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Review

A critical review of environmental management of the ‘not so Great’ Barrier Reef

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A R T I C L E I N F O

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A B S T R A C T

Recent estimates put average coral cover across the Great Barrier Reef (GBR) at about 20–30%. This is estimated to be a large reduction since the 1960s. The Great Barrier Reef Marine Park Act was enacted in 1975 and the Great Barrier Reef Marine Park Authority (GBRMPA) set up shortly afterwards. So the question is: why has coral cover continued to decline when the GBR is being managed with a management regime often recognised as ‘the best managed coral reef system in the world’, based on a strong science-for-management ethic. The stressors which are known to be most responsible for the loss of coral cover (and general ‘reef health’) are terrestrial pollution including the link to outbreaks of crown of thorns starfish, fishing impacts and climate change. These have been established through a long and intensive research effort over the last 30 years. However the management response of the GBRMPA after 1975, while based on a strong science-for-management program, did not concentrate on these issues but instead on managing access through zoning with restrictions on fishing in very limited areas and tourism management. Significant action on fishing, including trawling, did not occur until the Trawl Management Plan of 2000 and the rezoning of the GBR Marine Park in 2004. Effective action on terrestrial pollution did not occur until the Australian Government Reef Rescue initiative which commenced in 2008. Effective action on climate change has yet to begin either nationally or globally. Thus it is not surprising that coral cover on the GBR has reduced to values similar to those seen in other coral reef areas in the world such as Indonesia and the Philippines. Science has always required long periods to acquire sufficient evidence to drive management action and hence there is a considerable time lag between the establishment of scientific evidence and the introduction of effective management. It can still be credibly claimed that the GBR is the best managed coral reef system in the world but it must be realised that this is a relative assessment against other reef systems and management regimes and not an absolute claim for effective management.

1. Introduction

Degradation of coastal and marine ecosystems is a global issue and the subject of intense and prolonged research, analysis and management activity (Lotze et al., 2006; Murawski, 2007; Richmond et al., 2007; Halpern et al., 2007, 2008; Douvere, 2008; Doney, 2010; Aswani et al., 2012; Mee, 2012). The majority of coral reefs around the world are threatened by human activities (Burke et al., 2011) and many show signs of degradation (e.g. Pandolfi et al., 2003). Reefs are exposed to a combination of stresses including destructive fishing practices, overfishing or loss of herbivorous fish and other grazing organisms, increased discharge from the land of sediment, nutrients and pesticides, coral predator outbreaks linked to trophic changes in the system, increased bleaching associated with global climate change, and increased incidence of and severity of coral diseases. These pressures have led to precipitous declines in coral cover on many coral reef provinces from values near 60% more than 50 years ago to near 20% recently, and led to persistent shifts from coral dominance to non-coral and algal dominance (Mumby et al., 2007; Norström et al., 2009; Hughes et al., 2010).

The interaction of science and management and effective use of research to implement good management and policy in coastal areas has been the subject of considerable speculation and analysis. A relatively early analysis clearly documented the steps in such a process (Boesch, 1996) as:

(1) Sustained scientific investigation, responsive to but not totally defined by managers.
(2) Clear evidence of change, the scale of the change and the causes of the change.

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(3) Some level of consensus among the scientific communities associated with various interests.
(4) The development of models to guide management actions.
(5) Identification of effective and feasible solutions to the problems.

A large range of approaches to manage the coastal zone have been developed including Integrated Coastal Zone Management (ICZM), Ecosystem Based Management (EBM), Marine Protected Areas (MPAs) and Integrated Marine (and Spatial) Planning (IMP). Most of these initiatives acknowledge some sort of science-management integration as described by Boesch (1996), but in practice turning science into management is often problematic.

Since the United Nations Conference on Environment and Development in Rio de Janeiro in 1992, the Integrated Coastal Zone Management (ICZM; also called Integrated Coastal Management ICM) concept has been used by many nations and states as the basis for effectively and sustainably managing coastal areas. Most environmental management concentrates on improving integration in catchments (through Integrated Catchment Management, another ICM) and in coastal areas (through ICZM) but there is often little coordination between these two programs. Integration of catchment and coastal management is necessary to avoid duplication between management objectives, and to set out clear responsibilities for the authorities involved. Integrated catchment and coastal management can avoid duplication between management objectives and ensure the most appropriate planning tool is adopted to achieve better environmental outcomes and more effective management of natural resources. ICZM is a management process that acknowledges inter-relationships between catchment, coastal, and marine environments (Wilkinson and Brodie, 2011).

Many recent studies have documented the inadequacy of current Marine Protected Area (MPA) management around the world in terms of size, spatial planning, representativeness, focus on limited impacts and lack of enforcement (Mora et al., 2006; Christie and White, 2007; Osmond et al., 2010) and the lessons of marine environmental management in general (Hughes, 2011). However the Great Barrier Reef (GBR) is generally seen as the best example of Ecosystem Based Management (EBM) (Rosenberg and McLeod, 2005; Olsson et al., 2008; Ruckelshaus et al., 2008), MPA design and implementation (Day, 2002; Fernandes et al., 2005; Agardy et al., 2011), Integrated Marine Planning (Dickinson et al., 2010) and to some extent combined ICZM and MPA design (Douvere, 2008; Nobre, 2011). Despite this degree of management coral cover, a primary indicator of reef status, is declining in the GBR (Hughes et al., 2011) and the system is seen to have many other declining values (GBRMPA, 2009a). In this paper we will report on the status of the GBR, explore the history of anthropogenic impacts, examine the management regime and the science-management nexus, make an assessment of the success of the regime and suggest what the future may hold for the system.

2. The Great Barrier Reef

The GBR is an extensive coral reef system lying off the north east Australian coast on the shallow continental shelf (Fig. 1). The area is 344,000 km^2 with around seven percent of the area consisting of coral reefs (Day, 2011) and an adjacent catchment area of 400,000 km^2 (Brodie, 2003). It consists of a variety of tropical marine habitats including coral reefs, seagrass meadows (intertidal, sub-tidal and deep) and mangrove forest with major mobile biota including fish, turtles, dugong, whales and dolphins.

Biological diversity and significance within the GBR includes (taken from Day (2011)):

- Six of the world's seven species of marine turtle.
- The largest green turtle breeding area in the world.
- One of the world's most important dugong populations.
- Over 43,000 square kilometers of seagrass meadows, including 23 percent of the known global species diversity.
- A breeding area for humpback whales with at least 30 other species of whales and dolphin identified within the GBR.
- Over 2900 coral reefs built from over 450 species of hard coral.
- Over one-third of all the world's soft coral and sea pen species (150 species).
- Two-thousand species of sponges equalling 30 percent of Australia's diversity in sponges.
- Over 3000 species of molluscs, including 2500 species of gastropods.
- Six-hundred-and-thirty species of echinoderms, including 13 percent of the known global species diversity.
- Fourteen breeding species of sea snakes, including 20 percent of the known global species diversity.
- Approximately 500 species of seaweeds.
- More than 1620 species of fish, of which 1460 are coral reef species.

The GBR has been managed as a national Marine Park since 1975 (Great Barrier Reef Marine Park Act, 1975), and was listed as a World Heritage Area (WHA) in 1981 (Lawrence et al., 2002). It is recognised as a global Large Marine Ecosystem (Brodie, 2003) and has been held up as a paragon of good MPA design and management from the earliest days. The GBR has been subject to an intensive management regime involving both the Australian and Queensland State Governments for 35 years focussing on managed use and ecosystem protection. The human use impacts to be 'protected against' include tourism, recreation, shipping, farm and urban pollutant runoff from the adjacent land, fishing and hunting and climate change related environmental change. In general terms, the actual Marine Park falls under Australian Government jurisdiction, and the adjacent catchments are within the jurisdiction of the Queensland State Government. These differences lead to issues when adopting an ecosystem based approach to management, and in particular, in addressing land based impacts.

An additional complication to the management arrangements in the GBR arises from differences in boundaries between the Marine Park and the WHA. The Marine Park comprises 99.25 percent of the WHA. Parts of the WHA not included in the Marine Park comprise: islands under State (Queensland) jurisdiction (most of these are national parks); State waters and internal waters of Queensland (e.g. deep bays or narrow inlets, many of which are State Marine Parks); and a number of small exclusion areas around major ports/urban centres (e.g. Cairns). These boundary differences result in further jurisdictional complexities, and in many cases, have resulted in limitations in the management of GBR coastal freshwater ecosystems, estuaries and port exclusion areas. While the Australian Government's Environment Protection and Biodiversity Conservation Act 1999 provides the framework to protect and manage Australia's WHAs, and State legislation also exists to manage locations that fall within the WHA but not the Marine Park, there has been a lack of integration of research, management and monitoring activities in these areas. Current environmental issues associated with port development on the GBR coast provide an example of the inadequacies of the current management regime across jurisdictions. The World Heritage Committee recently had (March 2012) a team in Australia reviewing the status and management of the GBRWHA. The review was triggered by apparent inadequate management of port development near Gladstone (see following web page). http://www.abc.net.au/news/2011-11-07/health-of-barrier-reef-at-crossroads/3637104

3. Current status of the system

3.1. Monitoring, assessment and reporting

A number of long term monitoring programs that assess the status of values and attributes of the GBR have been established in the period since 1975 often driven by specific impacts at a specific time. The most prominent and still current (and those which are used in status reporting for the GBR and which form the basis for much of the current paper) include the Long Term Monitoring Program (LTMP) assessing GBR coral status since 1985 by the Australian Institute of Marine Science (AIMS) (e.g. Sweatman et al., 2011; Osborne et al., 2011); the GBR wide long term chlorophyll monitoring program run from 1991 by the GBRMPA and AIMS (e.g. Brodie et al., 2007; De'ath and Fabricius, 2008); the Reef Plan/Reef Rescue Marine Monitoring Program assessing water quality and ecosystem health since 2005 (e.g. Johnson et al., 2011; The State of Queensland, 2011; Schaffelke et al., 2011; Kennedy et al., 2011); aerial survey monitoring of dugong populations led by James Cook University (JCU) (e.g. Marsh et al., 2007); seagrass monitoring led by Queensland Department of Primary Industries (DPI) (from the 1970s onwards) and Seagrass Watch (e.g. Coles et al., 2007; McKenzie et al., 2010); and for fish, the Fisheries Long Term Monitoring Program (commencing in 1999; http://www.dpi.qld.gov.au/28_10738.htm) and the Fisheries Observer Program.

Reports on the current status of the GBR are prepared across a range of initiatives at different spatial and temporal scales. In 2009 the GBRMPA prepared the first 'outlook' report for the GBR, incorporating status and trend information across all aspects of the GBR ecosystem and making an assessment of the health of the GBR (GBRMPA, 2009a). Another coordinated reporting process for the GBR is an annual water quality report card which was first released in August 2011, reporting a 'baseline' using 2008/09 data (The State of Queensland, 2011). The Queensland Government also releases the State of Environment Report for Queensland every four years, with the latest report due for release this year (http://www.derm.qld.gov.au/environmental_management/state_of_the_environment/). Within these reports, the Queensland Government reviews the status of Queensland commercial fisheries. Annual status reports for all major fisheries are also produced (http://www.dpi.qld.gov.au/28_10916.htm) and stock assessments have also been developed for some commercial species (saucer scallops, stout whiting, snapper, mullet, tailor, barramundi, eastern king prawns, tiger and endeavour prawns, and spotted and Spanish mackerel). Risk assessments have been undertaken for various shark species (http://www.dpi.qld.gov.au/28_11062.htm).

Within these evaluation and reporting frameworks, there are a limited number of policy-set numerical targets and guidelines we can use to assess the status of the GBR and evaluate management success. There are no pre-set values for even simple (but possibly misleading) indicators such as coral cover, dugong numbers or commercial fish stocks which would show the system in satisfactory condition. Currently the clearest guidelines have been set for conditions in the water column including water quality guidelines (GBRMPA, 2009b) and temperature guidelines (Maynard et al., 2008). In Reef Plan 2009 (Queensland Department of the Premier and Cabinet, 2009) and Reef Rescue (Australian Government, 2007), the joint Australian and Queensland Governments' plans to protect the GBR from agricultural pollution (see Brodie et al. (2011b)), targets for reduction of specified pollutant loads discharged to the GBR were set (e.g. a 50% reduction in the load of nitrogen discharged by 2013). Assessment of the success of the catchment management initiatives put in place to achieve these targets has begun (The State of Queensland, 2011) but it is too early yet to make any definitive statements. While fixed targets have many problems in marine conservation management (Agardy et al., 2003) at least some idea of a satisfactory endpoint for important factors like coral cover is desirable.

An overview of the current status of the GBR is provided below. We have selected a number of indicators commonly assessed to report the status of the GBR and a full assessment is available in other publications such as the GBR Outlook Report (GBRMPA, 2009a). The stresses and management responses to these are discussed in Section 4.

3.2. Coral reefs

Coral cover (an indicator of coral reef status) on the GBR has declined, although the exact amount and time course of the decline is uncertain and controversial (Bellwood et al., 2004; Bruno and Selig, 2007; Hughes et al., 2011; Osborne et al., 2011; Sweatman and Syms, 2011; Sweatman et al., 2011). Much of the controversy centres on comparing datasets across time collected with different methodology. For example, the data in Osborne et al. (2011) collected using video transects at a depth of about 6–9 m shows little overall change in coral cover between 1995 and 2009, with cover remaining near 30%. However data collected from 6 to 9 m may miss changes due to flood plume salinity and bleaching impacts which are often manifest in shallower depths. In contrast, Sweatman et al. (2011) used manta tow data to show that coral cover across the GBR had declined from average 28% in 1986 to 22% in 2004. Manta tow techniques are used in depths of about 2 m and over a much longer section than video methods and may give a quite different result. Results presented in Bellwood et al. (2004) and Bruno and Selig (2007) (and reinforced by Hughes et al. (2011) using both pre-1986 data from individual studies plus data from the AIMS LTMP after 1986) suggest coral cover has declined by 20–30% overall from values near 50% in the 1960s to 20% currently. Sweatman and Syms (2011) comment on the inappropriateness of comparing data collected using different methods. Overall it is likely that coral cover (not necessarily the best indicator of coral status anyhow but the one for which we have data) has declined substantially from the 1960s but the exact amount is uncertain and declines have taken place more strongly in some regions than others (Sweatman et al., 2011). In addition, declines are interspersed with periods of recovery (Done et al., 2007; Osborne et al., 2011).

Other indicators of coral 'health' have also declined at different scaled areas in the GBR. In the area between Townsville and Cooktown coral diversity is much lower than expected and this is ascribed to the impact of terrestrial runoff (DeVantier et al., 2006). On Pandora Reef, just to the north of Townsville, while coral cover and species composition have varied through time in response to episodic impacts, the potential for the reef to recover from future impacts (resilience) is seen to be potentially compromised (Done et al., 2007). The ability to recover from crown of thorns starfish (COTS) damage on three reefs between Townsville and Cairns was examined by Done et al. (2010) who noted a potential loss of resilience associated with reduced coral fecundity.

There are many causes of this decline, often quite reef-specific including terrestrial runoff of sediment and nutrients with the associated COTS outbreaks (Brodie et al., 2005, 2008a, 2008b, 2011a; Fabricius, 2005; Fabricius et al., 2005, 2010; DeVantier et al., 2006; De'ath and Fabricius, 2010); coral bleaching and mortality associated with climate change (Berkelmans et al., 2004; Hoegh-Guldberg et al., 2007; Hughes et al., 2007); coral diseases (Haapkyla et al., 2011) and ocean acidification and its effects on coral calcification (Cooper et al., 2008; De'ath et al., 2009). These stressors do not act in isolation and interactions between them are

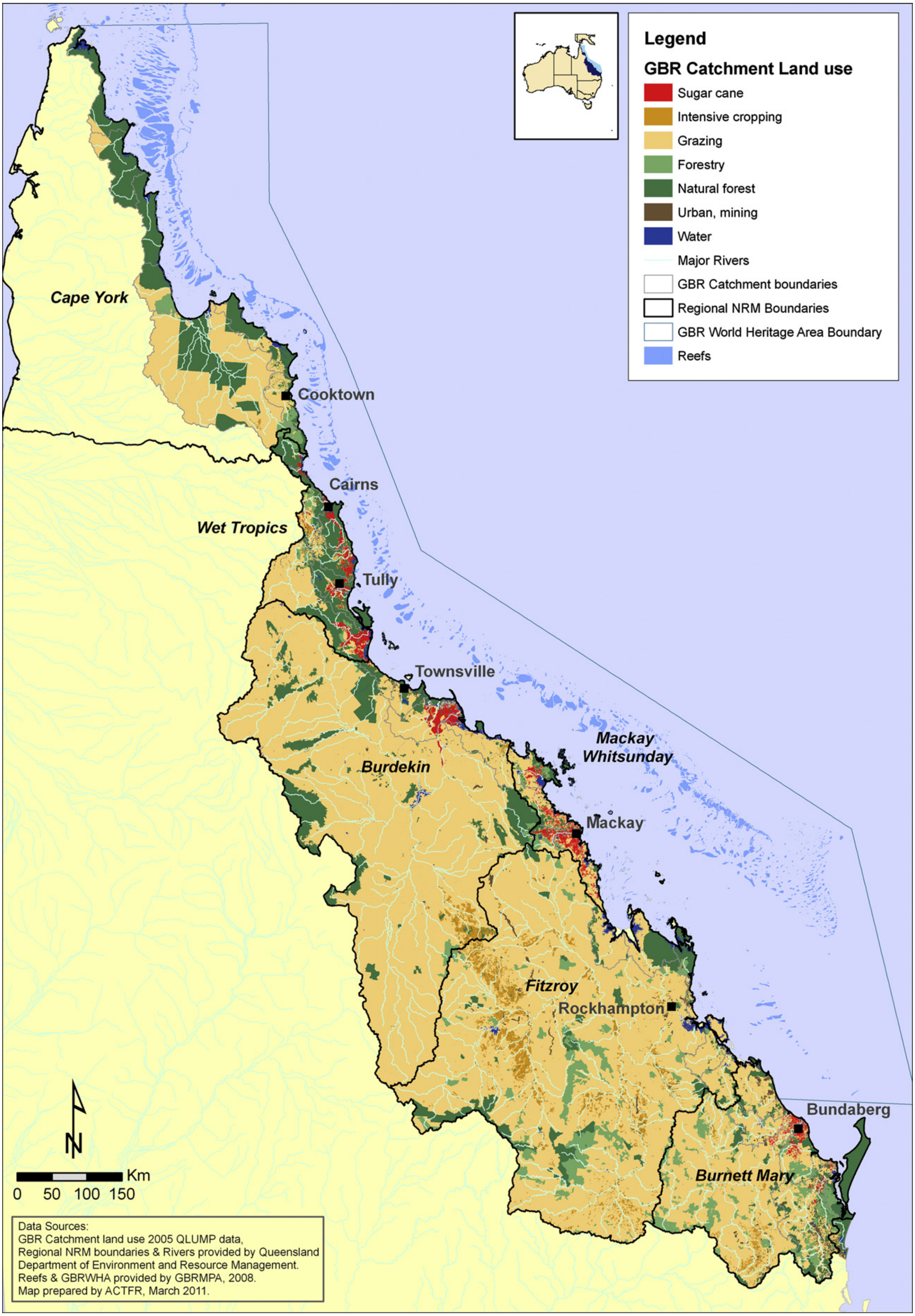

Fig. 1. The Great Barrier Reef showing the reefs, catchments and major rivers, land uses on the catchments and major cities and towns.

highly likely (Maina et al., 2011), and the subject of current research (S. Uthicke, pers. com.).

3.3. Seagrass and mangroves

Seagrass health and abundance is quite variable in space and time in the GBR, and as at 2007 no robust trends in area through time were observable (Coles et al., 2007). In recent times there is a suggestion that seagrass is declining in parts of the GBR (Waycott and McKenzie, 2010), particularly in the Townsville region (McKenzie et al., 2010). The indicators of this decline include evidence that 38% of sampling sites across the GBR are exhibiting shrinking meadow area, a large number of sites have reduced seagrass abundance, many sites have limited or no sexual reproduction producing seeds that would enable rapid recovery, and evidence that light limitation is the driver of seagrass abundance in many sites (Waycott and McKenzie, 2010). The 2011 major river discharge events from many of the GBR rivers (see Section 4.10) associated with the strong La Nina and the effects of Category 5 Tropical Cyclone Yasi have had devastating effects on large areas of GBR seagrass (GBRMPA unpublished data).

Mangroves are considered to be in excellent condition along the whole GBR coast with only small losses reported, associated with port and urban development (GBRMPA, 2009a). In 2006, mangrove and saltmarsh habitats covered an area of approximately 3800 km^2 along the GBR coast (Goudkamp and Chin, 2006). Due to the lack of historical data, the actual area of mangrove and saltmarsh habitat that has been lost, primarily due to coastal development, is unknown. The overall condition of remaining mangrove and saltmarsh areas along the GBR coast is reported to be relatively stable (Duke, 1997; Adam, 2002).

3.4. Fish

Long term datasets are not available to comprehensively report the status of fish populations in the GBR. Very limited information is available on the populations of non-commercial marine species, and recreational fishing is an important component of fishing effort in the GBR and currently accounts for approximately 40% (estimated to be 6 million fish in 2007) of the total catch (GBRMPA, 2009a). Efforts have improved in recent years, and the Queensland Government now reviews the status and undertakes an assessment of Queensland's commercial fisheries every five years. In 2006, it was concluded that apart from a few species, Queensland's commercial fisheries appear to be managed at sustainable harvest levels (DPIF, 2006; 2011 assessment in preparation). However, these sustainability assessments (based on stock and reported catch) are limited in some locations by the lack of information.

Updated figures in 2010 (DEEDI, 2010, 2011a,b) indicated that a majority of target species (including coral trout, redthroat emperor, Spanish mackerel, barramundi, banana prawn) are sustainably fished, however, limited information is available for several important species including snapper, emperor, black tip reef shark, several species of mackerel, Moreton Bay bug, saucer scallop and squid. Stock assessments of the Rocky Reef Fin Fishery show that snapper is under a high level of fishing pressure (DEEDI, 2010).

In many cases, the total catch of commercial species has decreased since 2004, coinciding with the rezoning of the Marine Park and additional management frameworks. For example, the total catch of coral trout increased from approximately 1250 tonnes (t) in 1990 (CRC Reef Research Centre, 2002) to around 2000 t in 2001. In 2004, a Total Allowable Catch of 1350 t was introduced (as part of a Coral Reef Fin Fish Management Plan) and since that time, the annual catch has been below 1110 t (DEEDI, 2011a). Catch of coral trout decreased from 1110 t in 2008–2009 to 922 t in 2009–2010, possibly reflecting a delayed response to impacts following Tropical Cyclone Hamish which tracked almost the entire length of the mid and outer GBR in March 2009. There are few species where total catch has increased over time, although an exception is the trend of total catch in commercial harvesting of mud crab which recorded the second highest annual catch reported in the last decade in 2010 (DEEDI, 2011c).

The status of shark populations within the GBR and in other regions nationally and internationally, has raised concern from managers about shark exploitation (Robbins et al., 2006; GBRMPA, 2009a). A 200% increase in shark landings on Queensland's east coast was recorded between 1993 and 2004 (Bensley et al., 2010). While some components of northern Australian shark fisheries have been reasonably well monitored and formal risk assessments or stock assessments have been used to inform management, other areas including the east coast of Queensland have received little attention (Harry et al., 2011). In response, the shark component of the inshore net fishery has been described (Harry et al., 2011), providing a baseline for further assessment and better understanding on the species composition of current catch.

3.5. Dugong and whales

Dugong numbers in the GBR have declined precipitously over recent decades with numbers reducing at a rate of 8.7% a year between 1962 and 1999 (Marsh et al., 2005). Overall this is estimated to have reduced dugong numbers from about 72,000 in the early 1960s to 4000 in the mid-1990s. Possible causes of mortality include incidental netting in fish nets and shark nets, loss of seagrass habitat due to water quality impacts and coastal development and hunting (Marsh et al., 2007). The combination of severe weather events in 2011 (see Section 4) has also increased dugong mortality and the long term effects of this in combination with the existing stresses has yet to be assessed.

The population of 'east Australian' humpback whales was as low as 500 animals when whaling ceased. The population in 2008 was estimated to have been more than 10,000 animals, which is about half of the estimated pre-whaling population size (Noad et al., 2008). Due to these improvements in whale populations, whale watching is now a major tourism industry focused on humpback whales and dwarf minke whales along the Queensland coast.

3.6. Turtles

Within Queensland and the GBR the population structure, distribution, range and status of the six species of marine turtle populations found in the region have been reasonably well documented (Hamann et al., 2007). All six species are listed as threatened under Queensland and Federal legislation, and the International Union for Conservation of Nature and Natural Resources (IUCN) Red List. Long term census data on green turtle populations indicate that although significant declines in population size are not apparent, other biological factors such as declining annual average size of breeding females, increasing remigration interval and declining proportion of older adult turtles to the population may indicate populations at the beginning of a decline (Limpus et al., 2003). In Queensland, the loggerhead turtle population has been monitored annually since the late 1960s and has undergone a substantial and well documented decline in the order of 85 percent in the last three decades (Limpus and Limpus, 2003). Long term monitoring data collected for the eastern Australian population of flatback turtle show no signs of a declining population (Limpus et al., 2000). No leatherback turtle nests have been reported in Queensland since 1996, despite annual nesting surveys for loggerhead turtles that use the same beaches (Hamann et al., 2006). Mortality of green turtles increased greatly in the year after the large flood and cyclone events of 2010/11 (see Section 4.10) with many turtles appearing to be starved (Bell and Ariel, 2011).

3.7. Comparison to other reef systems

In comparison with other reef systems in the world the GBR is considered the best managed (Wilkinson, 2008). In a number of global assessments of the condition and state of degradation of coral reefs the GBR scores in the lower categories of degradation (Pandolfi et al., 2003) with the inner-shelf reefs in worse comparative condition than the outer-shelf reefs. In more recent comparisons Burke et al. (2011) reported the outer-shelf GBR reefs in a low risk category, the inner-shelf reefs in a medium risk and some smaller number of inner-shelf reefs in high risk. Halpern et al. (2008) maps human impact on marine ecosystems at a global scale and shows the GBR is in the very low category in the northern GBR, low and medium–low in the southern two thirds of the area with small areas of medium–high in some central and southern sections. Maina et al. (2011) analyses global gradients of coral exposure to environmental stresses and the implications for local management, and for the GBR concludes:

> 'On the GBR, eutrophication is increasing principally due to land use in the adjacent coastal catchment area. From our 1520 sample points in GBR, there is great variability but the majority of coral locations are moderately to highly exposed to water quality reinforcing stress. Given that the exposure of GBR reefs to radiation stresses are relatively moderate a management strategy that improves water quality is predicted to increase reef resiliency.'

These rankings are in spite of the position of the main reefs of the GBR being well offshore and with low human population density on the coast.

Comparison of coral cover decline suggests that the situation on the GBR is little better than those in Indonesia and the Philippines (Bruno and Selig, 2007) with large declines in all three areas from roughly 50% in the 1970s to 20% in the 2000s (but see discussion in Section 3.2 Coral reefs earlier in this section). However the situation is better than in the Caribbean where coral cover has fallen from 50% to 10% in the period 1977–2002 (Gardner et al., 2003).

In an analysis of global seagrass loss Waycott et al. (2009) found Queensland to have no observed losses (and some gains) in comparison to areas in southern Australia, the eastern coast of North America and Europe where losses were high. This situation may have changed in more recent times with the loss of seagrass along the GBR in the major flooding and cyclonic events of 2009 and 2011 (see Section 4.10).

4. Stressors, impacts, the management response and analysis of success

Globally coral reef ecosystems are subject to range of anthropogenic threats and while there are differences between regions in many cases the list is surprisingly similar across the globe for all coastal marine ecosystems (Halpern et al., 2007) and for coral reefs specifically (Pandolfi et al., 2003; Burke et al., 2011). For marine ecosystems Halpern et al. (2007) lists nutrients (largely sourced from fertiliser), pesticides, pelagic, demersal and artisanal fishing (destructive and non-destructive), oil rigs, invasive species, shipping, Sea Surface Temperature, UV radiation and ocean acidification. For coastal coral reef systems we might add sediment delivery from the land and increased physical damage associated with climate change and increased frequency of extreme weather events.

For the GBR, a large number of actual impacts (already occurring) and potential impacts (may occur in future given current trends) have been identified from human activity (primarily in the last 200 years) for the GBR. In the following sections each of these is analysed using the titles: Stressors; Impacts; Management response; and Evaluation of management success.

4.1. Point source discharges – sewage and aquaculture

4.1.1. Stressors

Direct discharges of sewage effluent from island resorts and communities in the GBR; increasing discharges from coastal facilities into adjacent waterways (Waterhouse and Johnson, 2002). In 2001, 34 island resort facilities were documented in the study of Waterhouse and Johnson (2002), when 11 were tertiary treated (3 marine outfalls, 8 land irrigation), 12 were secondary treated (3 marine outfalls, 9 land irrigation) and 11 primary treated (absorption or evaporation trenches). At the same time, there were 42 major sewage facilities adjacent to the GBR Marine Park, a majority of which received secondary treatment and discharged into coastal waterways (Waterhouse and Johnson, 2002). In both cases, a majority of sewage discharged into the GBR Marine Park and adjacent waterways is now tertiary treated.

4.1.2. Impacts

Discharges of sewage to the marine environment have the potential to cause (reviewed in Waterhouse and Johnson (2002)):

- Eutrophication of coastal waters due to chronic inputs of nutrients and organic matter;
- Impacts associated with the accumulation of toxicants such as heavy metals in marine organisms and sediments;
- Changes to the species composition of marine communities to higher abundances of species that are tolerant to pollution; and
- Long term degradation of sensitive environments such as coral communities and seagrass meadows by chronic exposure to sewage effluent.

Potential impacts associated with aquaculture adjacent to the GBR Marine Park include high nutrient discharge, introduction of exotic pests and diseases and clearly or modification of coastal habitats.

4.1.3. Management response

The GBRMP Act requires a permission for discharge of sewage effluent directly into the Marine Park, supported by 1991 policy Sewage Discharges from Marine Outfalls into the Great Barrier Reef Marine Park setting out requirements for a permission to discharge treated sewage into the Marine Park with improvements in effluent discharges to meet tertiary or tertiary equivalent standards by 1998. Further revision in 2005 (GBRMPA, 2005) provided an incentive for operators to reduce nutrient loads in sewage effluent using an Environmental Management Charge. In contrast to the resort sewage, mainland city and town sewage discharges are not within the jurisdiction of the GBRMPA as the discharge structures are not located within but mostly adjacent to the Marine Park. Hence, close cooperation has been required with the Qld Govt. to gather further support to improve coastal discharges through the State Coastal Management Plan (Qld Govt.) in 2010. Currently most mainland discharges either do not discharge to waterways (with up to 100% reuse), or meet tertiary treatment standards.

4.1.4. Evaluation of management

Based on strong evidence from elsewhere, the management response to addressing discharge of poorly treated sewage effluent into the GBR Marine Park was relatively rapid. In addition, the strong political move to introduce the Great Barrier Reef Marine Park (Aquaculture) Regulations 2000, has resulted in significant improvement in the environmental performance of land based aquaculture facilities (GBRMPA, 2009a). Continued cooperation between the Australian and Queensland Government has also addressed issues associated with sewage and aquaculture discharges into coastal waterways that discharge in the Marine Park.

4.2. Terrestrial runoff of pollutants

Declining water quality is recognized as one of the greatest threats to the long term health of the GBR, and it is now agreed that management of this issue can aid in building ecosystem resilience to other pressures such as those associated with a changing climate (McCook et al., 2007; Wooldridge and Done, 2009; Hughes et al., 2010). There is well documented evidence of the adverse impacts of anthropogenic pollutants on the health of aquatic ecosystems both within the catchment and in the GBR (for example, see Brodie et al. (2008b)) and the relationship between land use, catchment management, declining water quality and GBR ecosystem health (Fabricius, 2005, 2011a, 2011b; Wolanski and De'ath, 2005; Brodie et al., 2007, 2010, 2011b; Lewis et al., 2009, 2011; Shaw et al., 2010; De'ath and Fabricius, 2010; Kennedy et al. (2011)).

Results from water quality monitoring in the GBR (e.g. Schaffelke et al., 2011) are assessed against the GBR Water Quality Guidelines (GBRMPA, 2009b). During flood plume conditions, the Guidelines for suspended sediment, chlorophyll and nutrient parameters are exceeded on almost all occasions (e.g. Devlin et al., 2010) (which may be expected given that the Guidelines are derived from 'ambient' datasets). Short-term concentrations of both particulate (in the range 5–20 μM nitrogen and 0.1–4 μM phosphorus) and dissolved inorganic nutrients (in the range 20–70 μM for dissolved inorganic nitrogen and 0.2–1.3 μM for dissolved inorganic phosphorus) in flood plumes are extreme compared to non-flood conditions (Devlin et al., 2001; Devlin and Brodie, 2005). However, water quality samples collected outside of flood plumes also exceed the Guidelines at different times of the year, and concentrations are variable between parameters and across regions of the GBR (De'ath and Fabricius, 2008; Johnson et al., 2011; Schaffelke et al., 2011).

River runoff also transports agricultural pollutants such as pesticides (predominantly herbicides) into the GBR lagoon. High concentrations of herbicides have been detected in flood plume waters, which for periods of weeks exceed water quality guidelines for the protection of aquatic life (Lewis et al., 2009, 2011; Shaw et al., 2010; Brodie et al., 2011b; Kennedy et al., 2011).

Each of these is discussed in further detail below.

4.2.1. Terrestrial runoff of sediments

4.2.1.1. Stressor. Increases in suspended sediment and particulate nutrient loads from many rivers occurred from the 1860s onwards associated with the introduction of sheep and cattle and subsequent enhanced erosion (McCulloch et al., 2003; Lewis et al., 2007).

4.2.1.2. Impact. Changed turbidity and sedimentation regimes resulting from increased river sediment loading (Fabricius et al., in press) can lead to adverse impacts on coral and seagrass communities. High sedimentation rates have been attributed to:

- reduced coral settlement and juvenile mortality (Baird et al., 2003; Fabricius, 2005);
- reduced coral recruitment rates and coral biodiversity with many sensitive species being under-represented or absent in sediment-exposed communities (e.g. high sedimentation rates are related to low abundances of coralline algae in coral reefs) (Kendrick, 1991; Fabricius and De'ath, 2001); and
- physiological impacts from reduced light availability for benthic communities (Fabricius et al., 2011) which may reduce photosynthesis leading to slower calcification and thinner tissues (Anthony and Hoegh-Guldberg, 2003).

The most common cause of seagrass loss is the reduction of light availability. This may be from chronic and pulsed increases in suspended sediments and particles leading to increased turbidity (Schaffelke et al., 2005; Lambrechts et al., 2010) or chronic increases in dissolved nutrients, which leads to proliferation of algae, thereby reducing the amount of light reaching the seagrass (e.g. phytoplankton, macroalgae or algal epiphytes on seagrass leaves and stems) (Waycott et al., 2005). In addition, changes of sediment characteristics may also play a critical role in seagrass loss (Mellors et al., 2005).

4.2.1.3. Management response. Management of agricultural runoff in Queensland has been addressed through several initiatives. These include the GBR Water Quality Action Plan (Brodie et al., 2001b), Reef Water Quality Protection Plan (Reef Plan) (Queensland Department of the Premier and Cabinet, 2003, 2009), Reef Rescue (Australian Government, 2007) and the Queensland Government Great Barrier Reef Protection Amendment Act, 2009 (Reef Protection Package) (see Section 5.2 for further discussion).

4.2.1.4. Evaluation of management. While the actions in the Reef Plan were progressed to some extent in the first 5 years, it was not until 2008 when the Australian Government announced a major incentives program – Reef Rescue – to improve agricultural management practices, that large scale changes in catchment management were implemented. Reef Plan was also updated in 2009 (Queensland Department of the Premier and Cabinet, 2009) to include more specific targets and an additional overarching goal related to the long term health of the GBR (until this point ecological outcomes for the GBR had not been defined). The Queensland Government also introduced regulations to target sugarcane and grazing activities in priority areas to reduce the amount of sediment, nutrients and pesticides discharged to the GBR (Great Barrier Reef Protection Amendment Act, 2009). To date, measurable water quality improvements from these management responses are limited, and are difficult to measure in the context of time lags in the system (see Bainbridge et al. (2009a)). However, quantification of sediment loss from selected management practices that are being implemented as part of Reef Rescue incentive program and the Queensland regulations indicates that reductions in sediment runoff are likely in the next 5–10 years.

4.2.2. Terrestrial runoff of agricultural nutrients

4.2.2.1. Stressor. Large (often five to ten times the pre-fertiliser use value) increases in dissolved inorganic nutrient (nitrogen and phosphorus) loads from many rivers have occurred from the 1960s onwards associated with inorganic fertiliser use on sugarcane, grains, cotton and horticultural industries (Furnas, 2003; Waterhouse et al., 2011; Kroon et al., 2011). In addition large increases in particulate nitrogen and phosphorus loads have occurred since the development of beef grazing on many catchments from the 1850s associated with increased erosion due to reduced grass cover and woodland clearing (Kroon et al., 2011).

4.2.2.2. Impacts. The potential impacts of increased nutrient loading on water bodies are known as eutrophication (Duarte et al., 2009) and specifically in coral reef and tropical seagrass areas eutrophication is manifest as (Brodie et al., 2011a; Fabricius, 2011b) outbreaks of COTS (see Section 4.3 and 5.1), algal blooms (and reduced light for benthic communities), organic matter enrichment and benthic macroalgal dominance. In the GBR several of these impacts are already well established (Fabricius et al., 2005; Brodie et al., 2011a) and are seen as a major contribution to loss of coral cover on the GBR (Hughes et al., 2011) and to seagrass decline (Waycott and McKenzie, 2010; McKenzie et al., 2010).

Brodie et al. (2011a) undertook an assessment of nutrient enrichment in the GBR, and developed a set of criterion from which to describe the characteristics of eutrophic conditions in the GBR. Using these criteria, water quality data from the Reef Rescue Marine Monitoring Program (Schaffelke et al., 2009), and chlorophyll values (measured in Brodie et al., 2007; De'ath and Fabricius, 2008, 2010) strongly suggest that parts of the inshore GBR, south of Cooktown (refer to Fig. 1), and small areas of the mid-shelf and outer-shelf GBR could be considered eutrophic at certain times of the year.

4.2.2.3. Management response. Refer to Management Response for sediments, Section 4.2.1.4.

4.2.2.4. Evaluation of management. The success of Reef Plan in reducing loads of nutrients to the GBR, given its recent implementation, is uncertain (The State of Queensland, 2011; Brodie et al., 2011a,b). However the measures being taken in terms of improved management practices in agriculture have been shown to work at paddock scale in reducing runoff of suspended sediment, nutrients and pesticides (e.g. Thorburn et al., 2011) and if their further large scale implementation is successful we can anticipate reduced loadings of nutrients to the GBR but perhaps not sufficient to meet ecological restoration requirements (Kroon, 2011).

4.2.3. Terrestrial runoff of pesticides

4.2.3.1. Stressor. The presence of measurable concentrations of numerous pesticide residues in GBR coastal and marine water bodies, sediments and biota was noted from the late 1990s (e.g. Haynes et al., 2000). In more recent times pesticides, mainly herbicides, were found widely in rivers (Mitchell et al., 2005; Packett et al., 2009) coastal freshwater systems (Davis et al., 2008, 2011a; Bainbridge et al., 2009b; Smith et al., 2011), estuaries (Magnusson et al., 2010, 2011; Davis et al., 2011b) and inner (Lewis et al., 2009; Kennedy et al., 2011) and outer (Shaw et al., 2010; Kennedy et al., 2011) GBR lagoon waters. The concentrations found were often above Australian water quality guidelines and calculated to present to the species and ecosystems present in the area some risk (Davis et al., 2011a,b; Lewis et al., 2011). Kroon et al., (2010) estimated annual herbicide (of the commonly used PS II type) loads to the GBR of 30 t.

4.2.3.2. Impacts. The main herbicides of concern, the PS II type – atrazine, hexazinone, diuron, ametryn, tebuthiuron and simazine, have a mode of action to suppress photosynthesis in all plants. This suppression of photosynthesis for seagrass, coral zooxanthellae, macroalgae and microalgae reduces the food available to the plant and may also in the longer term change plant species composition in a particular ecosystem (e.g. Magnusson et al., 2011).

4.2.3.3. Management response. Pesticide management in Australia is enforced through a combined effort of the Australian Government regulator, the Australian Pesticide and Veterinary Medicine Authority (APVMA), and the individual State Governments. It is widely believed that the APVMA is ineffectual in managing pesticides (King et al., in press) as shown by numerous exceedances of Australian water quality guidelines in water bodies around Australia for chemicals such as atrazine (and many others). The situation is particularly serious for water bodies in the GBR region, an international icon, found frequently contaminated (see references above).

In the GBR region itself pesticide use has been more strictly regulated through the mandatory Queensland Reef Protection Package (Brodie et al., 2011b) which requires the introduction of certain improved practices of sugarcane farmers in GBR catchments. In addition the Australian Government Reef Rescue initiative provides funding for farmers to improve management practices for pesticide use.

4.2.3.4. Evaluation of management. While the success of pesticide management through APVMA is judged to be low (King et al., in press) the Authority is now being reviewed with the aim of bringing the regulatory and management regime to international standards such as in the European Union. It is too early to assess the success of the Queensland GBR-specific regulatory approach or the incentive-based Reef Rescue initiative as both only commenced in 2008–2009. However the improved practices being promoted in both programs are known to reduce pesticide loss from the paddock (e.g. Silburn et al., 2011) and if continued to be funded and implemented should reduce pesticide loading to the GBR substantially.

4.3. COTS

4.3.1. Stressor

Crown of thorns starfish (*Acanthaster planci*) are a corallivorous starfish which have had three major population outbreaks over the last 50 years (Fabricius et al., 2010) approximately over the periods 1962–1976; 1978–1990; 1993–2005 (each period of outbreaks is referred to as a 'wave'). Each wave of outbreaks has severely reduced coral cover on the GBR especially in the central section. The outbreaks appear to be recent phenomenon or have become more frequent in recent times. Human causes suggested for the population outbreaks which are currently held include removal of predators (especially fish) (Sweatman, 1995) and/or increased larval survivorship due to increased phytoplankton food stocks associated with nutrient enrichment (Fabricius et al., 2010; Brodie et al., 2011a). The last wave of outbreaks wound down in 2005 and we have been in a low density population interlude. However since early 2011 a new population of starfish has been observed off Cairns (K. Fabricius pers. com.), the initiation area for the other three outbreak waves, and this is now believed to be the beginning of the fourth wave.

4.3.2. Impacts

Crown of thorns starfish population outbreaks have been the greatest external source of coral mortality on the GBR over the past 50 years. Osborne et al. (2011) notes that in their study COTS were responsible for 36.7% of the coral damage above all other causes including storms (33.8%), disease (6.5%), bleaching (5.6%) and unknown or multiple causes (17.4%).

4.3.3. Management response

No direct management response has been taken to prevent COTS outbreaks and the consequent coral damage. However small scale controls at prime tourism locations have been implemented to keep COTS away from the sites and these have been moderately successful (GBRMPA, 2009a). All other mitigation strategies involve reducing nutrient discharge from the land (Section 4.2.2) and reducing loss of predators through no-take zone implementation under the Marine Park rezoning in 2004.

4.3.4. Evaluation of management

COTS outbreaks continue to be a threat to the GBR. There is some evidence that the increase in the area of no-take zones in 2004 has had significant success as COTS numbers on closed reefs are lower than on reefs open to fishing (Sweatman, 2008; McCook et al., 2010). Site specific management (through removal) has been successful at a local scale, although it is very labour intensive. With the initiation of the fourth wave of outbreaks now confirmed it is clear that water quality management under Reef Plan (implemented really in 2008) has not had time to prevent further outbreaks. However further water quality management will be critical to prevent a fifth wave in the future, assuming such a fifth wave is even possible given the probable low coral cover (food for the adult COTS) likely to be available in about 2025–2030.

4.4. Shipping impacts

4.4.1. Stressors

Shipping and associated services are major activities in the GBR Marine Park. Total ship traffic has increased steadily in the GBR since the 1960s associated with container ship traffic and mineral product export. Approximately 6,000 ship movements of large vessels in excess of 50 m in length occur in the GBR and Torres Strait every year (GBRMPA, 2009a), most of which transit the inner route. Since 1987 over 700 shipping or marine pollution incidents have been recorded by the GBRMPA in the Marine Park; 33 of these were considered to be significant (Aston, 2006). There has not been a major pollution consequence within the region since the Oceanic Grandeur oil spill in the Torres Strait in 1970, however, several major groundings have occurred (e.g. the Doric Chariot in 2002 at Piper Reef which involved a large remediation program). There are 10 major ports operating in the GBR region for the transport of coal, sugar, iron ore, timber, oil and general cargo with the largest facilities in Townsville, Gladstone, Mackay (Hay Point) and Rockhampton.

4.4.2. Impacts

Potential environmental risks associated with shipping activities include dredging, oil spills or discharge of oil, chemicals and cargo, garbage and marine litter, toxic effects of antifouling paints, discharge of ballast water, introduction of pest species and physical damage from groundings and anchoring.

4.4.3. Response

The management of shipping activities in the GBR is complex due to the predominately international nature of the industry. The management framework for shipping activities is determined by a series of international conventions that are implemented through Australian law (including the United Nations Convention on the Law of the Sea 1982 and the International Convention for the Prevention of Pollution from Ships 1973 and the 1978 Protocol – MARPOL 73/78). To support this, the GBRMPA has implemented a range of activities to manage shipping through the Great Barrier Reef Marine Park Act (1975) and Regulations. These include compulsory pilotage in certain areas, restrictions on certain activities, wreck removal and penalties for causing environmental damage. In addition, the zoning plan and Plans of Management regulate entry and use of areas within the Marine Park and development and promotion of best environmental practices for the industry.

4.4.4. Evaluation of management

GBRMPA has implemented a range of activities to manage shipping in the Marine Park with a relatively high degree of success. Recent amendments to the legislation have also addressed vessel sewage discharge, and provisions for full cost recovery for the environmental rehabilitation of any damage associated with shipping incidents in the Marine Park.

4.5. Fishing and harvesting

4.5.1. Stressors

Finfish fishing increasing through the 20th century; refer to Section 3.4 regarding current status. Fishing in the GBR represents an important commercial contribution to the regional and national economy, and is a popular recreational activity (representing 40% of the total product).

4.5.2. Impacts

Overfishing can result in the inability of fish populations to recover and hence reduced biodiversity of fish population and coral reef ecosystems, extraction of top order predators (e.g. sharks), incidental catch of protected species and other species of conservation concern, illegal fishing (foreign and domestic) and death of discarded (bycatch) species. The ecosystem level impacts of fishing are not well understood.

4.5.3. Management response

Fishing activities are required to comply with Marine Park zoning and the Queensland's Department of Agriculture, Fisheries and Forestry manages the state's fish, mollusc and crustacean species. In the late 1990s, less than five percent of the Marine Park was within "no-take zones", that is, zones that prohibit the removal of resources by activities such as fishing or collecting. The rezoning of the Marine Park in 2004 resulted in over 30% of the Marine Park in no-take zones, with a large part of this area primarily in the remote northern sector of the GBR (Day, 2011).

Current approaches to management include: Size and bag limits; limited entry (restrictions in the number and size of boats which can operate in the fisheries); licence holders are allocated only a certain number of nights they can fish each year in the form of tradeable effort units; caps on effort; gear restrictions (for example, vessel length, net head rope length and mesh restrictions apply depending on the areas of operation); numerous and extensive permanent area closures for some fisheries; seasonal closures; daytime closures in some fisheries and locations to reduce any interactions with recreational users; mandatory use of turtle exclusion devices (TEDs) and bycatch reduction devices (BRDs) in the East Coast Otter Trawl Fishery; a range of by-product harvesting protection arrangements; and logbooks, surveillance by fisheries enforcement officers (the Queensland Boating and Fishing Patrol) and remote tracking of trawl effort and compliance of fishing operations.

4.5.4. Evaluation of management

Several success stories have been reported since the increase of no-take zones in 2005. For example, coral trout numbers have increased by 31–75 percent after about two years on the majority of reefs that were closed to fishing (Russ et al., 2008). This is further supported by long term experiments prior to the rezoning which clearly demonstrated the benefits of no-take zones over a period of ten years (the Effects of Line Fishing Experiment, Mapstone et al., 2004). Benefits have also been demonstrated for several other species within no-take zones including commercial species in the coral reef fishery (Williamson et al., 2004; Cappo et al., 2011) and sharks (Ayling and Choat, 2008; Huepel et al., 2010). These benefits have flow on effects across populations with fish densities almost two times higher in no-take reefs (Mapstone et al., 2008). However the effectiveness of no-take zones on the other species on reefs besides the targeted fish themselves has been more equivocal.

Myers and Ambrose (2009) found that in comparing benthic hard coral cover between reefs closed to fishing with those open the main factor influencing the cover was the disturbance history associated with cyclones and COTS outbreaks. Protected status only had a small effect in the absence of acute disturbance. Sweatman (2008) also noted that COTS numbers on no-take reefs were lower than those on reefs open to fishing but the effect was small at this stage (reefs having only been closed since 2005 while the study was carried out in 2007).

Trawl fishing management has had demonstrated success with fishing intensity now low at the scale of the GBRWHA with few areas trawled more than a couple of times a year (Grech and Coles, 2011). The decline in effort in the fishery as a result of the rezoning has resulted in a trend to fish only in the most productive areas which is likely to continue. This provides effective protection to most fishing grounds without any further legislative or management intervention (Grech and Coles, 2011).

4.6. Hunting and bycatch

4.6.1. Stressors

Hunting of dugong by aboriginal people had occurred for thousands of years but in the late 19th and early 20th century dugongs were hunted commercially for meat, medicinal oil, hides and tusks (Daley et al., 2008) and similarly turtles were hunted for meat. Whales which spend part of each year in the GBR (particularly humpbacks) were hunted to almost extinction in the southern oceans and on the Queensland coast in the 19th and first half of the 20th century. Incidental 'catch' of dugong and turtle in fishing nets (both set gill nets and prawn trawling nets) and swimmer-protection shark nets continued in the latter half of the 20th century (e.g. Marsh et al., 2005).

Certain species of holothurians (*bêche-de-mer*) were collected on a large scale for the export food industry in the 19th and 20th century and certain molluscs (clams, *Trochus* and others) collected for meat, button manufacture and other uses (Uthicke et al., 2004).

4.6.2. Impact

Large population declines of whales, dugong and turtles resulted from both commercial hunting and incidental catch, for example for dugong see Marsh et al. (2005). Fished holothurians and mollusc species were also severely reduced in population size but have now substantially recovered after fishing ceased or was more strictly managed.

4.6.3. Management response

Controls via fisheries legislation on the commercial hunting of dugong and turtles occurred in the late 19th century (e.g. discussed in Daley et al. (2008)) by the Queensland Government. In the last few decades incidental catch of turtles and dugong in fishing nets was addressed through the establishment by GBRMPA of Dugong Protection Areas (DPAs) in the late 1990s (Marsh et al., 1999). In addition shark nets were largely replaced by baited lines which accidently catch far fewer animals. Whaling largely ceased in 1962 through cooperative international action. Turtle bycatch in prawn trawling has been addressed through the introduction of mandatory use of turtle exclusion devices (TEDs) and bycatch reduction devices (BRDs) in the East Coast Otter Trawl Fishery (Grech and Coles, 2011).

4.6.4. Evaluation of management

In recent times the set up of DPAs, the trawl management plan, the Marine Park rezoning in 2004 and the reduced numbers of shark nets have likely led to reduced mortality of dugong and turtles as bycatch (Grech and Coles, 2011). However the already parlous state of dugong populations and to a lesser extent some turtle species means that such success may be ephemeral in the face of major seagrass loss events such as occurred in 2009 and 2011 (see Section 3) adding to the slow decline of seagrass, at least in the central GBR (McKenzie et al., 2010; Waycott and McKenzie, 2010). However the success of the international measures to protect whales is evident in the increased numbers of, in particular, humpback whales moving through the GBR (Grech et al., 2011).

4.7. Tourism

4.7.1. Stressors

Commercial marine tourism is a major commercial use of the GBR, beginning in the 1890s (GBRMPA, 2009a). In the early 1980s, tourism numbers to the GBR were increasing by about 30 percent annually (Skeat, 2003). Tourism numbers since 1994 show relatively stable visitation with almost 1.4 million visitors in 2008 (GBRMPA, 2009a). In 2006/07, the value of tourism in the GBR and its catchment was approximately $5.1 billion (Access Economics, 2008).

4.7.2. Impacts

The impacts associated with tourism activities in the GBR are relatively minor (GBRMPA, 2009a), although some activities can result in localised impacts. The best studied of tourism impacts are those associated with pontoons, anchoring and diving. A series of extensive impact assessments has found that impacts of pontoons on the surrounding reef areas are minimal, apart from the 'footprint' under the pontoon and its moorings (Harriott, 2002). Anchoring of both tourist and recreational boats can be a significant local issue in heavily visited sites in the Marine Park. Anchors and anchor chains are capable of breaking multiple coral colonies at each drop.

The impacts of diving and snorkelling have been well studied both in Australia and overseas (Harriott, 2002). Most divers do not break corals, but a small percentage of divers who swim too close to the coral may break many coral branches on each dive. Fragile branching corals are the most susceptible to breakage. Internationally, the carrying capacity of coral reefs has been determined to be about 5000 divers per site per year (e.g. Hawkins and Roberts, 1997; Jameson et al., 2007). Above this level of dive intensity, environmental deterioration has been noted. Because of the large choice of dive sites available, no GBR sites currently appear to approach this level of diving activity. Some studies of snorkellers have detected larger numbers of broken corals in active snorkel areas, including snorkel trails, but the level of breakage levelled off quickly and did not increase over time.

4.7.3. Management response

Tourism is managed in the GBR by a combination of zoning plans, plans of management of intensively used sites, vessel and group size limits, codes-of-practice and operational policy, and permits. Activities associated with construction activity and structures are regulated under permit requirements. Management of anchoring impacts includes installation of both private and public moorings, 'no-anchor' areas in heavily used places such as some of the Whitsunday Islands, and an education program for boaters, promoting codes-of-practice. Recommendations for reducing diver and snorkeller impacts, such as dive briefings and careful selection of sites have been taken up by the diving industry.

4.7.4. Evaluation of management

Targeted management in the 1990s has addressed earlier concerns associated with increasing visitation, and various accreditation schemes are in place to encourage operators to achieve a high standard. Tourism activities are considered to be generally low risk to the GBR.

4.8. Mining and oil exploration

4.8.1. Stressors

In the late 1960s and early 1970s there were plans to mine limestone from reefs in the GBR and also for exploratory drilling for oil (Lawrence et al., 2002). These proposals led to an intense controversy in which the potential negative environmental impacts of these activities were highlighted. In particular the possibility of oil spills was emphasised.

4.8.2. Impact

The negative effects of oil on corals, coral reefs and mangroves were known to some extent by 1970, although to nothing like the understanding we now have. The negative impacts of coral mining were also evident although arguments as to the environmental 'safety' of mining dead coral adjacent to living coral reefs was still debated.

4.8.3. Management response

The controversy led to a joint Australian and Queensland Governments plan to set up a large multi-use MPA (the GBR Marine Park) with a specific Federal legislation (Great Barrier Reef Marine Park Act, 1975) and active collaboration in management with the Queensland Government which was finally established in 1975. The Act banned all forms of mining within the boundaries of the Marine Park.

4.8.4. Evaluation of management

As mining is banned the Act can be said to be totally successful in protecting the GBR (inside the Park) from the impacts of mining in the Park. However the status of that part of the GBR outside the park (i.e. parts of the GBRWHA inshore of the Park and the portion in Torres Strait) and mining is less clear. In addition the potential impacts on the GBR of mining and its associated activities on the catchment of the GBR are not covered in the Act (except through Section 66(2)(e)). Contaminant runoff from mining was not covered in Reef Plan (2003 and 2009) and it is uncertain yet whether it will be covered in the next potential iteration of Reef Plan in 2014 (Brodie et al., 2011b; J. Brodie unpublished data). The management of mineral export port developments is also controversial at present.

4.9. Climate change

4.9.1. Coral bleaching

4.9.1.1. Stressors. Over the last 3 decades sea surface temperature across the GBR has increased by 0.4 °C (Lough, 2007) associated with global climate change (Lough and Hobday, 2011). It is likely that temperature will increase by another 2 °C by 2100 (GBRMPA, 2009a).

4.9.1.2. Impacts. Increased temperatures over a period of several days (with an interaction between the number of days and the temperature above a threshold) lead to coral bleaching and some subsequent mortality (Berkelmans et al., 2004). Bleaching events have become both more frequent and more intense over the last 25 years on the GBR and globally on coral reefs (Berkelmans et al., 2004; Hoegh-Guldberg et al., 2007; Anthony et al., 2011; Veron, 2011). Bleaching and a degree of subsequent mortality are seen as among the main drivers of the loss of coral cover on many reefs of the GBR over the last 20 years (Hughes et al., 2011). Reef wide bleaching occurred in 1998 and 2002 (Berkelmans et al., 2004) with further more localised events in, for example, 2006 (Diaz-Pulido et al., 2009). Impacts in the long term (Hoegh-Guldberg et al., 2007) are predicted to lead to loss of coral through annual bleaching, carbonate dissolution (associated with ocean acidification – see 4.9.2) and insufficient recovery time (Pandolfi et al., 2011).

4.9.1.3. Management response. Global action is required to address issues associated with increasing surface temperatures. As it is extremely unlikely sufficient action will be taken to reduce greenhouse gas emissions in time to prevent severe effects on the GBR, only local actions to make the GBR more resilient to climate change have been implemented (McCook et al., 2010) and recommended in the future (Hughes et al., 2010). These actions include managing other local impacts such as water quality (Carilli et al., 2009; Maynard et al., 2010) and fishing effects. Our current reluctance to manage climate change means the outlook is for increasing temperatures and further coral mortality into the future (Pandolfi et al., 2011).

4.9.1.4. Evaluation of management. To date international agreements have been insufficient to make a substantial change to carbon dioxide concentrations (Chapman, 2011). Major changes (phase shifts) in species composition, biodiversity and biological functioning are expected to occur on the GBR over the next 50 years despite the implementation of local and regional actions aimed at improving reef resilience.

4.9.2. Ocean acidification

4.9.2.1. Stressors. As carbon dioxide concentrations rise in the atmosphere due to human inputs more carbon dioxide dissolves in the ocean, lowering pH (Raven et al., 2005). This acidification effect is known to reduce calcification in marine organisms with a calcium carbonate skeleton (Doney et al., 2010) such as corals, many molluscs, coralline algae, foraminifera, and is seen as one of most serious threats to marine ecosystems associated with increased carbon dioxide in the atmosphere (Doney et al., 2010; Pandolfi et al., 2011). Whether the organism has a calcite or aragonite skeleton also changes the degree of effect. Ocean acidification also disrupts the innate ability of fish to detect predator using olfactory (smell) cues (Dixson et al., 2010).

4.9.2.2. Impacts. In the GBR declines of 21% in calcification have been noted in corals from northern GBR reefs between 1998 and 2003 (Cooper et al., 2008). At the whole of GBR scale, calcification declined by 14.2% at 69 reefs from 1990 to 2005 (De'ath et al., 2009). Direct evidence of the decline in ocean pH of between 0.2 and 0.3 units from the 1940s to the present is also measured in corals from the central GBR (Wei et al., 2009). These results are similar to those now being noted in other parts of the globe in both corals (Castillo et al., 2011) and other organisms (Doney et al., 2010).

4.9.2.3. Management response. Global action is needed to reduce greenhouse gas emissions and keep carbon dioxide concentrations below 350 ppm (Veron et al., 2009), probably an already out of reach target.

4.9.2.4. Evaluation of management. The likely success of management in the long term is poor given increasing levels of carbon dioxide in the ocean.

4.9.3. Bleaching and water quality interactions

4.9.3.1. Stressor. Strong interactions also exist between poor water quality and the susceptibility of corals to bleaching in high temperature periods (Carilli et al., 2009; Wooldridge, 2009;

Wooldridge and Done, 2009; Wooldridge et al., 2011). The presence of elevated nitrate concentrations leads to greater susceptibility to bleaching (Wooldridge, 2009) and this factor is considered to have contributed to greater severity in some locations in the major events of 1998 and 2002 on the GBR. Contaminants like copper can also reduce the tolerance of coral larvae to thermal stress (Negri and Hoogenboom, 2011), and it has been shown that the presence of herbicides (diuron, atrazine and hexazinone) increase the vulnerability of corals, and to a lesser extent coralline algae, to the negative effects of elevated temperatures on photosynthesis (Negri et al., 2011).

In the last few decades a variety of coral diseases have affected coral reefs globally. Human causes attributed to exacerbating the increased incidence of coral disease include thermal stress associated with climate change (Bruno et al., 2007) and poor water quality (Bruno et al., 2003) or both (Harvell et al., 2007). On the GBR, increasing incidence of many of the forms of coral disease are also being observed and coral disease is now seen as one of the major factors leading to loss of coral cover (Willis et al., 2004; Osborne et al., 2011) believed to be related to poor water quality (Haapkyla et al., 2011) and thermal stress (e.g. Boyett et al., 2007).

4.9.3.2. Impacts. Spatial analysis of bleaching response in the GBR shows a strong correlation between coral bleaching and areas of poor water quality, particularly elevated nitrogen. Laboratory studies indicated that more serious bleaching effects are predicted in areas of significant herbicide concentrations but these effects have not yet been detected in the field.

4.9.3.3. Management response. Current management responses to reduce loads of nutrients and herbicides to the GBR (e.g., Reef Plan; refer to Section 4.2) will align well with the only possible action in this area. Other measures to improve reef resilience will also be important.

4.9.3.4. Evaluation of management. The relationships between bleaching and water quality have only recently been published in the scientific literature. It is likely that it will be several years before the effect of current management responses to water quality and other stressors would be evident.

4.10. The influence of severe weather events

In the period from September 2010 through to November 2011 a series of extreme events occurred on the GBR. With the very strong La Nina beginning in mid 2010 extraordinary rainfall, both intense and prolonged, occurred across eastern Queensland. This produced record river flows (Table 1) in many rivers, especially in the southern half of the GBR but also above average throughout the GBR. In the Burdekin River (refer to Fig. 1) the Burdekin Falls dam flowed over the spillway for more than 300 days and the discharge at the mouth was the third highest in the instrumental record (approximately 35 million m^3). This followed greatly above average flows (mean approximately 8 million m^3) in the Burdekin River in both 2008 (26 million m^3) and 2009 (30 million m^3). To the south, the Fitzroy River had its largest flow in the instrumental record (approximately 38 million m^3) following large flows in 2008 and 2010, while the Burnett River had its first substantial flow (8 million m^3) for 20 years and about eight times the mean (Table 1). The Mary River had its largest flow for 10 years (Pickersgill et al., 2011). In all cases the instrumental record extends back about 80 years. Rivers in the Wet Tropics to the north of Townsville had above average flows by factors of x2–3 but not record flows. Low salinity water, with elevated concentrations of suspended sediment, nutrients and pesticides (M. Devlin, unpublished data) extended more than 50 km offshore for 1500 km along the coast from Hervey Bay to Princess Charlotte Bay (Fig. 2) and persisted in many places for several months. These unique combined flows (at least in the historic record) followed another series of acute events in 2009 including record rainfall in the Townsville area, an extended period of freshwater influence on reefs and seagrass beds from Townsville to Cairns, large river flows in the Burdekin River (Table 1) and independently the passage of Category 5 Tropical Cyclone Hamish through a considerable part of the southern offshore GBR reefs in March 2009 (GBRMPA, 2009a).

In February 2011 Category 5 Tropical Cyclone Yasi (Fig. 3) the largest in area of any ever observed and documented in Queensland, crossed the GBR between Cairns and Townsville. Extensive damage to coral and seagrass occurred in a 300 km wide band right across the continental shelf (GBRMPA, 2011). Coral damage was reported across an area of approximately 89,090 km^2 of the Marine Park (about 26% of the total). In total, approximately 15 percent of the total reef area in the Marine Park sustained some coral damage and six percent was severely damaged. It can be estimated that Cyclone Yasi by itself accounted for a 2% loss in coral cover across the GBR (GBRMPA, 2011).

The combined effects of the long period of low salinity, high contaminant concentration water (documented in Devlin and Brodie (2005), Devlin and Schaffelke (2009), Devlin et al. (2001, in press)) and physical damage from Cyclone Yasi has caused severe coral loss (GBRMPA, 2011) and devastating loss of seagrass (McKenzie and Unsworth, 2011; Coles et al., 2011) along the GBR coast from Hervey Bay to Cairns. Importantly these impacts come on top of declining seagrass health in the central GBR (see Section 3, McKenzie et al., 2010) and general coral decline (see above). Dugongs died in record numbers in Queensland through 2011 (Department of Environment and Resource Management, 2011) with 168 reported deaths reported between January and October 2011, compared to 73 in 2010, 47 in 2009 and 35 in 2008. This is believed to be due mainly to starvation associated with the loss of seagrass (Bell and Ariel, 2011). In the period from January to October 2011 approximately 1100 turtles (mostly green turtles) have been reported as stranded on the Queensland coast, compared with 624 in the same period in 2010, 715 in 2009 and 645 in 2008 (Department of Environment and Resource Management, 2011). This is not considered such a threat to the overall turtle populations as is the case for dugongs given the larger and better condition of turtle populations although this varies between the various species.

The combination of these acute impacts with the chronic stresses of poor water quality and climate change factors may tip these systems over the thresholds for a complete phase shift (Elmhirst et al., 2009). While it is impossible to definitely attribute the extreme events in Australia (and the rest of the world but see, for example, Lough and Hobday, 2011; Rahmstorf and Coumou, 2011) over the last few years to climate change they do give us potential understanding of the future in the sense that more frequent intense cyclones and correlated rainfall and runoff events are predicted by the climate change forecasting (Knutson et al., 2010). The implications of frequent intense events for the management and future ecosystem health of the GBR will be discussed in Section 6.

5. Scientifically-based management for the GBR

As indicated in the previous sections, management of the GBR has been largely driven by strong scientific evidence. Research on coral reefs has been intensive globally due to their aesthetic and visual beauty, their recognised high biodiversity, increased SCUBA capability after 1950 and the perceived threats from human activity (Richmond and Wolanski, 2011). An expedition of the British

Table 1
Annual flows in rivers from 2002 to 2011, in 10^6 m^3. The degree of magnitude of the flow above the long term average is show in colours: no colour = 0–1.5 times; yellow = 1.5–2 times; orange = 2–3 times; red = >3 times. Combined river flow increases greatly in the latter part of time period. Note: *Indicates where the long term average flow is calculated on a limited dataset.

	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Normanby*						1.74	3.65	2.35	2.94	5.94
Daintree		0.13	1.43	0.49	1.25	0.72	0.87		1.22	1.59
Barron	0.17	0.11	0.95	0.38	0.75	0.41	1.61	0.77	0.50	1.83
Mulgrave	0.18	0.33	1.13		0.94	0.74	0.93	0.67	0.68	1.32
Russell	0.43	0.62	1.35	0.99	1.28	1.28	1.09	1.13	1.22	1.67
North Johnstone	0.66	0.82	2.30	1.45	2.16	2.07	1.86	1.93	1.83	3.35
South Johnstone	0.35	0.31		0.54	1.01	0.89	0.79	1.02	0.71	1.58
Tully	1.21	1.44	3.28	2.20	3.62	3.95	3.20	3.60	3.09	4.18
Herbert	0.93	0.69	3.30	1.19	3.99	3.99	3.34	9.47	3.17	11.17
Burdekin	4.49	2.09	1.52	4.33	2.20	9.77	27.50	29.95	7.95	34.63
Proserpine	0.02	0.02	0.01	0.02	0.02	0.04	0.08	0.07	0.05	0.35
O'Connell	0.09	0.02		0.08	0.08	0.17	0.23	0.17	0.31	0.58
Pioneer*						0.88	1.35	0.91	1.43	2.31
Fitzroy	0.58			0.92	0.68	1.06	12.05	2.03	11.67	38.06
Burnett*	0.11	0.52	0.22	0.14	0.07	0.03	0.02	0.02	1.03	7.08

Museum to Low Isles (northern GBR) in 1928 created a precedent for long term integrated research and by the 1970s extensive research programs focussing on, for example, the COTS, coral reef fish behaviour and pollution effects on reefs had been established. Since the establishment of the GBRMPA in 1975 there has been a strong ethic of using research and monitoring results to guide and set policy. This was strongly seen in the use of science to inform the initial zoning of the GBR – the first large scale use of multiple use of zoning for an MPA (Day, 2002). Later the intensive research and monitoring programs such as those established to understand the COTS and water quality issues (discussed below) highlighted the effort expended to ensure the management of the GBR was based on the best available science.

From the early stages of Marine Park management, research into the methodology of reef management was also prominent with many of the methods developed after 1975 such as spatially optimal zoning strategies incorporated into the establishment of the Marine Park (reviewed in Day (2002)). With such a large area to manage, the initial priority was for the establishment of zones with legally mandated allowable (and forbidden) uses. The zoning covered tourism activities, fishing and recreational activities through permits. The multiple-use zoning system provides higher levels of protection from the above activities for specific areas, while allowing many uses to occur in other zones. These other uses include shipping, commercial fishing, recreational fishing, aquaculture, tourism, boating, diving, developmental works including dredging, and military training (Day, 2011). The zoning required a lengthy period to establish and the initial zoning was not completed until the 1990s. Zoning and permits could not, of course, be used to manage external (to the Park) impacts such as terrestrial pollutant runoff, shipping spills or global oceanic or atmospheric changes (Kelleher, 1994).

In essence the steps towards effective management of a GBR coastal ecosystem defined by Boesch (1996) (refer to the Introduction) have been followed closely for the management of the GBR. For Step 1, *sustained scientific investigation, responsive to but not totally defined by managers*, the following two case studies illustrate how scientific evidence was built up over an extended period prior to action. For Step 2, *clear evidence of change, the scale of the change and the causes of the change*, long term monitoring programs (Section 3.1) showed, for example, loss of coral cover (Bellwood et al., 2004; Sweatman et al., 2011). For Step 3, *some level of consensus among the scientific communities associated with various interests*, using the water quality issue well supported scientific consensus statements were published in 2002 (Williams et al., 2002) and 2008 (Brodie et al., 2008a). For Step 4, *the development of models to guide management actions*, a range of models have been developed and used to assist management. These include catchment models to estimate pollutant loading (e.g. McKergow et al., 2005a, 2005b), models explaining COTS population outbreaks in response to forcing functions (Fabricius et al., 2010), hydrodynamic models to explain and predict larval connectivity (Bode et al., 2006) and predictive integrated models addressing the future condition of the GBR (e.g. Wolanski et al., 2004; Brodie et al., 2011c). For Step 5, *identification of effective and feasible solutions to the problems*, taking again the water quality example intensive research has helped to develop a suite of land management improved practices which are both, at least, economically neutral for farmers and at the same time reduce pollutant loading to the GBR (e.g. van Grieken et al., 2011a, b; Webster et al., in press; Thorburn et al., 2011). What isn't fully considered in this 'perfect' scenario of process is the long timeframes necessary to get through the steps with the ultimate result that the management response is 'too little, too late'.

To examine in more detail the interaction of research and a management response we will use two examples, those of crown of thorns starfish and terrestrial pollutant runoff.

5.1. The COTS story

Coral-eating COTS have caused widespread damage to many coral reefs in the Indo-Pacific over the past five decades as population 'explosions' have occurred at regular intervals (Birkeland and Lucas, 1990). The cycles of outbreaks on the GBR have occurred from 1962 to 1976, 1979 to 1991, 1993 to 2005 (Brodie et al., 2005) and appear to be starting again in 2011. Outbreaks

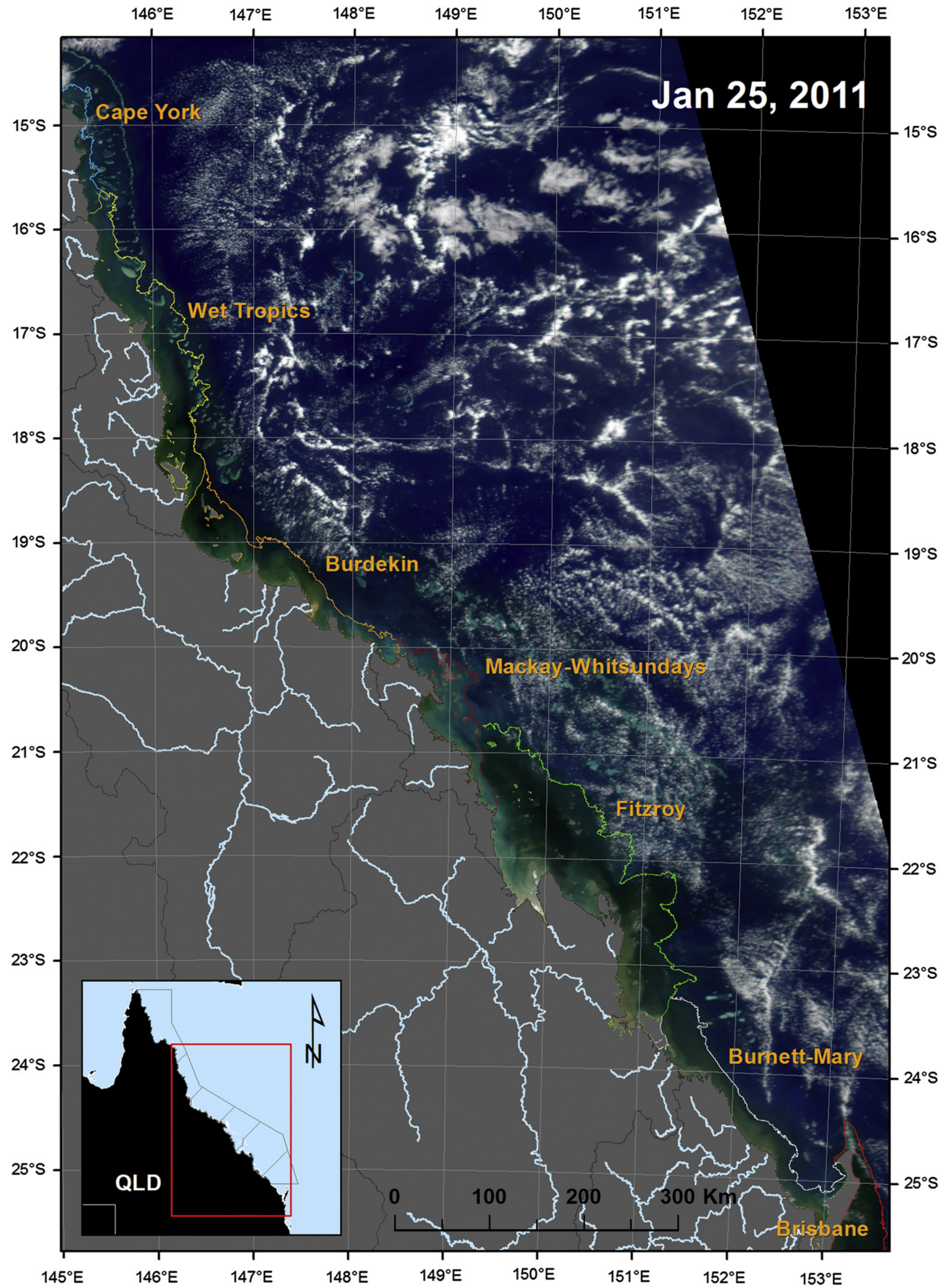

Fig. 2. Flood plumes in GBR waters on the 25th, January, 2011. Plumes from individual basins are identified (e.g. Burdekin) and the approximate outer boundaries of the plumes denoted by coloured lines. Plumes extend from 26°S to 15°S.

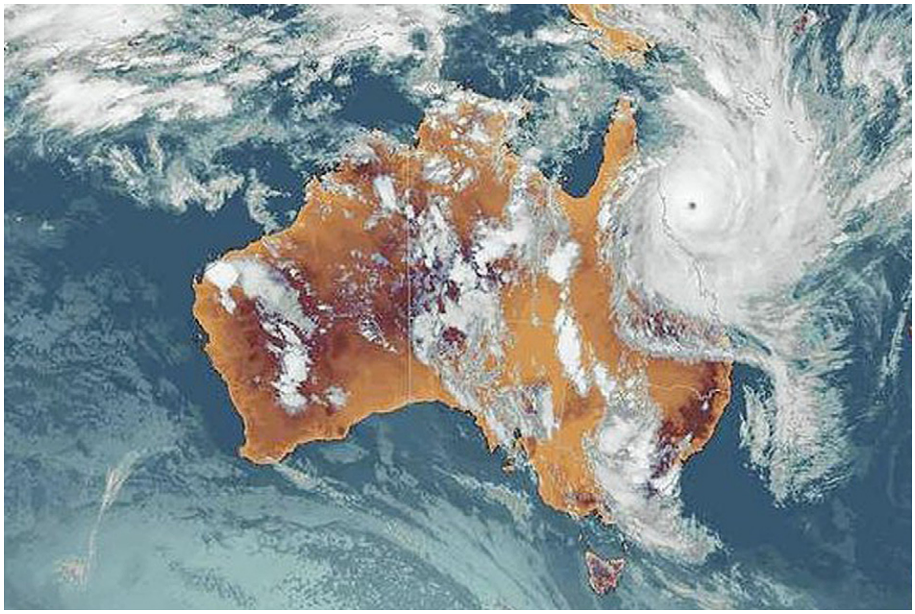

Fig. 3. Cyclone Yasi crossing the Queensland coast through the GBR in February 2011.

may have occurred before 1962 but were not observed or reported. Each cycle appears to have begun in areas adjacent to the Wet Tropics region in the northern GBR. The impact of outbreaks on the GBR is a major concern to the multi-billion dollar tourism industry. Over a number of years, there was an outbreak on reefs between Cairns and the Whitsundays which was estimated to cost tourism operators, and the Queensland and Australian Governments about $3 million a year for control measures (Waterhouse et al., 2009).

The cause (or causes) of the outbreaks has been, and remains, a controversial issue and originally there were several opposing views as to the origin of the outbreaks. One view postulates that population outbreaks are a natural phenomenon due to the inherently unstable population sizes of highly fecund organisms such as *Acanthaster planci*. Alternative views are that outbreaks are due to anthropogenic changes to the environment of the starfish with a range of possible anthropogenic causes including: removal of adult predators (particularly fish and gastropods; Sweatman, 1995); changes to population structures of predators on larval and juvenile stages, caused by pesticide pollution; destruction of larval predators, particularly corals, by construction activities on reefs; and larval food supply (phytoplankton) enhancement from nutrient enriched terrestrial runoff (Brodie, 1992). The terrestrial nutrient runoff hypothesis for the GBR was also postulated by Bell and Gabric (1991).

From the 1960s a large and expensive research and monitoring program has been carried out on the GBR to resolve the issues of the causes (and possible control mechanisms). The research program was particularly intensive between mid 1970s and late 1990s while monitoring of COTS numbers is ongoing to 2012 (and likely beyond). While much was learned about the ecology of COTS and their interaction with corals it was only finally after the years 2000 that more definite answers were produced that seemed to prove that terrestrial runoff of nutrients was the primary cause of outbreaks (Brodie et al., 2005; Fabricius et al., 2010) with some interaction with predators on some stage of the starfish's life also possible. Thus the management response of reducing nutrient discharge from the land 'folded' into the water quality management story (below) as a particular priority (Brodie et al., 2011a).

There are few options to manage outbreaks of COTS once they have started apart from having a comprehensive regime in place that maintains healthy and resilient reef ecosystems and their full suite of predatory species. Several techniques for specific site controls have been developed to reduce starfish numbers through direct interventions however they are labour intensive and expensive, and are only practical in small areas. Because starfish can quickly move from one area to another, control of a specific area must be an ongoing effort and may be required on a daily basis. The recommended control method involves trained divers injecting sodium bisulfate solution (dry acid which is non-toxic to other marine life) into the starfish, which kills them within a few days. During active outbreaks, operators may need to inject 200 to 500 starfish every day in an effort to keep selected sites free of starfish (http://www.reef.crc.org.au/discover/plantsanimals/cots/cotscontrol.html).

The sometimes challenging interactions between science and management can be highlighted for the COTs issue through recent events. Although Fabricius et al. (2010) already noted the possibility of a new initiation of outbreaks in the Cairns area due to large and early river floods from the Burdekin and Wet Tropics rivers in January 2008 and 2009 no action was taken to initiate more and finer scale surveys to detect the early stage of this process. It has now been confirmed (K. Fabricius, pers. com.) that new outbreaks did occur in the 2008/09 period from surveys carried out in late 2011 which detected approximately 2–3 years old animals. Early detection of these juveniles may have allowed some preventative action to slow or reduce the spread of the outbreaks. However as COTS had 'fallen off the radar' of management agencies (as there had been no major outbreaks for several years) nothing was done at the time. More recently (late 2011–early 2012) with the detection of outbreaks on many reefs in the Cairns area by tourism operators, scientists doing unrelated research, and finally the results of a deliberate survey at Briggs Reef, attention is once again being given to the COTS issue. The Briggs Reef survey detected both 2–3 years old animals as well as a population of less than one year olds representing a recruitment event in early 2011 most likely stimulated by the large discharge events of 2010/11 from north Queensland Rivers (K. Fabricius pers. com.). However, direct management action now (in 2012) to slow or reduce the fourth wave will most likely be too late to be effective.

5.2. The water quality story

Management of water quality issues in the GBR has really only made considerable progress in the last 10–15 years, with the exception of the management of point sources. Sewage discharges into the GBR Marine Park were addressed in the early 1990s through the implementation of permitting requirements and supporting policy for the management of sewage outfalls in the Marine Park. This was a management action that GBRMPA was able to progress within the existing regulations and evidence of the adverse, and in some cases severe, effects of poorly treated sewage effluent on coral reef ecosystems existed in other locations (e.g. Kaneohe Bay, Hawaii; Smith et al., 1981). In 2000, discharges from aquaculture facilities that discharged into waterways that flow into the Marine Park were also regulated, although this was much more complicated and politically sensitive process using the GBRMPA's ability to regulate activities adjacent to the Marine Park that have the potential to impact on plants and animals in the Marine Park.

Water quality issues associated with diffuse sources of pollutants including agricultural runoff have been a much more complex and controversial management issue for the GBR. Early efforts were characterised by targeted research programs in the 1980s (Hopley et al., 1991) and early 1990s coordinated by the GBRMPA which included series of workshops and conferences in the 1980s and a large research program in the 1990s investigating the potential influence of land based runoff on GBR ecosystems. Even at an early stage in this process the potential impacts of sediment from land clearing was recognised (Bennell, 1979) and potential sewage discharge issues identified (Baldwin, 1989; Woodley, 1989). A period of dispute as to the strength of the science supporting a case for chronic pollution of the GBR occurred in the early 1990s (Walker, 1991; Bell and Gabric, 1991; Kinsey, 1991; Hopley et al., 1991) followed by a renewed research effort through the 1990s to resolve the uncertainty, which was to some extent a response to the scientific controversy (Kinsey, 1991). Later analysis identified a range of water quality issues (Brodie and Furnas, 1994) including all the 'normal suspects' – sewage discharges, agricultural runoff, shipping pollution, port development and operation prominent among them.

Actions in the mid to late 1990's and early 2000's shifted focus to collation and communication of current knowledge, leading to a considerable increase in the political profile of the declining status of water quality in the GBR. Several major synthesis products were released during this period including books (e.g. Furnas, 2003), consensus statements of the current state of knowledge developed by eminent scientists (Williams et al., 2002; Great Barrier Reef Protection Interdepartmental Committee Science Panel, 2003), a government enquiry (Productivity Commission, 2003) and many seminal papers and reports (e.g. Moss et al., 1993; Bell and Elmetri, 1995; Furnas et al., 1997, 2011; Brodie et al., 2001a; Haynes et al., 2001; Brodie et al., 2003; McCulloch et al., 2003; Fabricius, 2005; Fabricius et al., 2005; DeVantier et al., 2006; De'ath and Fabricius, 2008, 2010; Brodie et al., 2011a, 2011b). Documented evidence of the issues surrounding water quality and ecosystem health in the GBR expanded substantially in this period, driving the progression of several policy initiatives. Perhaps the most important outcome was an agreement between the Australian and Queensland Governments that action was required to address water quality issues in the GBR and its catchments. This led to the preparation of the Reef Plan in 2003 (Queensland Department of the Premier and Cabinet, 2003), with a goal to halt and reverse the decline of water quality entering the Reef within 10 years (i.e. 2013). This policy was introduced in a political climate that was favourable for environmental initiatives in Australia under the direction of the Senator Robert Hill in an Australian Liberal (conservative) Government and a Queensland State Labor Government.

6. The future of the GBR

Based on the information we have outlined above, the long term viability of the GBR in anything like its current state must be called into question. Many species and ecosystems are in decline and only a few are stable or recovering from past degradation. In addition the heavy event-driven damage of 2009 and 2011 and the detection of the commencement of the fourth wave of COTS outbreaks raises significant concerns for the long term health of the GBR. Current (2011) unpublished estimates of coral cover on the GBR (G. De'ath, pers. com.) from the manta tow data analysed up to 2004 by Sweatman et al. (2011) suggest that cover is now at about 16% down from the 22% of 2004. Continuation of the current stresses due to COTS cyclones, bleaching, direct water quality impacts and coral diseases without management/mitigation of these factors suggest coral cover will fall to 5% by 2035 (G. De'ath, pers. com.).

It could be argued that the system has gained some resilience through the current management interventions in water quality management and the Marine Park rezoning in 2004. However, it is dubious whether this management response is adequate to prevent either a large scale phase shift in the system (Elmhirst et al., 2009; Hughes et al., 2010) or just continuing slow decline (Fung et al., 2011). Modelling of scenarios for the future state of the GBR (Costanza et al., 2011; Brodie et al., 2011c) show that with no action on climate change but substantial progress under Reef Plan (to the extent of halving loads of fine sediments and nutrients to the GBR), coral cover on the GBR is still forecast to fall to 5%. Even successful interventions are unlikely to return the GBR to some pristine or predisturbance state as has been shown from experience in restoration through management in other systems (Palumbi et al., 2008; Duarte et al., 2009). In many systems where long term management of fisheries decline or eutrophication have occurred, the systems have proved to have non-linear reversibility (Duarte et al., 2009). Thus when nutrient loadings to a marine waterbody have been returned to their original value, the system has not then automatically returned to its original state, although the managed state is generally 'more desirable' than the polluted state (Duarte et al., 2009). Whether the GBR falls into this category for nutrient loading is not known but is the subject of some speculation (Brodie et al., 2011a,b).

Current interventions in water quality management largely driven by Reef Plan but also covered by State Government legislation, do not effectively address many of the potential pollutants of concern for the GBR. In particular Reef Plan focuses only on agriculture and specific pollutants from agriculture – namely suspended sediment (from erosion), nutrients and selected pesticides, arising from a focus on diffuse source activities. This scope was based on the assumption that point sources were adequately addressed under existing policy and legislative frameworks. Accordingly, pollutants from other sources such as urban areas, ports, shipping, mining, industrial areas are not considered in Reef Plan and other pollutants, particularly micro-pollutants (pharmaceuticals, artificial sweeteners, PAHs, trace metals, endocrine disrupting substances, coal dust, nanomaterials and others), are ignored as well. Many of these micro-pollutants are recognised worldwide as serious threats to coastal and marine ecosystems (Schwarzenbach et al., 2006; Dachs and Méjanelle, 2010). As the Reef Plan has gained momentum, management of these other pollutants and pollutant sources has become less prominent in the political agenda.

Ten years on from the commencement of the Reef Plan, lack of attention (and hence lack of management response) to the impacts of water quality pollutants other than those derived from diffuse source agricultural land uses, is again emerging as a significant issue. These pollutants are most likely to impact on coastal ecosystems of the GBR many of which are outside the boundaries of the Marine Park, and therefore will impact on the whole of the GBR due to the strong connectivity with the coastal ecosystems within the GBRWHA. A prominent example is the port development occurring in the Gladstone region, part of the trigger for the current assessment of the GBRWHA by the World Heritage Commission. Another current example is the Barratta Creek system south of Townsville where runoff and tailwater discharges from irrigated cropping (mainly sugarcane) with extreme concentrations of nutrients and pesticide residues flows into the Bowling Green Bay Ramsar site which is co-located with the estuarine area inside the GBRWHA (Smith et al., 2011; Davis et al., 2011a, 2011b). As the receiving waters area falls outside the boundaries of the Marine Park little direct management action is being undertaken to address this pollution although some of the Reef Rescue initiatives may indirectly reduce pollutant loading by improving management practices.

Overall the continuing effects of climate change including ocean warming and ocean acidification (Pandolfi et al., 2011), more frequent extreme events (Min et al., 2011), continued COTS outbreaks and accelerating coastal development pressures associated with greatly expanded port and urban development will ensure that recovery of many of the key species and ecosystems of the GBR is unlikely. The only real hope is that the capacity of the GBR to adapt to climate change is greater than we now believe and as we improve the resilience of the GBR through mitigation of local stressors including water quality and fishing (e.g. see Fung et al., 2011; Maina et al., 2011; Hughes et al., 2010; Wooldridge et al., 2011) that the system may retain some level of acceptable value and not collapse completely.

7. Conclusions and the benefits of hindsight

The GBR has been managed under a complex but powerful regime with great governmental support, financing and research and monitoring expenditure since 1975. The management system is often regarded as the best possible or best in the world and the leading contender for the best example of Ecosystem Based Management (Ruckelshaus et al., 2008). Despite this impressive system, the success of the management regime in halting the decline of many species and ecosystems is mixed. There have been notable successes in recent times after the major rezoning of 2004 with new no-take zones showing increased fish populations (not surprisingly) but also apparent effects on COTS populations. Recent data on turtle populations indicates that numbers are declining, particularly after recent large scale flooding. Whales (humpbacks in particular) are slowly increasing in numbers again after the cessation of most commercial whaling. There has been little loss of mangroves as a result of strong prohibitions on damaging marine plants under the Queensland Fisheries legislation. Sewage effluent discharges from resort islands and mainland cities and towns have been improved dramatically. Strong action on compulsory pilotage and navigation equipment may have prevented many shipping accidents but ships still manage to run onto the reef every decade or so. Water quality may have started to improve with the very recent programs (Reef Plan/Reef Rescue) addressing river pollutant discharges but the success of Reef Plan is still uncertain and there will be no real proof of this for several years yet. On the other hand coral cover has declined considerably, seagrass health in the central GBR is in poor shape, dugong numbers have declined precipitously, shark populations are in serious decline (although perhaps recent management has reduced the rate of decline), many other large fish on the GBR have had large population declines (although data on many are incomplete) and the fourth wave of COTS outbreaks has commenced. Most notably coral bleaching has become more frequent, widespread and damaging and coral calcification has started to decline due to ocean acidification.

The reasons for this situation are complex but include, as described above, the need for reasonably 'certain' science before management action occurs (and the long times need to achieve this). Time lags in recovery after management action are long. For a slow breeding animal like a dugong (1 calf every few years) population recovery is a very slow process. Catchment management activities such as reafforestation of riparian areas take decades to reduce erosion and river sediment loads. In particular the need to get the political, organisational, scientific, economic and human elements to align at the right time so effective management can occur in time to avert phase change (Biggs et al., 2009) is a frighteningly difficult task. This alignment has occurred for the implementation of large no-take zones in the GBR after decades of research, monitoring, industry consultation and political discussion (Fernandes et al., 2005; McCook et al., 2010) and similarly for water quality management (Brodie et al., 2011a,b).

A considerable limitation in the management of the GBR is that there are no distinct targets for ecosystem health, even for such obvious indicators as coral cover. While we have targets for water quality end of catchment loads, they do not exist for individual catchments or management regions, and the GBR wide targets are not based on GBR ecosystem needs (Brodie et al., 2009; Kroon, 2011). These limitations make it difficult to formally access management effectiveness for the GBR.

For these issues outlined above it is easy now for us to claim that GBR management should have focussed on these from the start of the GBRMPA. However, as is often said, hindsight is a wonderful thing and both authors of this paper have been engaged for many years in a water quality management role for the GBR. It has been difficult to get comprehensive management into place until 2008 (despite some earlier success with the more minor issues such as resort sewage management) partly due to the need to gain some degree of scientific 'certainty' before management options were acceptable to the community and government. Bell and Gabric (1991) noted this problem in the title of their paper "Must GBR pollution become chronic before management reacts" and indeed this is what happened in the end. For the climate change issue even such an arrangement as occurred for no-take zoning and water quality management cannot occur. Our inability to manage climate change for the GBR, including increased temperatures, extreme weather events and ocean acidification, means that even in the light of some success in other management areas (e.g. fishing and water quality) and the fact that the GBR is the best managed reef system in the world means the long term prognosis for a healthy GBR system is poor. This likely outcome is despite the fact that the GBR is the best managed reef system in the world. The extension of the Reef Plan management actions beyond 2013, the continued strong management of no-take zones in the GBR and a better management regime for the coastal and estuarine areas of the GBR are thus even more essential to give us any hope of retaining some of the World Heritage values of the system.

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