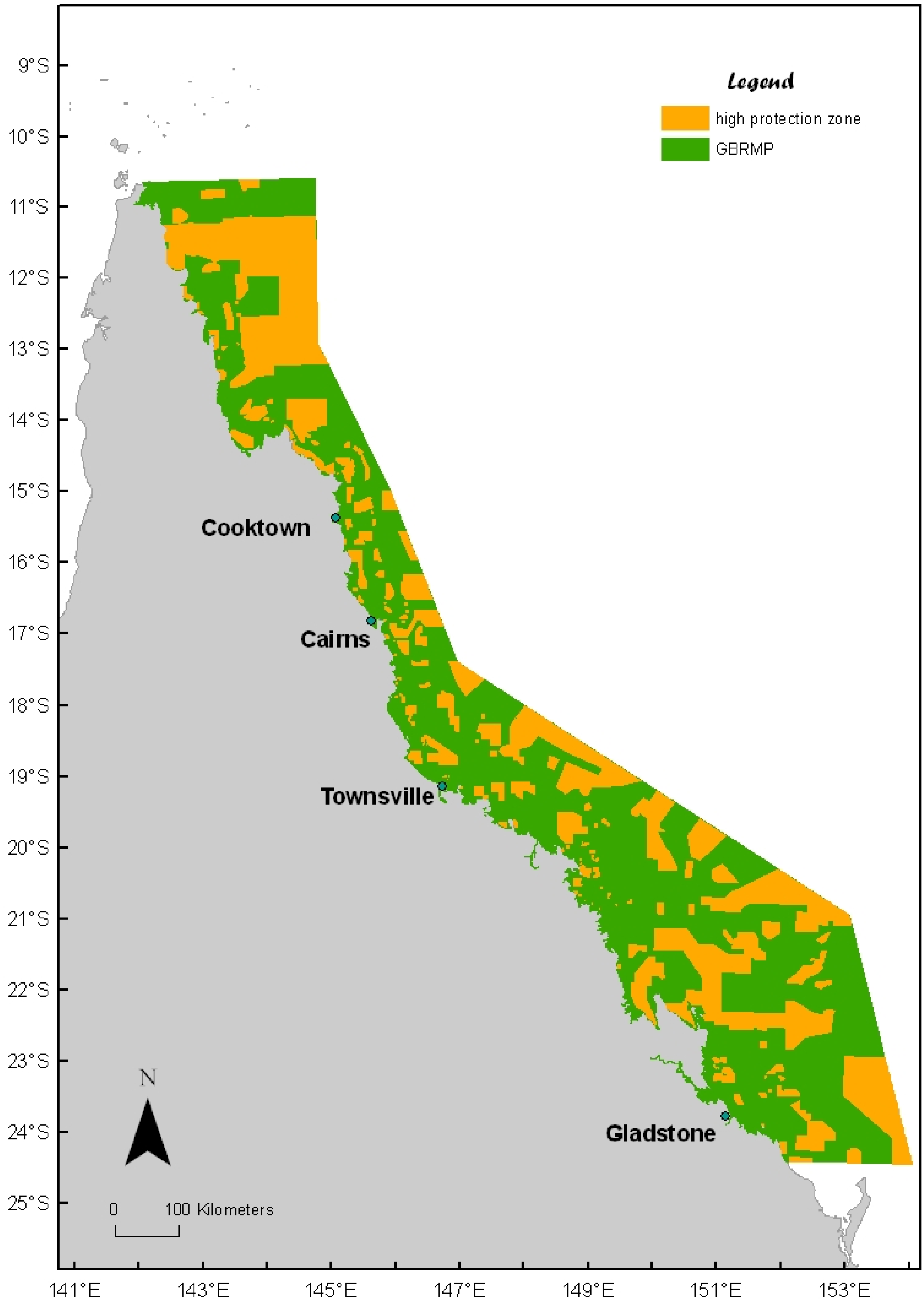


Figure 3.7. The GBR divided into low and high protection zones. The latter is defined as Marine National Park, Preservation and Scientific Research combined).

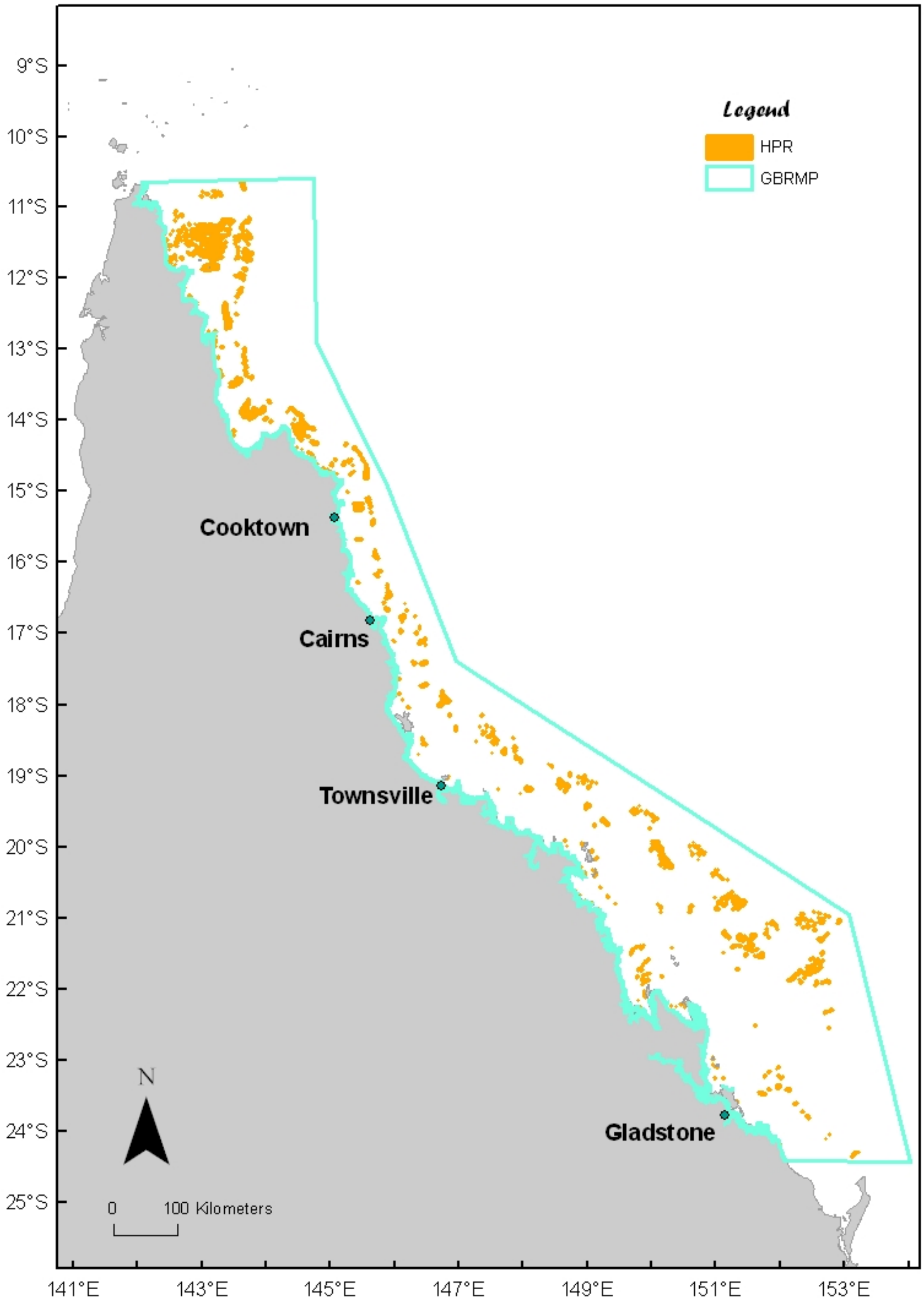


Figure 3.8. Distribution of highly protected reefs (HPR). These are the reefs of the GBR that are included in the high protection zones defined in Figure 3.7.

HPR were evenly distributed across the GBR region, thus likely to show similar patterns in cyclone disturbance to trends observed using the 1˚ latitude by 1˚ longitude boxes (Puotinen, 2005a).

3.5 Analysing descriptors of the cyclone disturbance regime

3.5.1 Frequency, intensity and timing

The dynamics of the cyclone disturbance regime over the GBR was described by Puotinen (2005a) using a range of interrelated descriptors: intensity, incidence and timing (Table 3.3).

Table 3.3. Descriptors of the tropical cyclone disturbance regime in the GBR region from 1969-2003. Adapted from Puotinen, 2005a, 2004b.

Please see print copy for Table 3.3

3.5.1.1 Intensity

One important factor affecting the potential for reef damage from cyclone waves is the magnitude and duration of locally-generated seas. The intensity of each cyclone was examined from the point of view of individual reef sites by using hindcast wind speeds as a proxy for locally generated sea state (Puotinen, in press). For the 85 cyclones that passed near the GBR from 1969-2003, Puotinen (in press) estimated thresholds in maximum wind speed and the duration of wind exceeding gale force beyond which the development of waves capable of damaging reefs was possible. These were set to $24.7 m.s^{-1}$ for minimum maximum wind speed and 19.5 hours for the minimum threshold duration of winds exceeding gale force predicted to be capable of damage (Table. 3.3). Applying these thresholds to wind fields generated for each cyclone (Puotinen, in press, 2005c) allowed a simple estimate of the risk of cyclone wave damage occurring somewhere along each reef across the GBR by examining the percentage of years during which one or both threshold values were experienced or exceeded (Puotinen, 2005a). The resultant map (Fig. 3.9), showing the spatial distribution of the number of times these thresholds were exceeded over the past 35 years, was categorized as infrequently intense (less than 30% of the time), frequently intense (30-50% of the time) and very frequently intense (> 50% of the time) and compared to the HPR of the RAP. This provided a crude estimate of the susceptibility of the HPR to cyclone disturbance.

Please see print copy for Figure 3.9

Figure 3.9. Percentage of years from 1969-2003 during which cyclone damage (widespread damage of any type) could be possible at reef sites exposed to local wind-sea and susceptible to damage. Highly protected reefs are shown in orange. Inset map shows highly protected reefs potentially affected more than 50% of the time (turquoise blue). Adapted from Puotinen, in press, 2005c.

Over the last 35 years, it appears that HPR in the GBR located in the far north (north of 12˚S) have been potentially less susceptible to wave damage than the rest of the GBR. Only three HPR were at risk more than 50% of the time (Fig. 3.9). Instead, HPR fall mainly (67.56% of HPR area) within the frequently intense category (Table. 3.4).

Table 3.4. Proportion of highly protected reefs in the GBR exposed to various frequencies of potential cyclone wave damage.

Intensity	% of time potential for cyclone damage was achieved	Number of HPR affected	Percentage (HPR affected area / total area of all HP reefs) *100
Infrequently intense	< 30 %	201	32.29
Frequently intense	30 – 50 %	630	67.56
Very infrequently intense	>50 %	3	0.15
	total	**834**	**100**

Although the potential for the development of heavy seas is important to the risk for reef damage, and useful for identifying coarse levels of disturbance to HPR, the exposure and vulnerability of reefs to cyclone-induced damage is equally important (Done, 1992, Van Woesik, 1992). Wave damage is typically very patchy in distribution because the local scale factors that affect reef exposure and vulnerability (proximity and orientation with respect to nearby wave-blocking obstacles, local bathymetry, water depth, slope, colony size, growth form and orientation, etc) are highly variable over time and across space (Harmelin-Vivien, 1994). Thus, Puotinen (2005a,c) developed a predictive model that also considers the latter. As previously mentioned (section 3.2.2 of this chapter), damage predicted as breakage, dislodgment, exfoliation and widespread damage of any type was successfully modelled in the latter study. When looking at the cyclone disturbance history and its impact on the effectiveness of the RAP, widespread damage of any type is most useful as it provides a broad measure as well as the worst-case scenario for damage types (Fig. 3.10).

Please see print copy for Figure 3.10

Figure 3.10. Estimated probability of widespread cyclone damage of any type across the GBR at any time during the period 1969-2003 across each 1˚ latitude by 1˚ longitude box. Grey boxes indicate that the probability of damage within the box over the study period was 25% or greater. As presented by Puotinen (2005c).

To assess the robustness of the RAP to cyclone disturbance, two descriptors (incidence and timing) illustrated by four calculated parameters (% of HPR affected per year, mean length of disturbance-free periods, maximum length of disturbance-free periods, time since last event) were selected from the dataset provided by Puotinen (2005a). Each of these descriptors was evaluated against the highly protected zones (defined earlier in this chapter) to determine the frequency and timing of damage to highly protected reefs of the GBR (Table. 3.5). HPR as a whole were then assessed based on their ability to provide ecological memory (i.e. act as sources of larvae for recovery) for the RAP to enable it to absorb cyclone disturbance over time.

Table 3.5. Descriptors of tropical cyclone disturbance to highly protected reefs of the RAP in the GBR region from 1969-2003 and associated disturbance ranking. Adapted from Puotinen, 2005c.

Please see print copy for Table 3.5

Presumably, if HPR generally experience a high level of cyclone damage, this ability to contribute to the effectiveness of the RAP would be reduced.

3.5.1.2 Frequency

The simplest way to estimate frequency of damage for a particular reef is to look at how often a cyclone passed directly over a reef (a 'direct hit'). However, this intuitive measure of the potential for cyclone damage frequency uses the distance of a reef to the nearest path as the sole indicator of the potential for disturbance has been suggested to only provide underestimate of the actual impacts from that cyclone (Puotinen, 2004b).

Therefore, modelled damage estimates from Puotinen (2005a) were used as a measure of cyclone damage frequency. Damage to HPR was evaluated using the number of times damage predictions for widespread damage of any type (as per the model developed by Puotinen, 2005a) were recorded to occur at each reef. HPR predicted to have a medium frequency of disturbance represented 65.02% of the total area and only ~6% of the HPR area was predicted to have no damage at all using the model results (Table 3.6). It is worth noting that even though the majority of the HPR (in number) belong to the low frequency disturbance category, the area these reefs represent is only a small percentage of the total highly protected areas under the RAP (Table. 3.6).

Table 3.6. Frequency of damage predicted at highly protected reefs across the GBR region between 1910-2003. The number of affected highly protected reefs and the percentage the sum of their respective area represent out of the total area of highly protected reefs are shown.

Frequency	Count of damaged sites	Number of HPR reef affected	Percentage (HPR affected area / total area of all HP reefs) *100
None	0	30	6.46
Low	1-10	618	21.31
Medium	11-100	184	65.02
High	>100	2	7.21
	total	**834**	**100**

Thus, it seems worthwhile to use modelled damage estimates from Puotinen (2005a) rather than rely on the ‘direct hits’ method.

3.5.2 Timing

The vulnerability of reefs to cyclone damage in a given year depends on the history of disturbances (from cyclones or other sources) at the particular location as well as the nature and magnitude of recent damage (Done, 1992). Where cyclones occur frequently, coral communities are likely to be composed of species with different life-histories (smaller sizes, wave-adapted growthforms) than where they are infrequent (Hughes *et al.*, 2003; Hughes & Connell, 1999; Done, 1992). The timing of cyclone disturbance from 1969-2003 is thus important for determining the influence of individual disturbances on reefs and their structure. The timing of cyclone disturbances in the GBR was described using three measures in this study: 1) mean number of years expected between successive disturbances (return interval), 2) maximum length of disturbance-free intervals, and 3) number of years since the last cyclone event. These were taken from Puotinen’s (2005a) characterisation of the tropical cyclone disturbance regime to be evaluated against the HPR of the RAP using various categories of timing of cyclone disturbance (Table. 3.5).

The return interval was obtained by dividing the total number of damage events predicted across the box over the time series by the number of reef sites found in that box multiplied by the number of years in the study period (Puotinen, 2005c). Based on this, reef sites from the vector point coverage characterising widespread damage of any type were categorised into two groups: mean length of disturbance-free period ≥ 5 years (more time to recover between events) or < 5 years (less time to recover between events). HPR were then intersected by location in GIS with the latter to identify HPR that are frequently disturbed and the area these represent compared to the total area represented by all HPR. This limit was chosen in accordance with the average number of years estimated to be required for recovery of coral communities to their state prior to disturbance along with the typical return time for this damage type as characterised by the cyclone disturbance history (Table. 3.7). Indeed, reefs have been observed to require recovery times of usually less than a decade (Connell *et al.*, 1997) as intense cyclone operating at large scales are rare through the GBR (Puotinen, 2005c; Puotinen *et al.*,1997) and their impact usually patchy therefore unlikely to create damage requiring extensive recovery periods.

Table 3.7. Summary of the predicted timing of cyclone disturbance in the GBR from 1969-2003 for widespread damage of any type. Adapted from Puotinen, 2005a.

Please see print copy for Table 3.7

The maximum length of the disturbance-free intervals was also used, as this indicates the longest time period during which reefs could have grown undisturbed (assuming other disturbances are held constant). HPR containing sites for which the maximum damage-free interval was less or equal to 10 years (less time to recover) were selected by location in GIS so that the area they represent could be evaluated against the entire HPR area. Finally, the timing of most recent disturbance-free interval was evaluated by comparing the number of years since the last cyclone event (measured from 2003) with the return interval. This indicates the degree to which current conditions at a site reflect what was typical for that site over the entire 35 years study period (Puotinen, 2005a). For widespread damage of any type, the latter author's findings suggested that reef sites have had more time to recover from the last cyclone disturbance than normal across the entire GBR. Therefore, the number of years since the last disturbance was divided by the mean disturbance-free interval in order to give an estimate of how much supplementary time the HPR have had to recover recently than normal.

3.6 Connectivity

Whatever the specific details, the rate of recolonisation and growth is as much a function of the location of the coral reef in regards to others as a property of the recolonising populations (Roberts *et al.*, 2003; Allison *et al.*, 1998). The ability of coral reefs to re-establish themselves after a disturbance (ecological memory) can highly depend on recruitment of new corals. This may vary spatially across the GBR as the extent of connectivity between a particular reef and others within the larger seascape largely determines the availability of coral larvae at a particular location (Nyström and Folke, 2001). Although the analyses described in the last section provide an insight into cyclone disturbance in relation to the protection level of the affected reefs (as defined by the RAP), it is worth investigating how the cyclone history may affect the connectivity of the HPR (as potential sources of larvae) to the set of reefs least protected from human activities (potential sink reefs). To this end, a connectivity index was generated to determine changes in connectivity between a no-disturbance and a cyclone-disturbed scenario where HPR estimated to be highly impacted (Table. 3.5) were excluded from the complete set of highly protected reefs. First, the centroid of each HPR (sources), and then the centroid of each non-HPR (sinks) were found. Then, the minimum distances between each source and sink centroid were complied using an Arc Macro Language (AML) script in ArcInfo GIS (Appendix 2). Change in connectivity under disturbance was then monitored under various scenarios for which source reefs where categorised using timing of cyclone disturbance (A: no disturbance, B and C: cyclone disturbance – Fig. 3.11). Distances were calculated from each sink centroid to the nearest centroid of (A) all HPR (source) centroids, (B) only the HPR (source) centroids that had more than five years to recover on average from cyclones and (C) only the HPR (source) centroids that had at least one 10-year period to recover from cyclones. Because only three reefs belonged to the high disturbance frequency class (Fig. 3.9), the connectivity index associated with this class wasn't generated as it wasn't expected to substantially change general patterns of connectivity relevant to them. The connectivity index showing how connectivity changed under these disturbance scenarios was then derived by subtracting the distances of the latter scenarios (cases B and C) from the distances of the first set scenario (A) for each sink reefs (i and ii - Fig. 3.11).

The connectivity measure developed and applied in this study is a simplistic representation. It uses straight distances between reefs as the sole indicator of GBR connectivity without taking into account factors such as coral gene flow, local parameters (e.g.: oceanic circulations) and also assumes that all reefs are equally connected to each other. Thus, it can only be expected to roughly define variations in connectivity that reefs can experience under cyclone disturbance.

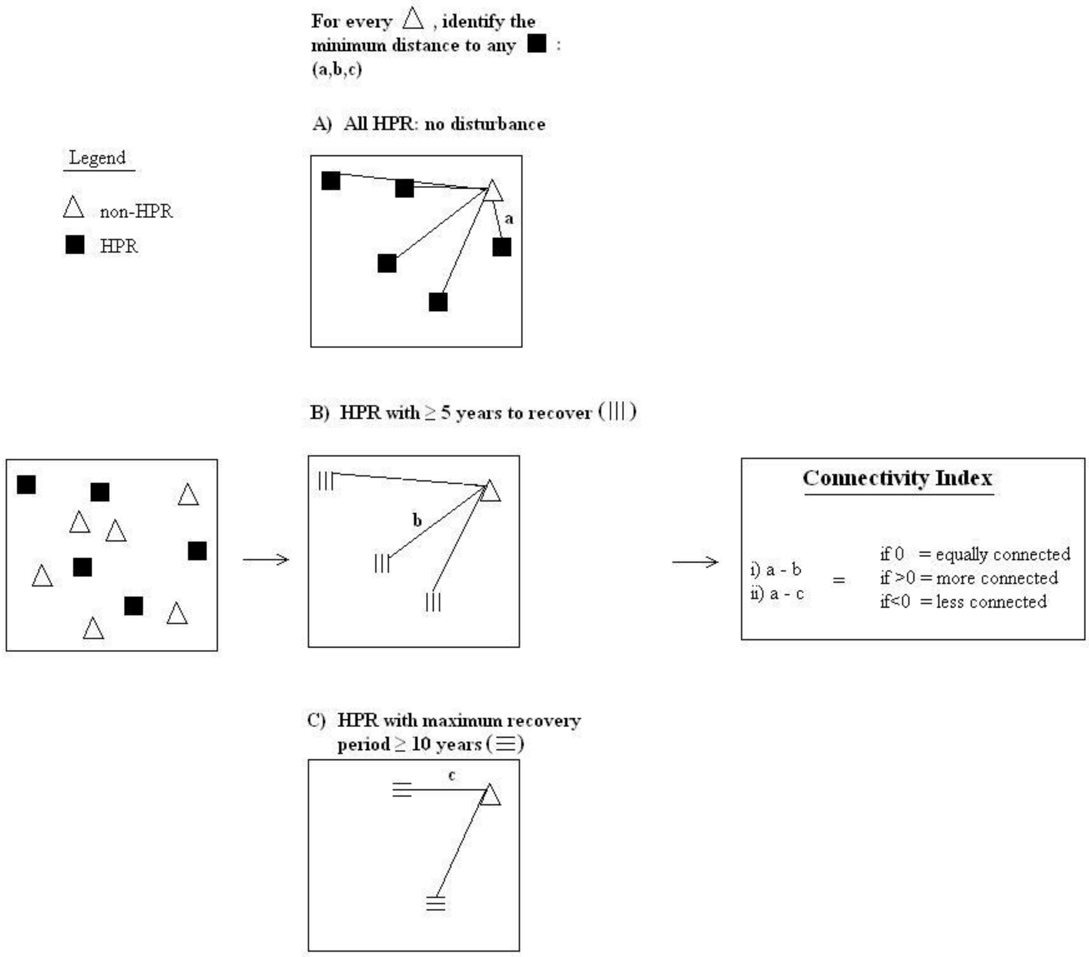


Figure 3.11. Calculation of the connectivity index presenting 3 disturbance scenarios: A) no disturbance, B) and C) cyclone disturbance.

3.7 Insurance factor

Where expectations of a loss of HPR due to a frequent exposure to cyclone damage (i.e. section 3.5) and/or connectivity change (i.e. section 3.6) is thought to be possible, an effort should be made to account for these disturbances so that the functional goals of the reserve will still be ensured within the given disturbance regime.

3.7.1 Calculating the insurance factor

The maintenance of structure and functioning of an ecosystem within a reserve is dependent upon the processes and events occurring both within and external to it. Over the long term and across large areas, severe disturbances in marine ecosystems are not uncommon. For example, tropical cyclones are one large natural disturbance returning regularly to affect the GBR (Puotinen, 2004b; Puotinen *et al.*, 1997). A high level of site-specific threats might disqualify certain areas from inclusion in a reserve network. One way to increase the effectiveness of a reserve network is to allow for the inevitable impacts of large-scale natural events such as cyclones by increasing the percentage of area in reserves. This can be done using an insurance factor which calculates the minimum effective size of a reserve network necessary to meet the goals for the reserve in a stable environment (Allison *et al.*, 2003).

The insurance factor is calculated by using an insurance multiplier that takes into account the frequency of the disturbance to the environment and the estimated time for recovery as shown below (after Allison *et al.*, 2003):

[1] $$M = 1 / U$$

Where M = insurance multiplier
U = fraction unaffected by cyclones

If the desired goal of the reserve network is to represent, on average, R% of the sites in a recovered state then M * R% must be set aside (the insurance factor). For the simplest form of the insurance factor, the mean chance of not being affected by a disturbance is defined by the following equation.

[2] $$U = (1 - h)^{T}$$

Where h = fraction of the reserve hit each year

T = time to recovery (in years)

Using equation [2] makes the assumptions that:

1. The concerned reserve is large in extent
2. the fraction h is constant each year
3. The disturbance hits the reserve randomly so that the probability of any point being affected is constant and independent of the point's prior history of disturbances
4. It takes T years for a site to recover from the disturbance at which point it becomes valuable for management or conservation again.

To advise on how the GBR design is able to withstand the impact of external disturbance such as tropical cyclones, the insurance factor was calculated for each box from the prediction of widespread damage of any type. In the particular case of cyclones and the GBR, assumption 2 is violated because the percentage of reef sites that has not been rendered ineffective by cyclones greatly varies from year to year. This was taken into account by using the geometric mean of the annual affected fraction from year to year (relaxing assumption 2). Equation [2] is therefore modified for the 35 year sequence as described below:

[3] $$U = \left[\left(\prod_{i=1}^{n} (1 - h) \right)^{1/n} \right]^{T}$$

Where n = total number of years in the time period (n = 35)

Although in reality assumption 3 is also violated because disturbance isn't spatially homogeneously distributed and reef vulnerability depends on history, this wasn't completely accounted for due to a lack of field data needed to model it. However, the insurance multiplier was determined for various recovery time scenarios for each of the 43 individual 1˚ latitude by 1˚ longitude boxes spanning the GBR, to help reduce these issues of spatial assumption violation (assumption 3). Indeed, boxes separate hot spots of damage existing over parts of the GBR from less disturbed areas therefore increasing the likelihood of the spatial independence to be valid (Allison *et al.*, 2003) by delineating areas of greater homogeneity. Before calculation of the insurance factor was possible, the unaffected fraction of the GBR (U) needed to be established. For each box, the number of HPR sites showing widespread damage of any type (h) was recorded per year, adjusted to account for the difference between reef front vs. back (total number of damaged sites / 2) and the proportion of all sites these represented taken, before the geometric mean of the unaffected fraction for the 35 year sequence could be obtained (using equation [3]) for that particular box.

3.7.2 Applying the insurance factor

The percentage of an area to be included in a reserve network depends on the goals of the reserve. Scientists recommended reserving an area of 30 to 50 % of all representative habitats in each bioregion under no-take areas in marine reserve design after consideration of both conservation goals and the risk from human threats and natural perturbations (Jago *et al.*, 2005; Airamé *et al.*, 2003; Allison *et al.*, 2003, Roberts *et al.*, 2003b). A recent awareness of the inadequacy of the old zoning to effectively protect the full range of biodiversity of the GBR led to an increase in the degree of protection required for the GBRMP to 33.3% of marine areas being included in no-take zones (Jago *et al.*, 2005). Allowing an additional amount of HPR to account for cyclone disturbance would ensure their role as source for recovery and replenishment of highly disturbed reefs already prone to impacts by other disturbances. Ideally, a network of marine reserves for a particular area should be planned within the context of other reserves in adjacent areas or as part of a larger system. Whether the contribution of the HPR to the reserve system operates at a local (10s to 100s of m) or ecosystem (100s to 1000s of kms) level is still uncertain and much controversy remains among the scientific community on the topic of connectivity of marine systems. In this regard, various scenarios were investigated to determine adjustments to the amount of complementary highly protected sites to set aside in the face of cyclone disturbance across the GBR. Once the insurance multiplier defined for all GBR boxes, the additional number of highly protected sites necessary under disturbance for the reserve to be able to fulfil its function for replenishment and support of surrounding areas was defined considering connectivity may operate at:

1. a local scale: thereby only reef sites within a box could be included as additional reserve,
2. a regional scale: only reef sites from directly adjacent boxes could contribute to the supplementary area needed, and
3. an ecosystem scale: reef sites from anywhere in the GBR could be added in the amount of area to set aside (‘open’ marine reserve scenario).

The insurance factor was then derived for each scenario from the protective multiplier based on a range of recovery scenarios (5, 10, 20, 50 years). The feasibility of adopting the results for the entire GBR was also assessed by examining whether incorporating the additional insurance reserve was actually possible for each connectivity and recovery scenario.

Chapter 4: Evaluating the RAP network – a HPR perspective

4.1 Introduction

Using predictions of widespread damage of any type, HPR of the GBR were classified as functional or not as potential sources of coral larvae for disturbance recovery based on levels of cyclone disturbance. As HPR are located in zones where human activities are most restricted, these reefs represent the best potential sources for replenishment and perpetuation of surrounding less protected reefs and associated habitats, provided they are not also situated within high cyclone disturbance zones. This chapter presents the reality of the latter case and uses this information to i) estimate how it may affect connectivity across the GBR and ii) assess how many additional sites (if any) would need to be protected to take long-term cyclone disturbance into account under various recovery scenarios.

4.2 Timing of cyclone impact

4.2.1 Mean length of damage-free interval

As mentioned in the previous chapter, reef sites were categorised into two groups: mean length of disturbance-free period ≥ 5 years or < 5 years. The return interval for the period 1969-2003 indicates the average number of years that coral reefs had to recover following cyclone events in that period (Puotinen, 2005a). If this interval was shorter than the time needed for recovery, sites generally didn't have enough time to recover from one disturbance before the next one hit. Most (75.05%) HPR were frequently damaged by cyclones (short recovery periods on average) over the last 35 years (Fig. 4.1).

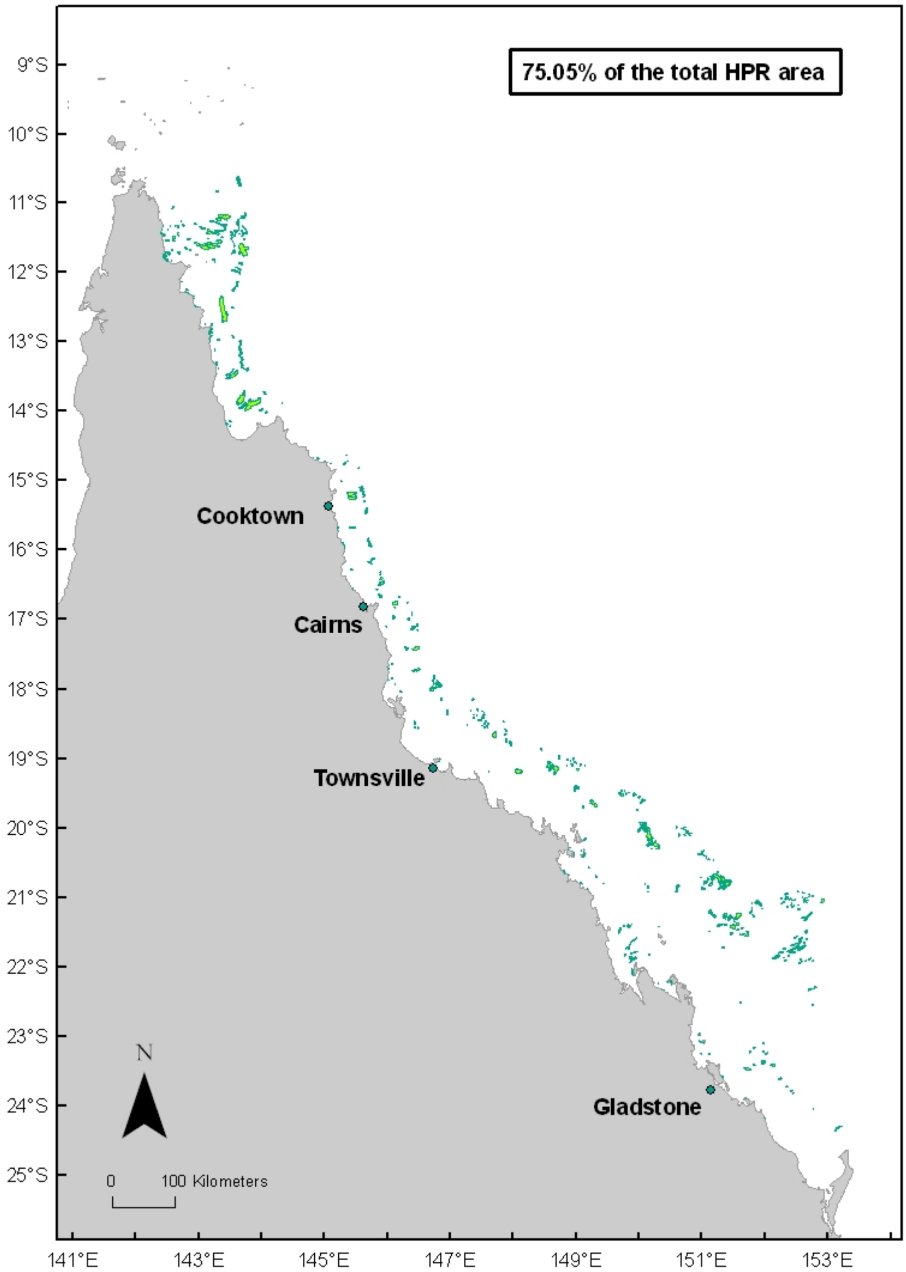


Figure 4.1. Highly protected reefs of the GBR for which the mean length of disturbance-free intervals was ≤ 5 years from 1969-2003. Percentage is given relative to the total area represented by all reefs comprised in the high protection zones.

As concluded by Puotinen (2005c) for all reefs in the GBR, HPR displaying a short typical return interval have been observed to be evenly spread across the entire region. This suggests that HPR from the RAP may not be able to fulfil their functional role as sources for surrounding least protected reefs.

4.2.2 Maximum length of damage-free interval

In contrast, less than half (45.16%) of the HPR had a maximum damage-free interval of ≤ 10 years representing reefs that are likely to never have had enough time to recover between successive damage events (Fig. 4.2).

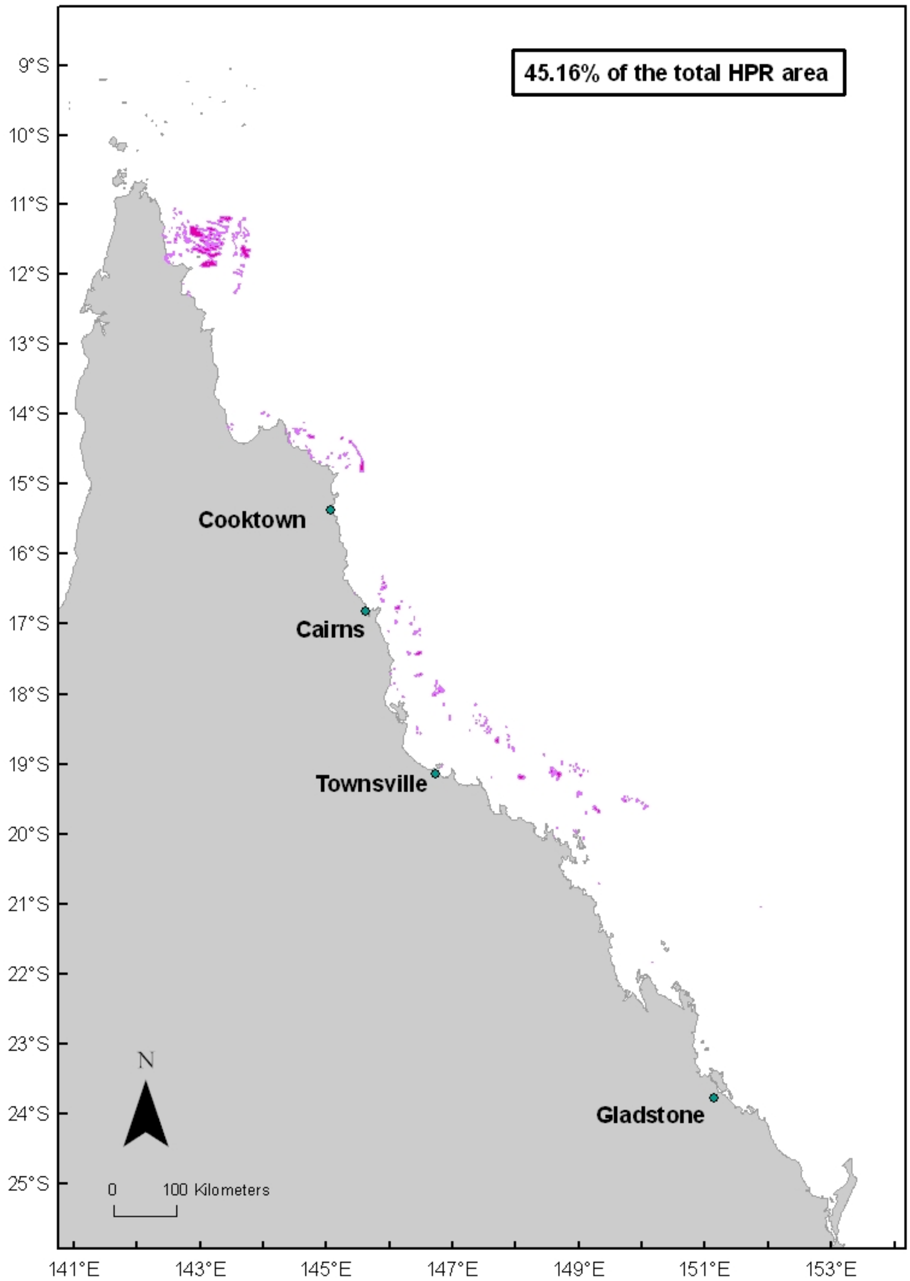


Figure 4.2. Highly protected reefs of the GBR for which the maximum length of disturbance-free intervals was ≤ 10 years from 1969-2003. Percentage is given relative to the total area represented by all reefs comprised in the high protection zone.

As shown in the previous section, most HPRs did not have enough time to recover from cyclone disturbances over the past three decades (return interval ≤ 5 years, i.e. shorter

that the time needed for recovery). Here, 54.84% of HPRs were found to have a maximum damage-free interval of ≥ 10 years between disturbances showing sufficient time for reef sites to recover at least once during the study period.
This indicates that even though HPR experienced short typical recovery period over the last 35 years, more than half of them had sufficient time at least once to recover.

4.2.3 Timing of most recent interval

The timing of the most recent disturbance was generated by dividing the number of years since the last disturbance by the return interval (see Fig. 3.4) in order to give an estimate of how much more time HPR have recently had to recover than normal.
In general, it appears that HPR have had between two to four more time to recover recently than normal with HPR located in the central GBR (between 18°S, 146°E and 19°S, 150°E) having had the longest period for recovery (Fig. 4.3).

	Longitude												
Latitude	142	143	144	145	146	147	148	149	150	151	152	153	Mean
10	1.83	1.83	1.67										1.78
11	2.00	2.00	1.80										1.93
12		2.50											2.50
13		2.25	2.25										2.25
14		2.40	2.50	2.00									2.30
15				1.5									1.50
16				2.67	2.00								2.33
17					3.67								3.67
18					4.00	3.67	4.33						4.00
19					4.33	4.33	4.00	3.67	4.00				4.07
20							3.00	3.33	3.00	2.50	3.25		3.02
21								2.67	2.75	3.00	3.33		2.94
22								3.67	2.67	1.00	3.00		2.58
23									1.00	1.67	3.00		1.89
24										3.67	2.75	2.75	3.06
Mean	1.92	2.20	2.05	2.06	3.50	4.00	3.78	3.33	2.68	2.37	3.07	2.75	2.77

Figure 4.3. Timing of the most recent widespread damage-free interval averaged in each 1˚ latitude by 1˚ longitude box across the GBR from 1969-2003 showing amount of supplementary time (x times more) highly protected reefs had compared to the typical recovery time. The colours of each box indicate the relative additional number of years: white < 2, grey = 2-4 and orange ≥ 4 times for time than normal to recover.

When HPR were overlayed in GIS onto the selection of reef sites attributed a category of relative supplementary time of either ≤ 2 or ≥ 2 times the typical amount of time for recovery, 75.3 % of the total area of all HPR had twice as much time to recover than what was typical over the entire 35-year study period (Fig. 4.4). This observation should be carefully interpreted as it only provides an estimate of the recent history of disturbance and suggests that the state of the reefs at the time the RAP was set up may not be indicative of what may occur in future time.

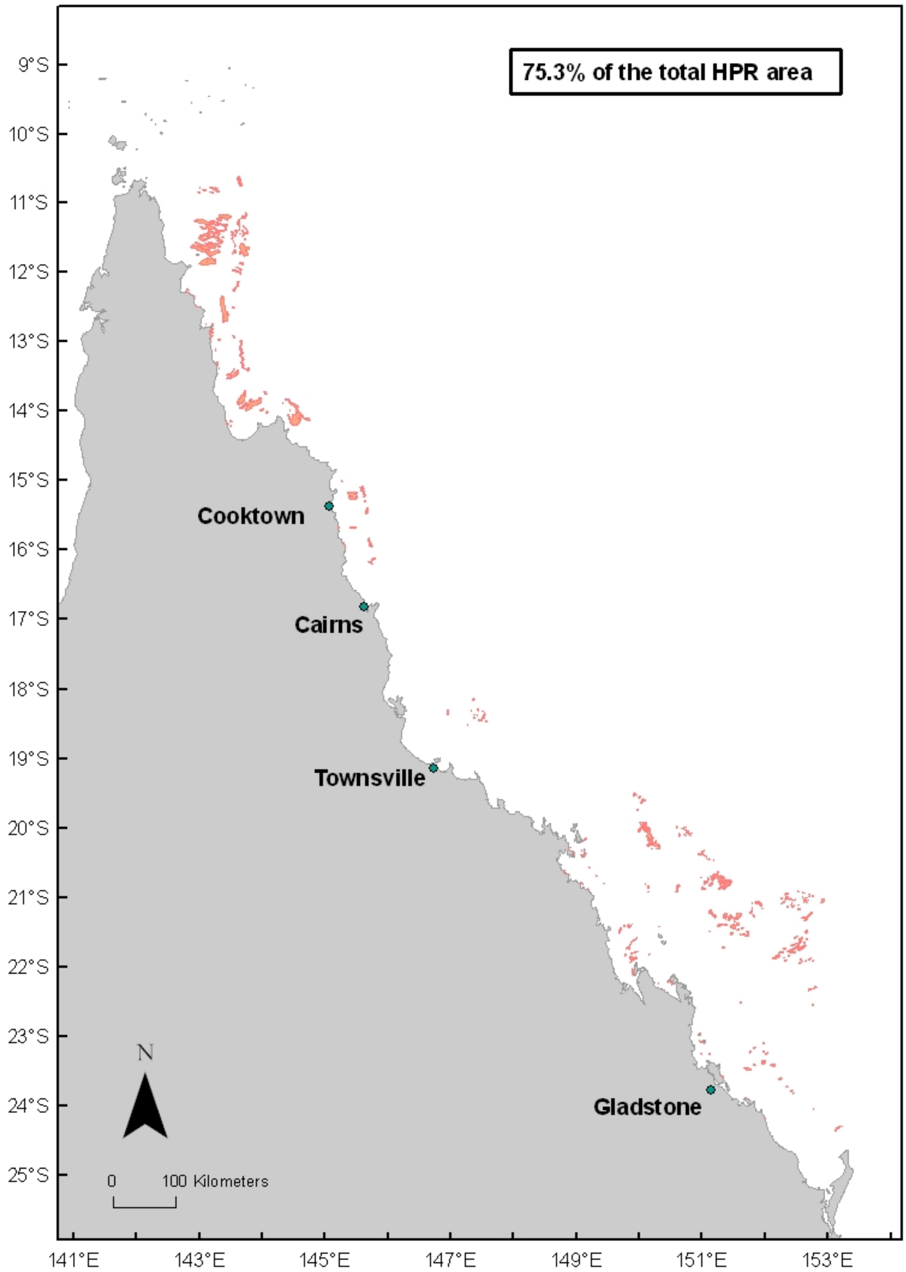


Figure 4.4. Highly protected reefs of the GBR for which the relative timing of disturbance-free interval was two times or more the typical timing of the most recent disturbance-free interval from 1969-2003. Percentage is given relative to the total area represented by all reefs comprised in the high protection zones.

Thus it appears that most HPR have had the chance to recover at least once between cyclone events from 1969-2003, though disturbance is still generally frequent. Clearly, the HPR have not been placed to ensure infrequent exposure to cyclone damage. This may be because the design of the RAP was created based on information available at a time where conditions weren't representative of the typical cyclone disturbance experienced by the GBR.

4.3 Connectivity

The index of connectivity developed according to the two scenarios described in section 3.6 of the previous chapter characterised each sink (non-HPR) reef as less connected, equally connected or more connected under disturbance (Fig. 3.11). Because the analysis was conducted by excluding the most highly impacted reefs from the set of HPR to investigate connectivity between the remaining HPR (sources) and the rest of the GBR reefs (sinks), it was expected that connectivity with disturbance could only be equal or less than that without it (disturbance not being able to shorten the minimum distance between reefs). For both parameters describing the timing of disturbance on HPR over the entire time period, connectivity between sources and sinks was observed to generally decline under cyclone disturbance (Fig. 4.5A and 4.6A). Additionally, equally connected sinks were grouped around the sources least affected by cyclone disturbance. Given that only ~ 25% of HPR had five years or more on average to recover between disturbances, it makes sense that the majority of sinks showed large minimum distances to the sources (Fig. 4.5B). Similarly, the spread of greatest minimum distances between sources and sinks coincided with the distribution of sinks surrounded by sources that never had 10 years or more to recover over the last 35 years, most of which are found between 17°S to 20°S (Fig 4.6B). However, for this scenario of timing of disturbance (ii – Fig. 3.11), ~ five times more sinks were equally connected to HPR least affected by cyclone disturbance (sources).

This characterisation of changes to connectivity under cyclone disturbance is simplistic because it uses linear distances and it also assumes that all reefs are equally connected to each other. This may not be the case as local parameters such as oceanic circulations may limit connectivity. Further, the connectivity index is calculated using the centroid of each reef rather than its edge which introduces errors in the determination of minimum distance between reefs, especially for large-size reefs (largest HPR area: 356 km^2). This method can only be expected to crudely identify changes in connectivity that reefs are susceptible to experience given various disturbance parameters. Once more detailed data describing factors that influence connectivity (such as ocean current and wave patterns and larval behaviour) are available, a more detailed analysis should be developed.

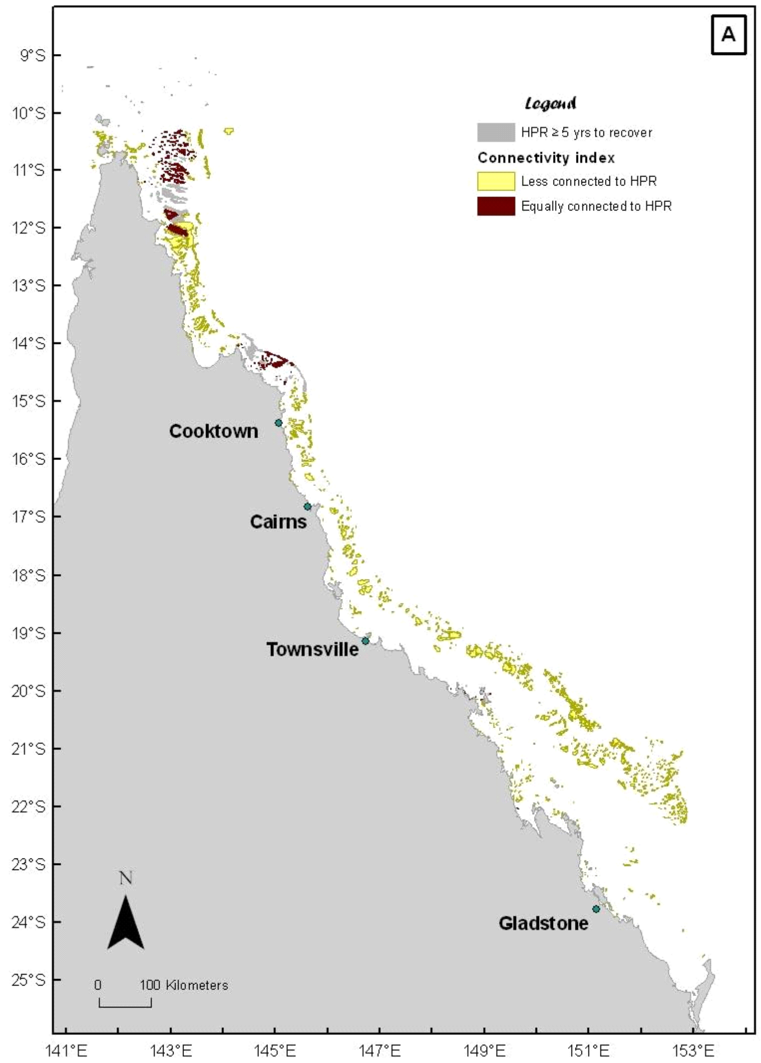


Figure 4.5. Index of connectivity as measured by the minimum distance between the centroids of each sink reef (non-HPR) to the nearest potential source reef (HPR displaying ≥ 5 years recovery in average from 1969-2003): **A** - spatial distribution of sink reefs less and equally connected to source reefs and **B** - distribution of distances to source reefs for each individual sink reef from north (10°S) to south (25°S).

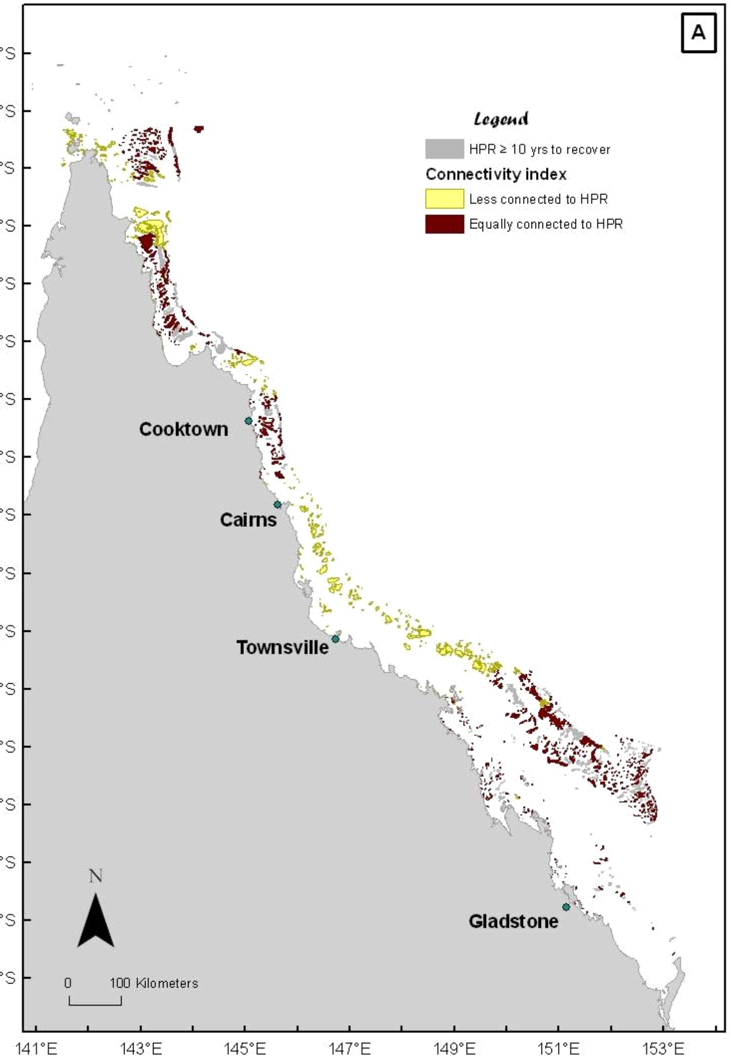


Figure 4.6. Index of connectivity as measured by the minimum distance between the centroids of each sink reef (non-HPR) to the nearest potential source reef (HPR displaying ≥ 10 years recovery once at least from 1969-2003): **A** - spatial distribution of sink reefs least and equally connected to source reefs and **B** - distribution of distances to source reefs for each individual sink reef from north (10°S) to south (25°S).

In the meantime, the characterisation of connectivity changes under frequent cyclone disturbance presented here indicates that the RAP may not adequately protect the GBR once cyclones are considered, stressing the need to address this issue. This thesis proposes doing so by determining an insurance factor used to calculate the additional reserve fraction necessary to buffer the GBR against cyclone damage.

4.4 Insurance factor

For each 1° latitude by 1° longitude box, the number of HPR sites (Fig. 4.7A) was used with the cyclone history to calculate the fraction of the GBR HPR sites unaffected by the annual cyclone disturbance using the geometric mean over the 35 year period (Fig. 4.7B). Overall, the annual fraction of HPR affected is fairly small, less than 20% at the most.

A	Longitude												
Latitude	142	143	144	145	146	147	148	149	150	151	152	153	Total
10	0	150	17										167
11	127	1440	170										1737
12		286											286
13		325	169										494
14		38	417	205									660
15				204									204
16				110	82								192
17					186								186
18					170	230	12						412
19					2	4	254	162	8				430
20							59	137	456	351	8		1011
21								184	29	402	602		1217
22								44	32	6	48		130
23									186	117	52		355
24										2	5	29	36
Total	127	2239	773	519	440	234	325	527	711	878	715	29	7364

B	Longitude												
Latitude	142	143	144	145	146	147	148	149	150	151	152	153	Mean
10	/	88%	87%										88%
11	88%	87%	86%										87%
12		86%											86%
13		87%	87%										87%
14		84%	86%	84%									85%
15				83%									83%
16				83%	82%								83%
17					83%								83%
18					84%	84%	83%						84%
19					86%	81%	85%	88%	85%				85%
20							93%	90%	88%	86%	87%		89%
21								92%	91%	87%	87%		89%
22								93%	91%	89%	87%		90%
23									99%	89%	88%		92%
24										89%	87%	87%	88%
Mean	88%	86%	87%	83%	84%	83%	87%	91%	91%	88%	87%	87%	87%

Figure 4.7. Proportion of the GBR HPR sites affected by tropical cyclone disturbance averaged for each 1° latitude by 1° longitude box across GBR from 1969-2003: A - number of HPR reef sites per box for which damage data was recorded, white < 50, light grey = 50-100, dark grey = 100-500 and black > 500 and B - geometric mean of the number of HPR sites showing widespread damage of any type.

Subsequently, for each box, the geometric mean permitted the determination of insurance multiplier values derived under three scenarios of connectivity: 1) local (Fig. 4.8), 2) regional (Fig. 4.9) and 3) at ecosystem level (Fig. 4.10) for estimated recovery times varying from 5 to 50 years.

A

Latitude	142	143	144	145	146	147	148	149	150	151	152	153
10	/	1.83	1.95									
11	1.88	1.98	2.15									
12		2.06										
13		2.00	1.96									
14		2.33	2.10	2.32								
15				2.47								
16				2.47	2.66							
17					2.49							
18					2.42	2.43	2.58					
19					2.08	**2.80**	2.25	1.93	2.21			
20							1.44	1.7	1.84	2.09	2.00	
21								1.48	1.56	2.00	2.04	
22								1.45	1.58	1.81	1.97	
23		**T = 5**							**1.03**	1.74	1.85	
24										1.81	2.00	2.00

B

Latitude	142	143	144	145	146	147	148	149	150	151	152	153
10	/	3.34	3.82									
11	3.52	3.91	4.65									
12		4.25										
13		4.00	3.87									
14		5.44	4.43	5.39								
15				6.09								
16				6.10	7.10							
17					6.19							
18					5.88	5.91	6.67					
19					4.34	**7.86**	5.07	3.72	4.88			
20							2.08	2.88	3.39	4.37	4.00	
21								2.21	2.42	4.02	4.17	
22								2.09	2.49	3.28	3.87	
23		**T = 10**							**1.06**	3.04	3.44	
24										3.28	4.00	4.00

C

Latitude	142	143	144	145	146	147	148	149	150	151	152	153
10	/	11.17	14.58									
11	12.45	15.3	21.59									
12		18.11										
13		16.03	14.96									
14		29.58	19.62	29.08								
15				37.11								
16				37.18	50.40							
17					38.36							
18					34.56	34.93	44.54					
19					18.86	**61.88**	25.73	13.87	23.77			
20							4.34	8.27	11.49	19.14	16.00	
21								4.87	5.86	16.17	17.37	
22								4.38	6.20	10.70	14.96	
23		**T = 20**							**1.12**	9.25	11.84	
24										10.77	16.00	16.00

D

Latitude	142	143	144	145	146	147	148	149	150	151	152	153
10	/	417	812									
11	547	920	2167									
12		1396										
13		1028	866									
14		4760	1706	4562								
15				8392								
16				8427	18038							
17					9117							
18					7020	7209	13242					
19					1544	**30124**	3358	716	2756			
20							39	197	448	1603	1024	
21								52	83	1053	1258	
22								40	96	380	865	
23		**T = 50**							**1.34**	260	483	
24										380	1024	1024

Figure 4.8. Scenario 1): insurance factor values for tropical cyclones over the GBR from 1969-2003 and associated achievability assuming <u>local connectivity</u> for various recovery times averaged in each 1˚ latitude by 1˚ longitude box: A) T = 5 years, B) T = 10 years, C) T = 20 years, and D) T = 50 years. Colour code indicates the feasibility for implementation of the additional highly protected sites in view of the total number of sites present within each box: green = number of sites needed for additional protection < total number of sites, red = number of sites needed for additional protection > total number of sites. *Note: For some boxes, no determination of the insurance factor can be made because no HPR fell within this box ('/' symbol). The insurance factor was calculated using equation [1] + [3].*

When local connectivity is assumed for the GBR (only reefs within the same 1˚ latitude by 1˚ longitude box are assumed to be able to play a role in contributing to the replenishment of adjacent reefs), the insurance multiplier values increase with increasing estimated time for recovery (Fig. 4.8). This is also true for the two other connectivity scenarios (fig. 4.9 and 4.10).

A	Longitude											
Latitude	142	143	144	145	146	147	148	149	150	151	152	153
10	/	1.83	1.95									
11	1.88	1.98	2.15									
12		2.06										
13		2.00	1.96									
14		2.33	2.1	2.32								
15				2.47								
16				2.47	2.66							
17					2.49							
18					2.42	2.43	2.58					
19					2.08	**2.80**	2.25	1.93	2.21			
20							1.44	1.7	1.84	2.09	2.00	
21								1.48	1.56	2.00	2.04	
22								1.45	1.58	1.81	1.97	
23		T = 5							**1.03**	1.74	1.85	
24										1.81	2.00	2.00

B	Longitude											
Latitude	142	143	144	145	146	147	148	149	150	151	152	153
10	/	3.34	3.82									
11	3.52	3.91	4.65									
12		4.25										
13		4.00	3.87									
14		5.44	4.43	5.39								
15				6.09								
16				6.1	7.1							
17					6.19							
18					5.88	5.91	6.67					
19					4.34	**7.86**	5.07	3.72	4.88			
20							2.08	2.88	3.39	4.37	4.00	
21								2.21	2.42	4.02	4.17	
22								2.09	2.49	3.28	3.87	
23		T = 10							**1.06**	3.04	3.44	
24										3.28	4.00	4.00

C	Longitude											
Latitude	142	143	144	145	146	147	148	149	150	151	152	153
10	/	11.17	14.58									
11	12.45	15.30	21.59									
12		18.11										
13		16.03	14.96									
14		29.58	19.62	29.08								
15				37.11								
16				37.18	50.40							
17					38.36							
18					34.56	34.93	44.54					
19					18.86	**61.88**	25.73	13.87	23.77			
20							4.34	8.27	11.49	19.14	16.00	
21								4.87	5.86	16.17	17.37	
22								4.38	6.20	10.70	14.96	
23		T = 20							**1.12**	9.25	11.84	
24										10.77	16.00	16.00

D	Longitude											
Latitude	142	143	144	145	146	147	148	149	150	151	152	153
10	/	417	812									
11	547	920	2167									
12		1396										
13		1028	866									
14		4760	1706	4562								
15				8392								
16				8427	18038							
17					9117							
18					7020	7209	13242					
19					1544	**30124**	3358	716	2756			
20							39	197	448	1603	1024	
21								52	83	1053	1258	
22								40	96	380	865	
23		T = 50							**1.34**	260	483	
24										380	1024	1024

Figure 4.9. Scenario 2): insurance factor values for tropical cyclones over the GBR from 1969-2003 and associated achievability assuming <u>regional connectivity</u> for various recovery times averaged in each 1˚ latitude by 1˚ longitude box: A) T = 5 years, B) T = 10 years, C) T = 20 years, and D) T = 50 years. Colour code indicates the feasibility for implementation of the additional highly protected sites in view of the total number of sites present when neighbour boxes sites are included: green = number of sites needed for additional protection < total number of sites, red = number of sites needed for additional protection > total number of sites. *Note: For some boxes, no determination of the insurance factor can be made because no HPR fell within this box ('/' symbol). The insurance factor was calculated using equation [1] + [3].*

For most of the GBR, insurance multiplier values are relatively small (1.03 to 2.8) for short recovery times (5 years) (Fig. 4.8) indicating that reserve goals associated with this relatively quick recovery time could be met by adding 10 to 30 % of the desired reserve area to the actual fraction of highly protected reef sites already set aside within the RAP. When the expected recovery time is much longer (T = 50 years), the insurance factor increases and significantly more area would need to be added to account for the larger fraction of the reserve anticipated to be recovering at any particular time. Reef areas at greater risk would require more area to be protected (Allison *et al.*, 2003).

A	Longitude											
Latitude	142	143	144	145	146	147	148	149	150	151	152	153
10	/	1.83	1.95									
11	1.88	1.98	2.15									
12		2.06										
13		2	1.96									
14		2.33	2.1	2.32								
15				2.47								
16				2.47	2.66							
17					2.49							
18					2.42	2.43	2.58					
19					2.08	**2.80**	2.25	1.93	2.21			
20							1.44	1.7	1.84	2.09	2.00	
21								1.48	1.56	2.00	2.04	
22								1.45	1.58	1.81	1.97	
23		T = 5							**1.03**	1.74	1.85	
24										1.81	2.00	2.00

B	Longitude											
Latitude	142	143	144	145	146	147	148	149	150	151	152	153
10	/	3.34	3.82									
11	3.52	3.91	4.65									
12		4.25										
13		4.00	3.87									
14		5.44	4.43	5.39								
15				6.09								
16				6.1	7.1							
17					6.19							
18					5.88	5.91	6.67					
19					4.34	**7.86**	5.07	3.72	4.88			
20							2.08	2.88	3.39	4.37	4.00	
21								2.21	2.42	4.02	4.17	
22								2.09	2.49	3.28	3.87	
23		T = 10							**1.06**	3.04	3.44	
24										3.28	4.00	4.00

C	Longitude											
Latitude	142	143	144	145	146	147	148	149	150	151	152	153
10	/	11.17	14.58									
11	12.45	15.3	21.59									
12		18.11										
13		16.03	14.96									
14		29.58	19.62	29.08								
15				37.11								
16				37.18	50.40							
17					38.36							
18					34.56	34.93	44.54					
19					18.86	**61.88**	25.73	13.87	23.77			
20							4.34	8.27	11.49	19.14	16.00	
21								4.87	5.86	16.17	17.37	
22								4.38	6.20	10.70	14.96	
23		T = 20							**1.12**	9.25	11.84	
24										10.77	16.00	16.00

D	Longitude											
Latitude	142	143	144	145	146	147	148	149	150	151	152	153
10	/	417	812									
11	547	920	2167									
12		1396										
13		1028	866									
14		4760	1706	4562								
15				8392								
16				8427	18038							
17					9117							
18					7020	7209	13242					
19					1544	**30124**	3358	716	2756			
20							39	197	448	1603	1024	
21								52	83	1053	1258	
22								40	96	380	865	
23		T = 50							**1.34**	260	483	
24										380	1024	1024

Figure 4.10. Scenario 3): insurance factor values for tropical cyclones over the GBR from 1969-2003 and associated achievability assuming <u>ecosystem level connectivity</u> for various recovery times averaged in each 1˚ latitude by 1˚ longitude box: A) T = 5 years, B) T = 10 years, C) T = 20 years, and D) T = 50 years. Colour code indicates the feasibility for implementation of the additional highly protected sites in view of the total number of sites present anywhere across the GBR: green = number of sites needed for additional protection < total number of sites, red = number of sites needed for additional protection > total number of sites. *Note: For some boxes, no determination of the insurance factor can be made because no HPR fell within this box ('/' symbol). The insurance factor was calculated using equation [1] + [3].*

The degree to which adding highly protected sites to the HPR network already in place is achievable decreases as time needed for recovery increases. This negative relationship is also applicable for lessened connectivity: the more connectivity operates at local scales, the more difficult it would be to protect enough supplementary sites to account for cyclone disturbance. For example, for a recovery time of 20 years, the likelihood of finding additional sites for the RAP was almost non-existent under a local connectivity scenario (Fig. 4.8) while the opposite was true when connectivity was considered at the scale of the whole GBR (Fig. 4.10). This observation is further emphasized for local scale connectivity and recovery times of 50 years (Fig. 4.8) at which it would be impossible to protect enough highly protected reefs so that at least part of the reserve network of highly protected areas is in a recovered state.

This indicates that it would be feasible to allow for the frequent, low intensity cyclone events that regularly occur in the GBR (for which a short recovery time (i.e. 5-10 years) would be expected) by incorporating an insurance factor. However, if extreme events (large and intense cyclones, rare in the GBR - Puotinen, 2005c) were to occur more frequently, taking them into account would hardly be possible, especially under a local connectivity scenario. Common sense suggests that the latter is unlikely to be the case, as evidenced by the continued existence of reefs in spite of cyclone disturbance over millennia (Pandolfi, 2002) although it might eventually occur if tropical cyclones are to increase in frequency under global climate change (Pittock, 1999) or their effects are inadvertently combined with human disturbances as occurred in Jamaica (Hughes, 1994).

Chapter 5: Summary and conclusions

5.1 Introduction

Over the past 35 years (1969-2003), frequent disturbance from tropical cyclones potentially generated direct (wave damage) or indirect (decreased salinity) damage to reefs of the GBR. The recent improvement of the RAP led to an increase in high levels of protection (no-take areas) of the GBR reefs to 33.3%, helping coral reef communities to recover while protected from additional human-induced disturbances. The aim of this chapter is twofold: (i) comment on whether the RAP protects those reefs least affected by cyclones (potentially representing the best source for support and replenishment of surrounding areas) and (ii) provide recommendations for improved management of the GBR given the cyclone disturbance history.

5.2 Summary: management implications and recommendations

Overall, cyclone disturbance over the GBR as a whole was reported to be steady (Puotinen, 2005a,c) implying that the GBR ecosystem can 'handle' the cyclone disturbances that periodically occur within its boundaries. This study deals with the question: does the RAP effectively protect those reef communities that have had time to recover completely between cyclone disturbances under its high protection scheme? This is important because the HPR are the reefs most likely to effectively support recruitment and larval dispersal for replenishment of adjacent areas within the GBRMP, thus more likely to fulfil its conservation goals.

5.2.1 Managing the disturbed ecosystem

Disturbances have always been a part of the environment of coral reefs, however their impacts on coral reef ecosystems are poorly characterised (Done, 1992). To evaluate the effectiveness of reef protection through marine reserves, it is important to understand the spatial and temporal characteristics of unmanageable natural disturbances such as cyclones. Tropical cyclones affect reefs both directly (waves impact on reef structures, burial of corals by resuspended sediments) and indirectly (reduced salinity due to freshwater plumes from associated flood events). Of these, this project considered only direct impacts from cyclone-generated waves.

5.2.1.1 Magnitude and extent of disturbance

The intensity of cyclone disturbance was estimated as the percentage of the whole time series (1969-2003) for which thresholds in magnitude and duration of cyclones were reached or exceeded, resulting in conditions suitable for potential damage to reefs. Overall, most HPR of the RAP lie within the intermediate intensity boundaries for disturbance. That is, most of the area represented by the HPR was found to be affected at an intermediate frequency by cyclones. Very few HPR recorded a high frequency of cyclone disturbance (~ 7%) or no cyclone-induced damage at all (~ 6%). These observations suggest HPR had, at times (if left undisturbed), enough time for coral coverage and large colonies size to be regenerated. However, the degree to which this was actually the case at a given disturbed site depends on the site history of disturbance.

5.2.1.2 Timing of disturbance

Recently, Puotinen (2005a) reported that coral reefs, in general, have had more time to recover than normal across the GBR. Consequently, 3/4 of HPR were observed to exhibit twice as much time to recover than was typical over the entire time series, with some displaying recent recovery intervals of ≥ four times than usual. When put into context of the cyclone disturbance regime by comparing it to the average or maximum timing for disturbance, this observation rather appears as a warning. It suggests that overall most HPR (~ 75%) may be more at risk of cyclone disturbance in the near future. Indeed, the typical history of cyclone disturbance over the GBR for the last 35 years highlighted that most of the HPR (75 %) haven't had time to recover on average between successive cyclone disturbances and almost half of them (45 %) never had a change to fully recover at all. This has important implications as it raises the issue of whether the positioning of the highly protected zones has resulted in protecting reefs suitable to act as sources for non-protected reefs. Further, as the time balances out and storminess likely increases with global climate change (Pittock, 1999), repeated cyclone occurrence may lead to increased frequency of cyclone disturbance potentially affecting the HPR to a greater extent. The occurrence of such a phenomenon would increase the patchiness in the reef matrix at local and global scales as is already illustrated by clustering of HRP remaining under current levels of disturbance (Fig. 4.1 and 4.2). This could further jeopardise the robustness of the RAP by reducing the connectivity within the GBR ecosystem.

5.2.1.3 Connectivity, recovery and resilience

The recovery of a coral reef is related to the degree of openness to its surroundings. Understanding the degree of connectivity between reefs is fundamental to managing marine biodiversity and resources (Andréfouët *et al.*, 2002). The use of oceanic current patterns to map linkages among reefs could aid the design of reserve networks. The degree to which currents link areas depends on their magnitude and direction, and the distance between reefs. Although an investigation of currents and oceanic circulation patterns across the GBR was clearly beyond the scope of this study, a simple method was used to crudely characterise variations in levels of connectivity under typical cyclone disturbances observed across the GBR by quantifying changes in minimum distance between potential source and sink reefs. It identified a noticeable decline in connectivity with increasing distance from HPR remaining after disturbance, for both scenarios of timing of cyclone disturbance. Spatial variation in connectivity could produce variation in recovery of corals as the supply and recruitment of larvae is likely to be more similar within habitats than at widely separated sites in different habitats (Connell *et al.*, 1997). Indeed, the extent of patchiness following disturbance is a factor influencing ecosystem recovery and the spatial and temporal variation of recruitment rates (Ayre & Hughes, 2000). If cyclone damage reduces HPR's ability to act as sources for low protected reefs by reducing connectivity and increasing reef patchiness, recovery of the latter from human impacts is further threatened by cyclones. The reestablishment of an individual coral reef will depend on a matrix of reefs in the surrounding seascape and their resilience including dispersal and migration for which currents and distance are key components (Nyström & Folke, 2001). The ecosystem can be manipulated to alter its vulnerability, its resistance, or its response to large natural disturbances so that it does not compromise management goals. However, this largely depends on connectivity and recovery patterns determining resilience of the ecosystem for which much knowledge remains to be acquired.

5.2.2 Managing the ecosystem prior to disturbance – insurance reserves

It is clear that the substantial improvement of the network of no-take areas provided by the RAP to meet internationally recognised standards of 20-50% of habitat protected in reserves (Jago *et al.*, 2005; Airamé *et al.*, 2003; Allison *et al.*, 2003, Roberts *et al.*, 2003b) is of great value for biodiversity conservation. However, the new zoning scheme for the GBR released by the GBRMPA is threatened by spatial and temporal patterns in cyclone disturbance across the region, as its main contributors (i.e. HPR, potential sources of larvae) are at risk of being rendered ineffective by frequent disturbances. Events such as cyclones that have the potential to remove protected habitat from the network will effectively prevent the goals of the reserve from being met until that habitat recovers. Therefore, in addition to the usual concerns driving the design of marine reserves (e.g. area needed regarding conservation goals to achieve, degree of protection required, the location of reserves in a network, etc), there is an added need to consider the influence of rare but disastrous events such as tropical cyclones. It was difficult to determine the extent to which ecosystem connectivity should constrain reserve design in the GBR due to a lack of data. Therefore, the estimation of an insurance factor provided a solution to the risk of region-wide negative impacts from a large natural disturbance (tropical cyclones) under various scenarios of linkage between reefs and recovery times. As mentioned in the previous chapter, this index can be applied to a reserve design which aims to define a fraction of the total reserve area that is necessary to accomplish a particular conservation goal. It is determined to assure reserve goals are met even in the face of natural disturbances by building into the planning process the expectation of some loss and reserving a compensatory amount of area to assure a minimum percentage of the reserve in a recovered state at any time (Allison *et al.*, 2003). Across the GBR, only for short recovery times (five years) and ecosystem level connectivity (operating across the entire GBR) could a sufficient additional fraction of the RAP be realistically added to provide a buffer against cyclone disturbance. However, this is likely to be acceptable as long recovery times should rarely be needed across broad areas because damage from events needing such recovery times are likely rare and isolated in space (Puotinen, 2005a).

To implement this, the choice of supplementary sites should be guided by the key biophysical principles used to originally determinate the HPR (e.g. (i) have no-take area the minimum size of which is 20kms along the smallest dimension, (ii) only whole reefs should be incorporated into no-take zones, (iii) represent cross-shelf and latitudinal diversity in the network of no-take areas, to only cite a few - Table 2.2, Chapter2), as well as cyclone damage susceptibility/potential, and connectivity patterns as defined in this study. As a result, candidate reefs to be added to the high protected pool could be identified for each 1° latitude by 1° longitude box, highlighting where an extension of the highly protected zone will be necessary (Fig. 5.1).

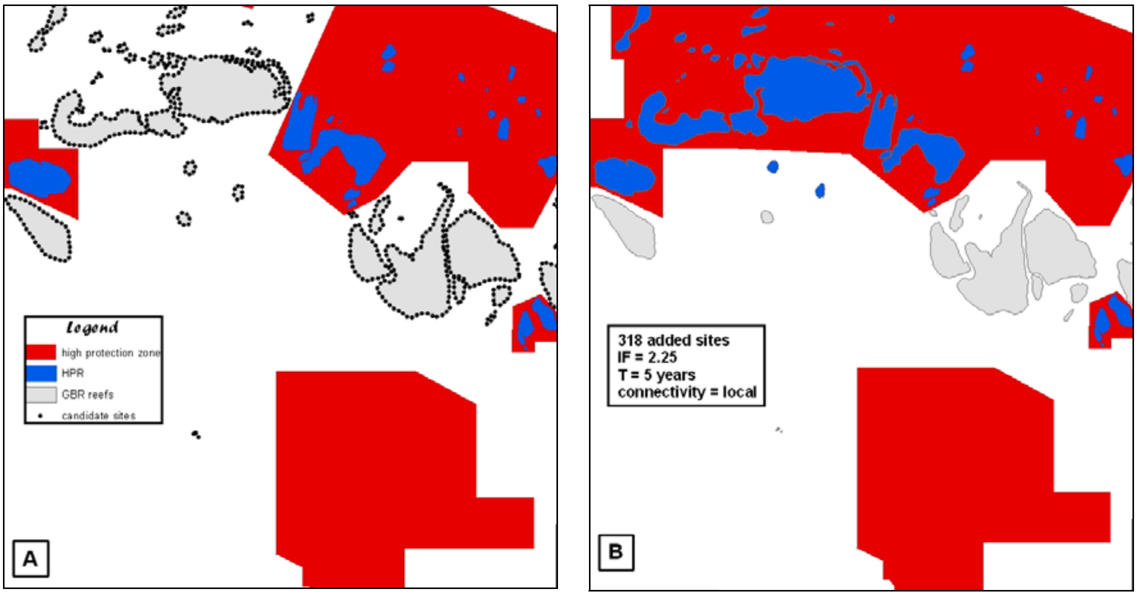


Figure 5.1. Potential extension of the highly protected zones (B) to include sites determining additional reefs to be included into the HPR present in a 1° latitude by 1° longitude box (box 22: 19°S, 148°E) in order to incorporate cyclone disturbance (based on models from 1969-2003). Decision rules based on cyclone damage exposure, the connectivity decline potential and adequacy of biophysical principles application have been applied to candidate reefs (A), the amount of which was recommended using the insurance factor (IF) relating to specific recovery time (T) and connectivity level.

The determination of recovery time is obviously critical to the calculation of the insurance factor. For the GBR, previous studies have suggested that recovery of coral cover following severe cyclones can range from three to 14 years depending on the coral community structure at the site (Connell *et al.*, 1997). As suggested by Puotinen (2005c) using the disturbance dynamic 'state-space' diagram (Turner *et al.*, 1993), this study predicted that the practicality of planning for cyclone disturbance through the use of the insurance factor declined with increasing time needed for coral recovery. As the necessary recovery interval increased, the predicted nature of disturbance regime dynamics shifted from stable to unstable (Puotinen, 2005a, c), and the insurance factor values subsequently increased. Thus, the extent of the additional fraction of the reserve needed to account for typical cyclone disturbance also increased, making it less feasible to accommodate cyclone disturbance in the GBR management regardless of connectivity levels. As suggested by Puotinen (2005a) for cyclone damage predictions, it may be possible that insurance factor values were also over-predicted as it was assumed that reef vulnerability factors as well as cyclone disturbance regime and characteristics were present at modelled sites at all times. Such issues will be further discussed in the context of limitations associated with this study (next section (5.3) of this chapter) however, it is expected that the major trends observed here will generally remain the same with increasing recovery time.

5.2.3 Managing the ecosystem after the disturbance

5.2.3.1 The advent of dynamic reserves

Several views on the role of reserves emphasize a conflict between conservation and sustainable use. One view puts a focus on reserves as fully protected areas versus those areas that can be used or exploited to their full capacity. In contrast, another view presents reserves as sources to preserve biodiversity and function as an insurance for the rest of the seascape surrounding them (Bengtsson *et al.*, 2003). Both have neglected the fact that impacts from large disturbances will prevent their ability to recover unless sufficient ecological memory is available outside the disturbed area. If the areas surrounding a reserve do not contain sufficient spatial resilience in the form of internal and external memory to restore the ecosystems that were to be preserved, the reserve will fail in its objective (Bengtsson *et al.*, 2003). Simply setting aside such reserves will be insufficient for maintaining biodiversity and ecosystem functioning in the seascape. To deal with this, the possibility of developing several new types of dynamic reserves at the ecosystem level by reserving additional area in temporally dynamic highly protected zones would secure resilience as well as a buffering capacity that can only benefit conservation goals. While establishing additional static insurance reserves prior to disturbance may not provide an effective buffer to disturbance at all times (c.f. performance on the insurance factor for various recovery time and connectivity scenarios), dynamic insurance reserves determined using the insurance factor previously described could be set aside after a particularly severe disturbance event (strong cyclones large in extent, but these are rare (Puotinen, in press)) for a limited time until the reserve is not needed, progressively allowing some management and resource utilisation. However, the degree to which implementation of such temporary insurance reserves can be achieved should be experimentally tested to ensure its manageability before it can be applied at a larger scale. A useful guide for designing such experiments may be found in GBRMPA’s ‘Effects of Line Fishing’ program (CRC, Reef Research Centre, 2005).

5.2.3.2 Landscape modelling for reserve siting

More knowledge is now available about the characteristics and implications of tropical cyclone disturbance that can be added to the series of criteria modifying the value of sites as reserves in the reserve design process for the GBR. For example, the data presented here along with characteristics of the cyclone disturbance history documented by Puotinen (2005a), could be used to help provide rough guidelines for the spacing and number of insurance reserves required to spread the risk of widespread cyclone perturbation through replication of reserves within the RAP network across the GBR.

Even though marine reserves are inherently a multispecies, ecosystem-level approach to management, the theoretical basis for their design remains largely focused on single species (Lubchenco *et al.*, 2003). Thus connectivity must be considered in light of the wide range of life-history characteristics and ecological processes occurring at the ecosystem level. Siting reserves from a connectivity perspective involves evaluation of whether there is sufficient connectivity to allow exchange and replenishment within the reserve and whether the populations in a reserve connect with others in unprotected areas. This largely depends on dispersal distances, reserve size, and local oceanography. The degree to which a site, ecosystem, or network is connected and the ability of organisms to move, disperse, migrate, or recolonise varies with the species. Because species' characteristics vary widely, the ideal distribution and sizing of reserves for one species may be very different from that for another (Roberts *et al.*, 2003b). Connectivity, species' life history, recovery, reserve extent as well as local and regional oceanography are areas where more research is needed for marine environments.

The ability to incorporate various criteria in applied conservation decisions is rapidly increasing as new tools and techniques become available (e.g. GIS, simulation modelling and long-term datasets). New ecological research, increasing availability of powerful new technologies for assessing ecological systems, and growing conservation focus on the dynamic nature of ecosystems will all help managers incorporate ecosystem- and seascape-level concepts into biodiversity conservation to the greatest extent possible (Poiani *et al.*, 2000). Spatial models of landscape change are now becoming available that may enable simulation of future landscape structure under a variety of disturbance regime and management scenarios (Baker, 1992). The potential impacts of environmental change would need to be assessed through sensitivity and risk analyses that require a set of values establishing critical or unacceptable outcomes (Pittock, 1999). If linked to climatic projections, these models could be used to simulate future ecosystem dynamics given particular climatic change scenarios.

5.2.3.3 The context of other disturbances

This study examined cyclone damage on coral reefs that are relatively free of human impacts. However, the effect of a particular disturbance often depends critically on the impact of previous perturbations that can obscure its signature. Many disturbances are also the result of synergistic effects of natural and anthropogenic processes (Dale *et al.*, 1998) coupled with routine ecological processes (e.g. predation, competition for space). The extent to which these disturbances combine to impact on coral reefs (synergism) can greatly affect the severity of damage (McClanahan *et al.*, 2002).

A growing appreciation of the enormous complexity and dynamic nature of ecological systems led to the concept of ecosystem management, wherein success is best assured by conserving and managing the ecosystem as a whole (Poiani *et al.*, 2000). When the natural dynamics of communities and ecosystems are taken into account, a reconsideration is required of how reserves are designed and managed as parts of dynamic landscapes increasingly dominated by humans (Bengtsson *et al.*, 2003). With human dominance of marine ecosystems resulting in loss of diversity leading to decreased ability to buffer disturbances, it can no longer be assumed that dispersal and natural variation among local reef assemblages in the seascape will buffer perturbations. Instead, the capacity to renew, reorganise and re-establish reefs after disturbance has to be actively managed at the ecosystem level (Nyström *et al.*, 2000). Current recommendations for biodiversity conservation focus on the need to conserve dynamic, multiscale ecological patterns and processes that sustain the full complement of biota and their supporting natural systems (Poiani *et al.*, 2000). Coral reef management for conservation must expand beyond individual reefs to an understanding of how the shifting matrix of reefs contributes to ecosystem resilience, as disturbance and resilience are crucial for coral reef conservation. The former edits the seascape, contributes to ecosystem reorganisation and builds adaptive ability to undergo changes, while the latter is the dynamic capacity to cope with disturbance, maintains flexibility and avoid exceeding critical thresholds at various spatial and temporal scales (Nyström & Folke, 2001). Changes in the magnitude, frequency, and duration of natural disturbance regimes and alterations of ecosystem dynamics and resilience, often as a consequence of human impacts, pose major challenges to the management of reefs for conservation purposes.

5.2.3.4 Global change perspective

One of the implications of recent rapid changes in climate may be alterations in the frequency and intensity of natural disturbances. Evidence is accumulating that under conditions of global climate change, tropical cyclones may increase not only in maximum intensity but also in average by 10 to 20 % by the 2070's, they may travel further polewards as sea surface temperatures increase and shift towards a greater frequency of occurrence that would tend to dominate the damage impacts (Pittock, 1999) and lead to a shorter time for recovery between recurrences. Moreover, over geological time, reefs have been affected by global scale changes in seawater chemistry, temperature, and sea-level fluctuations. Future changes in ocean chemistry due to a higher atmospheric CO_2 may cause weakening of coral skeletons and reduce the accretion of reefs, especially at higher latitudes (Hughes *et al.*, 2003). Where global change is manifest as a reduction in the return interval between highly destructive events such as cyclones, the stage, age and size frequency distributions of coral populations and communities across regional seascapes will be skewed more to earlier successional stages (Done, 1999).

5.3 Limitations associated with this research

Uncertainty may exist for many reasons: inability to measure precisely, unintended alteration of values during processing or, at a more fundamental level, natural variability in the phenomena being measured. Tropical cyclones are phenomena that are highly variable both in space and time, with characteristics that are difficult to measure accurately. Modelling them represents a complex interaction of human and instrumental factors, and acquiring the raw components of the model, the data themselves, is also subject to a host of uncertainties. For example, human observations as well as diverse methods of measurement of tropical cyclone parameters have been used by the Bureau of Meteorology (BOM) to compile the cyclone database. There is considerable error in the positioning and attribute allocation of cyclones in the Bureau of Meteorology database (Table 5.1).

Table 5.1. Description of the method used to record cyclone parameters in the Bureau Of Meteorology (BOM) database and its associated uncertainty estimate (in kms).

Method of eye location	Assigned uncertainty distance
no satellite, no radar, no observation	300
no satellite, no radar, observation only	200
satellite, no clear eye	100
satellite, clearly defined eye	75
aircraft radar report	50
land-based radar report	50
satellite & radar & observation	25
Report inside eye	10

The list of all uncertainties associated with the cyclone disturbance regime is extensive (see Puotinen 2004a, 2005c for a full discussion) of which uncertainty in cyclone path location is notably applicable to this project. Because the latter study provided the basic data relevant for the present project, other issues relating to the prediction of cyclone damage (Puotinen, 2005a) remain relevant to this study such as:

- likely overestimates of high-energy types of damage due to the limited field data upon which predictive modelling was based,

- likely overestimates of damage to reefs due to the lack of consideration of disturbance history and vulnerability factors such as the nature of coral community structure and how it has been affected by disturbance over time,

- likely underestimates in the determination of the return interval due to censoring of the data (see Puotinen, 2004b) from ‘open’ intervals at the start and end of the time series, and

- exclusion of the effects of other disturbances (such as human activities, natural disturbance: i.e. predation, diseases).

Some of these issues are unlikely to be accounted for as the information required would be very time consuming, difficult to gather and is never likely to be acquired or only partially (i.e. characterisation of local vulnerability factors for each reef of the GBR). However, further research could help address synergistic effects of other disturbances. For example, the determination of the insurance factor could be extended to a form that incorporate multiple disturbance types, potentially illustrating synergisms between both natural disturbances or natural and anthropogenic disturbances (see appendix in Allison et al., 2003). Further, Puotinen's (2005a) predictive model could be refined using field data recently acquired during an extensive damage survey (n = 490) conducted in the far northern GBR following cyclone Ingrid in May 2005 (Fabricius *et al.*, in prep).

5.4 Conclusions

For the last 35 years, widespread damage of any type has been characterised as an intermediate (stable) disturbance for the GBR as a whole. However, this is largely influenced by estimated recovery time of the coral communities present at the sites and, for the future, by the global effects of climate change. The recovery time of coral is highly variable and depends on the nature of the damage as well as connectivity between reefs across the GBR. These are important characteristics of marine ecosystems that need to be addressed in the agenda for marine research. Under a scenario of increased cyclone frequency leading to a shift in disturbance level (from intermediate to high), the capacity of coral reefs to self-organise and re-establish could be severely altered resulting in a loss of spatial ecosystem resilience (Nyström *et al.*, 2000). This study emphasizes that there is considerable spatial and temporal variation in the effects of relatively rare events such as cyclones. Cyclones are an example of an ecological process that operates at time and space scales that differ from those of the patterns they produce (Connell *et al.*, 1997). Large-scale observations cannot resolve fine-scale temporal and spatial heterogeneity, nor detect the ecological mechanisms that produce these patterns. As Connell *et al.* (1997) pointed out, there is a need for observational and experimental studies at as many scales as possible if we are to understand the mechanisms underlying these variations. Until such scientific knowledge is available, the insurance factor is a valuable guarantee against environmental and management uncertainty. Indeed, while the disturbing force can still occur with its full intensity, the system will not be altered to the extent it would have been without the management intervention (Dale *et al.*, 1998).

Nyström *et al.* (2000) noted that disturbance regimes on a long-term scale have been important for the development of species diversity, community structure and dynamics of coral reefs. This study suggests that the new zoning of the RAP does not fully account for tropical cyclone disturbance, and thus may not be able to ensure comprehensive protection of the wide array of biodiversity values of the GBR. This could be reversed to a certain extent by allowing for a larger fraction of highly protected areas to be set aside in temporary dynamic insurance reserves as the awareness of the atypical nature of the recent history of cyclone disturbance on reef ecosystems suggests a stronger impact in the future. A shift towards dynamic reserves in the design and management of nature reserves as part of a large-scale adaptive landscape management strategy may be necessary if the goal of long-term biodiversity conservation and socioeconomic sustainability in a changing world is to be achieved, especially given the likelihood of increased frequency of cyclones in the future (Pittock, 1999).

Finally, addressing spacing issues of additional reserve is not within the scope of this study. However, areas that are focal points for episodic disturbances, if they can be identified, should be avoided as sites for reserves since species will have to recolonise form elsewhere following disturbances. The more frequent and widespread the disturbance, the less desirable the site (Roberts *et al.*, 2003b; Allison *et al.*, 2003). If natural disturbances are present region-wide, there will be a need for a greater proportion of the area to be protected, and more replication of reserves. Therefore, setting aside areas of the ocean for protection from all direct human activities is a valuable step. Establishing these no-take areas in an adaptive management framework will further allow to account for indirect disturbances over which we have no control (natural disturbances such as cyclones and disease outbreaks, global climate change). Success of these precautionary measures will require environmental scientists to educate the public and policy makers concerning the importance of action despite scientific uncertainty. While precautionary strategies are implemented, major research efforts are still required in several areas relating to the marine environment such as life-history characteristics and their linkage with environmental shifts, disturbance regimes (of human-induced origin or other natural disturbances besides cyclones), level of connectivity and typical dispersal distances and processes of marine populations, and recovery processes that may provide the information required to incorporate these criteria effectively into reserve siting decisions.

REFERENCES

Airamé, S., Dugan, J., E., Lafferty, K., D., Leslie, H., MacArdle, D., A. and Warner, R. R. (2003). Applying ecological criteria to marine reserve design: a case study from the California Channel Islands. *Ecological Applications*, **13**, (1), S170-S184.

Allison, G. W., Gaines, S. D., Lubchenco, J. and Possingham, H. P. (2003). Ensuring persistence of marine reserves: catastrophes require adopting an insurance factor. *Ecological Applications*, **13**, (1), S8-S24.

Allison, G. W., Lubchenco, J. and Carr, M. H. (1998). Marine reserves are necessary but not sufficient for marine conservation. *Ecological Applications*, **13**, (1), S79-S92.

Andréfouët, S., Mumby, P. J., McField, M., Hu, C. and Muller-Karger, F. E. (2002). Revisiting coral reef connectivity. *Coral Reefs*, **21**, 43-48.

Ayre, D. J. and Hughes, T. P. (2004). Climate change, genotypic diversity and gene flow in reef-building corals. *Ecology Letters*, **7**, 273-278.

Ayre, D. J. and Hughes, T. P. (2000). Genotypic diversity and gene flow in brooding and spawning corals along the Great Barrier Reef, Australia. *Evolution*, **54**, (5), 1590-1605.

Baker, W. L. (1992). The landscape ecology of large disturbances in the design and management of nature reserves. *Landscape Ecology*, **75**, 181-194.

Ball, I. R. and Possingham, H. P. (2000). MarXan (V1.2) Marine Reserve Design using Spatially Explicit Annealing, A manual prepared for the Great Barrier Reef Marine Park Authority, March, 2000, 63 pp.

Beck, M. W. and Odaya, M. (2001). Ecoregional planning in marine environments: identifying priority sites for conservation in the northern Gulf of Mexico. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **11**, 235-254.

Bellwood, D. R. and Hughes, T. P. (2001). Regional-Scale Assembly Rules and Biodiversity of Coral Reefs. *Science*, **292**, (1532).

Bengtsson, J., Angelstam, P., Elmqvist, T., Emanuelsson, U., Folke, C., Ihse, M., Moberg, F. and Nyström, M. (2003). Reserves, Resilience and Dynamic Landscapes. *Ambio*, **32**, (6), 389-396.

Botsford, L. W., Micheli, F. and Hastings, A. (2003). Principles for the design of marine reserves. *Ecological Applications*, **13**, (1), S25-S32.

Bryan, B. A., Kinloch, M. and Gerner, D. B. (2003). GIS and Remote Sensing techniques for the assembly of a database characterising the spatio-temporal character of the South Australian continental shelf environments. In C. D. Woodroffe and R. A. Furness (eds), Coastal GIS 2003: an integrated approach to Australian coastal issues. Centre for Maritime Policy, The University of Wollongong, Wollongong, Australia, pp 87-104.

Cabeza, M., Araùjo, M. B., Wilson, R. J., Thomas, C. D., Cowley, M., J. R. and Moilanen, A. (2004). Combining probabilities of occurrence with spatial reserve design. *Journal of Applied Ecology*, **41**, 252-262.

Carr, M. H., Neigel, J. E., Estes, J. A., Andelman, S., Warner, R. R. and Largier, J. L. (2003). Comparing marine and terrestrial ecosystems: implications for the design of coastal marine reserves. *Ecological Applications*, **13**, (1), S90-S107.

Connell, J. H. (1978). Diversity in tropical rainforests and coral reefs. *Science*, **199**, (24), 1302-1310.

Connell, J. H., Hughes, T. P. and Wallace, C. C. (1997). A 30-year study of coral abundance, recruitment, and disturbance at several scales in space and time. *Ecological Monographs*, **67**, (4), 461-489.

Cowen, R. K., Lwiza, K. M. M., Sponaugle, S., Paris, C. B. and Olson, D. B. (2000). Connectivity of marine populations: Open or Closed? *Science*, **287**, 857-859.

CRC Reef Research Centre (2002) The Great Barrier Reef Fact Sheet. Available: http://www.reef.crc.org.au.

CRC Reef Research Centre (2005) Effects of Line Fishing (ELF) Project. Available: http://www.reef.crc.org.au/research/fishing_fisheries/elf.html

Dale, V., H., Lugo, A., E., MacMahon, J. A. and Pickett, S. T. A. (1998). Ecosystem management in the context of large, infrequent disturbances. *Ecosystems*, **1**, 546-557.

Davis, F. W., Stoms, D. M., Estes, J. E., Scepan, J. and Scott, J. M. (1990). An information systems approach to the preservation of biological diversity. *International Journal of Geographic Information Systems*, **4**, 55-78.

Day, J., Fernandes, L., Lewis, A., De'ath, G., Slegers, S., Barnett, B., Kerrigan, B., Breen, D., Innes, J., Oliver, J., Ward, T. and Lowe, D. (2002). The Representative Area Program for protecting biodiversity in the Great Barrier Reef World Heritage Area. *Proceedings of the Ninth International Coral Reef Symposium*, Bali, Indonesia.

Day, J., Fernandes, L., Lewis, A. and Innes, J. (2003). RAP - An ecosystem level approach to biodiversity protection planning. *Paper for International Tropical Marine Ecosystems Management Symposium (ITMEMS)*, Manila, Philippines.

Done, T. J. (1992). Phase shifts in coral reef communities and their ecological significance. *Hydrobiologia*, **247**, 121-132.

Done, T. J. (1999). Coral community adaptability to environmental change at the scales of regions, reefs and reef zones. *American Zoologist*, **39**, (1), 66-77.

Fabricius, K., Done, T. J. and Puotinen. M. L. (In prep). Damage survey of severe cyclone Ingrid's impacts on the far northern GBR.

Fiske, G. (2003). AML script 'info_merge.aml'. Available : http://support.esri.com/index.cfm?fa=listserve.message. Accessed [May, 20th 2005].

Friedlander, A., Sladek Nowlis, J., Sanchez, J. A., Appeldoorn, R., Usseglio, P., McCormick, C., Bejarano, S. and Mitchell-Chui, A. (2003). Designing Effective Marine Protected Areas in Seaflower Biosphere Reserve, Colombia, Based on Biological and Sociological Information. *Conservation Biology*, **17**, (6), 1769-1784.

Gerner, D. B. and Bryan, B. A. (2003). Representative marine protected area selection: setting priorities using spatial information technology. In C. D. Woodroffe and R. A. Furness (eds), Coastal GIS 2003: an integrated approach to Australian coastal issues. Centre for Maritime Policy, The University of Wollongong, Wollongong, Australia, pp 415-430.

Great Barrier Reef Marine Park Authority (2003) What is the representative areas program? Published on-line at: http://www.gbrmpa.gov.au/corp_site/key_issues/conservation/rep_areas/documents/tech_sheet_05.pdf .

Great Barrier Reef Marine Park Authority (2004) GBRMPA website: www.gbrmpa.gov.au. Accessed [June, 1st 2004].

Gunderson, L. H. and Pritchard, L. J. (2002). Resilience and the Behavior of large-scale systems. Island Press, Washington, USA, 287pp.

Harmelin-Vivien, M. L. (1994). The Effects of Storms and Cyclones on Coral Reefs: A Review. *Journal of Coastal Research*, **12**, (Special Issue), 211-231.

Hixon, M. A., Boersma, P. D., Hunter, M. L., Micheli, F., Norse, E. A., Possingham, H. P. and Snelgrove, P. V. R. (2001). Oceans at risk: research priorities in Marine Conservation Biology. In M. E. Soulé and G. H. Orians (eds), Conservation Biology: Research Priorities for the Next Decade. Island Press, Covelo, CA., pp 1-28.

Hughes, T. P. (1994). Catastrophes, phase shifts, and large-scale degradation of a Caribbean coral reef. *Science*, **265**, 1547-1551.

Hughes, T. P., Baird, A. H., Bellwood, D. R., Card, M., Connolly, S. R., Folke, C., Grosberg, R., Hoegh-Guldberg, O., Jackson, J. B. C., Kleypas, J., Lough, J. M., Marshall, P., Nyström, M., Palumbi, S. R., Pandolfi, J. M., Rosen, B. and Roughgarden, J. (2003). Climate change, Human impacts, and the Resilience of coral reefs. *Science*, **301**, 929-933.

Hughes, T. P. and Connell, J. H. (1999). Multiple stressors on coral reefs: A long-term perspective. *Limnology and Oceanography*, **44**, (3, part 2), 932-940.

Jago, B., Day, J., Fernandes, L., Thompson, L., Hall, J. and Sampson, K. (2005) Bringing the Great Barrier Reef Marine Park zoning into the 21st century: an overview of the Representative Areas Program. Published on-line at: http://www.gbrmpa.gov.au/corp_site/management/zoning/zoning_publications.html. Accessed [January, 2005].

Kelleher, G. and Kenchington, R. (1991). Guidelines for Establishing Marine protected Areas. A marine conservation and development report. *International Council for Conservation of Nature (IUCN)*, Gland, Switzerland, 79pp.

Knowlton, N. (2001). Coral reef biodiversity - Habitat size matters. *Science*, **292**, (5521), 1493-1495.

Leslie, H., Ruckelshaus, M., Ball, I. R., Andelman, S. and Possingham, H. P. (2003). Using siting algorithms in the design of marine reserve networks. *Ecological Applications*, **13**, (1), S185-S198.

Lewis, A., S., S., Lowe, D., Muller, L., Fernandes, L. and Day, J. (2003). Use of spatial analysis and GIS techniques to re-zone the Great Barrier Reef Marine Park. In C. D. Woodroffe and R. A. Furness (eds), Coastal GIS 2003: an integrated approach to Australian coastal issues. The University of Wollongong, Wollongong, pp 431-451.

Lubchenco, J., Palumbi, S. R., Gaines, S. D. and Andelman, S. (2003). Plugging a hole in the ocean: the emerging science of marine reserves. *Ecological Applications*, **13**, (1), S3-S7.

McClanahan, T. R., Polunin, N. V. C. and Done, T. J. (2002). Resilience of coral reefs. In L. H. Gunderson and L. J. Pritchard (eds), Resilience and the Behavior of large-scale systems. Island Press, Washington, USA, 111-163pp.

McConochie, J. D., Mason, L. B. and Hardy, T. A. (1999). A Coral Sea cyclone wind model intended for wave modelling. In: Coasts and Ports '99: Challenges and Directions for the New Century. *Proceedings of the 14th Australasian Coastal and Ocean Engineering Conference and the 7th Australasian Port and Harbour Conference*, Perth, Western Australia, 14-15 April, Vol 2, 413-418.

McDonnell, M. D., Possingham, H. P., Ball, I. R. and Cousins, E. A. (2002). Mathematical methods for spatially cohesive reserve design. *Environmental Modelling and Assessment*, **7**, 107-114.

Murray, S. N., Ambrose, R. F., Bohnsack, J. A., Botsford, L. W., Carr, M. H., Davis, P. K., Dayton, D., Gotshall, D. R., Gunderson, M. A., Hixon, M. A., Lubchenco, J., Mangel, M., MacCall, A., McArdle, D. A., Ogden, J. C., Roughgarden, J., Starr, R. M., Tegner, M. J. and Yoklavish, M. M. (1999). No-take reserve networks: protection for fishery populations and marine ecosystems. *Fisheries*, **24**, 11-25.

Nyström, M. and Folke, C. (2001). Spatial resilience of coral reefs. *Ecosystems*, **4**, 406-417.

Nyström, M., Folke, C. and Moberg, F. (2000). Coral reef disturbance and resilience in a human-dominated environment. *Trends in Ecology and Evolution*, **15**, (10), 413-417.

Ogden, J. C. (1997). Marine managers look upstream for connections. *Science*, **278**, (5342), 1414-1415.

Pandolfi, J. M. (2002). Coral community dynamics at multiple scales. *Coral Reefs*, **21**, 13-23.

Pittock, B. A. (1999). Coral reefs and environmental change: Adaptation to what? *American Zoologist*, **39**, (1), 10-23.

Poiani, K. A., Richter, B. D., Anderson, M. G. and Richter, H. E. (2000). Biodiversity conservation at multiple scales: Functional sites, Landscapes, and Networks. *BioScience*, **50**, (2), 133-146.

Possingham, H., Ball, I. R. and Andelman, S. (2000). Mathematical methods for identifying representative reserve networks. In S. Ferson and M. Burgman (eds), Quantitative methods for conservation biology. Springer-Verlag, New York, pp 291-305.

Puotinen, M. L., Done, T. J. and Skelly, W. C. (1997). An atlas of tropical cyclones in the Great Barrier Reef, 1969-1997. Townsville: CRC Reef Research Centre (Technical Report No.19), 203 pp.

Puotinen, ML (2003). Modelling tropical cyclone disturbance of the Great Barrier Reef using GIS. *Proceedings of the MODSIM 2003 International Congress on Modelling and Simulation*, Townsville, Queensland, Australia, July 2003.

Puotinen, M. L. (2004a). Mapping tropical cyclone disturbance of the Great Barrier Reef. *Journal of the Australian Map Circle*, **55**, 31-42.

Puotinen, M. L. (2004b). Tropical cyclones in the Great Barrier Reef Region, 1919-1999: A first step towards characterising the disturbance regime. *Australian Geographical Studies*, **42**, (3), 378-392.

Puotinen, M. L. (in press). Modelling the risk of cyclone wave damage to coral reefs using GIS: a case study of the Great Barrier Reef, 1969-2003. *International Journal of Geographical Information Science*. Accepted 1 June 2006.

Puotinen, M. L. (2005a). Tropical cyclone disturbance of coral communities of the Great Barrier Reef, 1969-2003. In R. J. Morrison, S. Quinn and E. A. Bryant (eds), Planning for Natural Hazards: how can we mitigate the impacts? *Proceedings of a symposium held at University of Wollongong, 2-5 February 2005, GeoQuEST Research Centre*, Wollongong, New South Wales, 153-166.

Puotinen, ML (2005b). A fully automated method for measuring fetch in complex reef-island systems: case study of the central GBR. In A. Zerger and R. M. Argent (eds), *MODSIM 2005 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand*, December 2005, 170-176. Available: http://www.mssanz.org.au/modsim05/papers/puotinen.pdf

Puotinen, M. L. (2005c). Tropical cyclone impacts on coral reef communities: modelling the disturbance regime in the Great Barrier Reef region, 1969-2003. PhD thesis, School of Tropical Studies and Environmental Geography, James Cook University, Townsville, Queensland, Australia.

Roberts, C. M. (1997). Connectivity and Management of Caribbean Coral Reefs. *Science*, **278**, (5342), 1454-1457.

Roberts, C. M., Andelman, S., Branch, G., Bustamente, R. H. and others, (2003a). Ecological criteria for evaluating candidate sites for marine reserves. *Ecological Applications*, **13**, (1), S199-S214.

Roberts, C. M., Branch, G., Bustamente, R. H., Castilla, J. C., Dugan, J., E., Halpern, B. S., Lafferty, K., D., Leslie, H., Lubchenco, J., McArdle, D. A., Ruckelshaus, M. and Warner, R. R. (2003b). Application of ecological criteria in selecting marine reserves and developing reserve networks. *Ecological Applications*, **13**, (1), S215-S228.

Soulé, M. E. and Terborgh, J. (1999). Continental conservation. Island Press, Washington, D.C., USA, 227pp.

Turner, M. G. and Dale, V., H. (1998). Comparing large, infrequent disturbances: What have we learned? *Ecosystems*, **1**, (6), 493-496.

Turner, M. G., Romme, W. H., Gardner, R. H., O'Neill, R. V. and Kratz, T. K. (1993). A revised concept of landscape equilibrium: Disturbance and stability on scaled landscapes. *Landscape Ecology*, **8**, (3), 213-227.

Van Woesik, R. (1992). Contemporary disturbances to coral communities of the Great Barrier Reef. *Journal of Coastal Research*, **7**, (2), 551-558.

White, P. S. and Pickett, S. T. A. (1985). Natural disturbance and patch dynamics: An introduction. In S. T. A. Pickett and P. S. White (eds), The Ecology of Natural Disturbance and Patch Dynamics. Academic Press, New York, pp 3-13.

Wilkinson, C. R. (1999). Global and local threats to coral reef functioning and existence: review and predictions. *Marine and Freshwater Research*, **50**, 867-878.

Woodley, J. D. (1992). The incidence of hurricanes on the north coast of Jamaica since 1870: are the classic reef descriptions atypical? *Hydrobiologia*, **247**, 133-138.

Young, I. R. and Hardy , T. A. (1993) Measurement and modelling of tropical cyclone waves in the Great Barrier Reef. *Coral Reefs*, **12**, 85-95.

APPENDIX 1: Revising existing zoning plans of the GBR

One of the primary tools for protecting and preserving the GBR, as specified by the *Great Barrier Reef Marine Park Act 1975,* is zoning (GBRMPA, 2004). A multiple-zone approach to zoning provides an ecologically (recognising that marine ecosystems operate at temporal and spatial scales), practically (easier to manage, potentially buffering and diluting impacts of various nature) and socially (help resolve and manage conflicts) effective model to conservation (Day *et al.*, 2002). The principle objectives of any zoning plan (according to sec. 32(7) of the Act) are:

- the conservation of the GBR;
- the regulation of the use of the Marine Park so as to protect the GBR while allowing reasonable use of the GBR Region;
- the regulation of activities that exploit the resources of the GBR Region so as to minimise the effect of those activities on the GBR;
- the reservation of some areas of the GBR for its appreciation and enjoyment by the public; and
- the preservation of some areas of the GBR in its natural state undisturbed by man except for the purposes of scientific research.

The zoning of the GBR separates activities that may conflict with each other, such as commercial fishing and tourism. Marine Park Zoning Plans have been regulating activities that are as-of-right, with permission or prohibited. Zoning also allows areas that need permanent conservation to be protected from potentially threatening processes by being placed ‘off limits’ to users (except for the purpose of scientific research) for varying lengths of time.

The original zoning scheme (in place until July 2004) was reviewed in a number of stages, starting with the collation of biophysical data to help map the 70 bioregions found to represent the many distinctive and interconnected habitats of the GBR (30 reef (Fig. A1.1) and 40 non-reef bioregions (Fig. A1.2)).

Please see print copy for Figure A1.1

Figure A1.1. Reef bioregions of the GBR reflecting variations in the biological and physical environments within the Marine Park. Changes in depth, water quality, substrate type, tidal range, wave energy, and latitude are some of the characteristics that are clearly reflected in the pattern of the bioregions. (*Source*: *http://www.gbrmpa.gov.au*)

Please see print copy for Figure A1.2

Figure A1.2. Non-reef bioregions of the GBR reflecting variations in the biological and physical environments within the Marine Park. Changes in depth, water quality, substrate type, tidal range, wave energy, and latitude are some of the characteristics that are clearly reflected in the pattern of the bioregions. (*Source*: *http://www.gbrmpa.gov.au*)

Once the bioregional diversity of the GBRMP was described, the level of protection in place within the old zoning system was assessed based on the number, size, distribution of no-take areas and proportion of the bioregion area in no-take areas at the time (Day *et al.*, 2002). Scientific knowledge about the GBR's ecosystem gained from the data collected clearly indicated that the old network of protected areas needed to be improved (Jago *et al.*, 2005).The development of the RAP then followed seven steps through which draft zoning maps were created, revised after public consultation and adopted after finalization to be submitted to the Commonwealth Minister for the Environment and Heritage for approval (Fig. A1.3). The preparation of the new zoning included one of the most extensive and comprehensive formal community consultations in Australia's history.

Please see print copy for Figure A1.3

Figure A1.3. Current (b), revised draft (c) and proposed RAP (d) zoning of the GBR as of May 2004. *(Source:* http://www.gbrmpa.gov.au

APPENDIX 2: AML script for connectivity analysis

Once the distances between each sink centroid and each source centroid were calculated, an AML script was used to select the minimum distance from each of the 1,911 sink centroids to the nearest source centroid. First the minimum distance from each sink reef to the source reefs from each of the three scenarios of disturbance was found. Then this minimum distance was appended to a list before the next minimum distance was found for the following sink reef. Each of the 1,911 minimum distances was therefore appended into a single table before this procedure was applied to the other disturbance scenarios. This script was adapted from the ‘info_merge.aml’ AML created by Fiske (2003) that appends all ArcInfo info files in a directory to one.

```
/*mindistest.aml
/*
/* apply loop to various original files
/*
&sv count := [filelist * filelist.txt -info]
&if [null %count%] &then
&return No info files exist in this directory./&
&sv flistorig := [open filelist.txt ostat -read]
&do I := 1 &to %count%
  &s types := [read %flistorig% rstat]
  &do &while %rstat% = 0
    &works d:\sophie\distance
    createworkspace %types%
    &works sophie\distance\%types%

 /*Loops through each ‘type’ INFO file to find the minimum distance within
ALLCTR_PT record
    &sv .count = 1
    &do &until %.count% = 1912
      &do
      arcplot
      reselect d:\sophie\distance\%types% info ALLCTR_PT# = %.count%
      statistics d:\sophie\distance\%types% info allctr_pt# %types%_min%.count%
      minimum distance
      end
      quit
      &end
    &sv .count = %.count% + 1
    &end
  &sv output := %types%_min
      copyinfo %types%_min1 trash.out

      /*creates a list of the info files and reads it
      &sv files := [filelist %types%_min* fl%types%.txt -info]
      &if [null %files%] &then
      &return no info files in this directory./&
```

```
    &sv flist [open fl%types%.txt ostat -read]
    &sv minfile [read %flist% rstat]

    tables
    /*loops through the info list and dumps the contents of each to text file temp.out
    &do &while %rstat% = 0
    sel %minfile%
    unload temp.out
    &sv minfile [read %flist% rstat]
    &end
    &sv c [close %flist%]

    /*put contents into predefined trash.out INFO table
    sel trash.out
    add from temp.out
    quit

    /*export to dbf
    infodbase trash.out %output%.dbf

    &type /& info files have been appended and exist now as %output%..../&
    &type reminder: the data from the first INFO file is copied twice in the final
output.dbf /&
  &sv types := [read %flistorig% rstat]
  &end
&end
&sv c [close %flistorig%]
```