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Introduction

The Great Barrier Reef (GBR) is the largest coral reef system in the world, a mosaic of over 2,000 reefs stretched over 14 degrees of latitude along the Queensland (Australia) coast. The region is immensely diverse in the thousands of species from nearly all living phyla and in what these reefs look like, how they respond to environmental change, and how they contribute to the GBR's overall identity (GBRMPA 2014). Due to the GBR's biological, social, and economic value and singularity, deemed "outstanding universal value," it was recognised with UNESCO World Heritage Area status in 1981.

The GBR catchment is home to over 1.2 million people, and is the fastest growing population within Australia (GBRMPA 2014). Coastal Queenslanders have a multitude of uses for, and benefits from the GBR: coastal protection, tourism, fisheries, recreation (fishing is one of the most popular past-times and a large voter base), and commercial shipping (GBRMPA 2014). Agricultural, development, mining, and port expansion activities can have a significant impact on reef health via sediments, pesticides, and nutrients carried offshore in river plumes (Alongi & McKinnon 2005).

Connectivity is a central concept to management coastal reef systems, such as the GBR and its catchment area. In such an interconnected region, neither physical nor ecological processes occur in isolation. While the individual reefs are different, they all communicate with others, the open ocean, other aquatic habitats, and the land to varying extents. Understanding and regarding this connectivity is crucial for effective management (Sale et al. 2010).

In 2014, the UNESCO World Heritage Committee requested an updated report on the state of the GBR and its management. This review was sparked by concerns of declining coral cover, increasing coastal development, and proposed port expansion plans within the World Heritage

Area. In response, the Australian and Queensland Governments completed a Comprehensive Strategic Assessment that led to the development of the Reef 2050 Long-Term Sustainability Plan. This paper will provide contextual background of connective processes and threats facing the GBR, outline and critically evaluate its management, particularly in context of the Plan.

Connective processes within the Great Barrier Reef

Patchy distribution of reef structures generates a substantial spectrum of variation among reef communities. Not only a mosaic of reef variability, the Great Barrier Reef is a mosaic of other habitats. River estuaries, muddy and rocky intertidal areas, sandy beaches, mangrove forests, seagrass beds, sandy bottoms, and pelagic areas all exist within the region (GBRMPA 2014). All of these different habitats communicate in varying ways: nutrient fluxes, larval sources and sinks, movement of organisms, physical protection, among others (Harrison et al. 2012, GBRMPA 2014). Furthermore, these habitats communicate with terrestrial environments (Larcombe et al. 2001). This section will provide a brief summary of relationships within and among habitats in the Great Barrier Reef, as they relate to management.

As a barrier reef, the GBR exists entirely on the Australian continental shelf, which means it exists between opposing gradients of terrestrial and oceanic influences. This trend acts along the shelf as well as across it. In the southern region, higher rates of development and larger rivers carry terrestrial influence farther off shore. As the continental shelf is transversed, sedimentation rates and nutrient input decrease away from land (Larcombe et al. 2001).

These opposing gradients are fundamental to GBR ecology, as coral dominance and disease prevalence can be significantly altered by nutrient availability and sedimentation (McCook 2001, Haapkyla et al. 2011). Highly active browsing herbivorous fishes control macroalgal stands, thus enabling the dominance of reef-building coral on inner-shelf reefs (Hoey & Bellwood 2010). Outer shelf reefs are characterised by high coral cover and abundant scraping and excavating herbivorous fishes which clear space for coral recruits (Hoey & Bellwood 2008). Other fish communities differ significantly across the continental shelf as well, based on sediment loads, topographic complexity, and oceanic exposure (Williams 1982). This apparent dichotomy in resilience mechanisms has important implications for successful management, as will be discussed later in this paper.

Sale et al. (2010) define ecological connectivity as adult and larval dispersal between and within coral reefs. Pre-settlement reef fishes are known to be able to control their dispersal to an extent (Stobutzki & Bellwood 1997), even targeting individual reefs (Jones et al. 1999), and capable of supporting populations over considerable distances (Harrison et al. 2012). In the latter, coral reef networks contain larval sources and sinks, a useful framework for effective management (Evans et al. 2008). Although adult movement of site attached species is limited by distance and topographic complexity (Kerry & Bellwood 2012, Welsh & Bellwood 2012), more transient species often travel between reefs (Sale et al. 2010).

Landscape and human land use primarily affect the reefs via terrestrial runoff into rivers, discharged as effluent into the GBR lagoon. Mangroves and seagrass habitats act as a buffer between terrestrial sediments and reefs (Gacia & Duarte 2001, Alongi & McKinnon 2005), supply nutrients to corals (Granek et al. 2009), and enhance functionally important reef fish biomass (Mumby et al. 2003). Naturally drier landscapes in the south and central GBR are less able to retain rainfall as are the northern rainforests, resulting in large pulse expansions of river plumes. Seasonality of the vegetation also leads to larger amounts of sediments flowing into rivers within the south and central regions (Alongi & McKinnon 2005). In average wet season conditions, the Burdekin River (central GBR) plume can reach 50km seaward and over 200km up the coast (Lewis et al. 2006).

Physical processes connecting habitats are responsible for nutrient transfer and sediment retention, both of upmost importance to coral health and dominance of reefs. Ecological connectivity enhances biomass and resilience of coral reefs via population support mechanisms of larval supply and nursery areas. Disruption or alteration of these processes may undermine coral reef resilience (Bellwood et al. 2004), and therefore are ideal focal points for management (Graham et al. 2013).

Great Barrier Reef Management

In 1975, Australian Parliament passed the Great Barrier Reef Marine Park Act, establishing the Great Barrier Reef Marine Park Authority (GBRMPA) and its federal authority to impose restrictions on activities within the marine park. The 1979 Emerald Agreement established a formal working relationship between federal (GBRMPA) and state (Queensland) governments, with oversight by the Great Barrier Reef Ministerial Forum. Under this agreement, local, state, and federal regulations are proposed, enacted, reviewed, and enforced by respective bodies toward an ecosystem-wide approach. GBRMPA and Fisheries Queensland are generally responsible for activities within the marine park, and several entities within the Queensland Government are responsible for port activities (following the Queensland Ports Strategy) and management of the GBR catchment area. Since inception, numerous international, federal, and state conventions and legislation have been empowered to improve protection of ecosystems within the GBR, as well as uses and benefits to people and industries dependent upon them.

Since the arrival of Europeans, the GBR catchment has been significantly altered, and river discharge increased four-fold (with similar increases in nutrient input, suspended sediments, and nutrients). The increase in pollutant loads has been a result of coastal development, agricultural practices, mining, and deforestation (Brodie et al. 2001). The largest agricultural industries, sugar cane and cattle, fall under the Environmental Protection Act 1994 (regulating runoff mitigation) and the Chemical Usage Act 1988 (restricting pesticides application). Although outside of its direct legislative jurisdiction, GBRMPA contributes advisement in the joint Reef Water Quality Protection Plan.

In the mid-1980s, a regional zoning scheme established by GBRMPA became the foundation of management. By the early 1990s significant inadequacies in the scheme coupled with increasing intensity and diversity of use impacts prompted a review. 94% of the marine park is non-reefal habitat, but was not protected. Due to spatial bias within existing data and to provide a descriptive method inclusive of habitat connectivity, 70 distinct bioregions were identified for use as management units (Fernandes et al. 2005).

To counter these inadequacies, the Representative Areas Program (RAP) was established, informed by various steering committees, to re-zone the marine park (Day et al. 2002). The first step involved the definition of several operational principles to set minimum standards for ecological objectives and socio-economic, cultural, and management feasibility principles to minimize conflict and maximise compliance. Goals and compromises for and between the principles were guided by independent experts and public input (Fernandes et al. 2005). Spatial data was input to MarXan software, specifically programmed for optimising protection and minimising conflict from millions of alternative marine reserve schemes (Ball & Possingham 2000). However, this software was not able to process the format of some data collected during the review. A final decision was made combining the MarXan results, personal expertise of those involved, and GIS software for mapping and application (Fernandes et al. 2005).

The RAP resulted in a network of no-take areas that protected 33% of the marine park (up from 4.5%), nearly 20% of every major bioregion, and increased five-fold the average no-take area size (Fernandes et al. 2005). It was established with transparency, independent review, and in consideration of public comment and use for resources contained. Although compromises were made, largely the objectives were achieved, and in theory, compliance was maximised by consideration of public input. This reserve network was designed to maximise ecological connectivity within and between each bioregion. When possible, entire reefs were protected rather than parts. This has two-fold advantages: it reduces edge effects, and makes compliance easier (no ambiguous boundaries) (Fernandes et al. 2005).

Monitoring, Enforcement, and Adaptive Management

Within the Great Barrier Reef marine park, monitoring is split between two objectives: ecosystem health and user compliance monitoring. The former utilises indicators of ecosystem health to monitor trends and threats to various ecosystems and inform adaptive management. The latter uses surveillance and reporting techniques to ensure compliance of marine park restrictions for enforcement.

Various departments of the Queensland Government, James Cook University, and CSIRO monitor suspended sediments and potential contaminants within river effluents, as well as general water quality. Combined with plume modelling research, managers can track sediment and nutrients input to the system to monitor coral smothering and crown-of-thorns-starfish (COTS) outbreaks. Weather and sea surface temperature, which can be used to track storm damage and bleaching events are monitored by the Australian Institute of Marine Science (AIMS) and the Bureau of Meterology.

Established within the Reef Water Quality Protection Plan 2013, the ‘Paddock to Reef Integrated Monitoring, Modelling and Reporting Program’ functions to monitor and assess water quality via inter-agency collaboration. The Paddock to Reef program is comprised of 10 integrated components. Management practice adoption involved assessment of agricultural practices in terms of risk of degrading water quality. Paddock monitoring (via case studies) is based on samples of farm runoff, and linked to practices for modelling (differing scenarios to apply case studies on a broader scale). Annual mapping ground cover to estimate amount of runoff and extent of erosive processes. Riparian vegetation and wetland extent are mapped every four years to estimate pollutant movement and sediment loss. Wetland values and processes involve reporting on indicators and system states to adapt management toward improved water quality. Catchment loads modelling (for management improvement and forecasting), and catchment loads monitoring (modelling validation) follow and anticipate long-term trends in water quality of water entering the lagoon. Maritime monitoring uses reef health and resilience indicators and monitors linkages to terrestrial sourcing.

One of the primary objectives of GBR management is the protection of corals and reef associated animal populations. The use of standardised methods (e.g. transects and manta tows) and indicators (e.g. coral cover) are useful for detecting changes in fish abundances, benthic cover, and the extent of problems such as bleaching or COTS outbreaks (McCook et al. 2010, De'ath et al. 2012). GBRMPA conducts regular transects with trained volunteers, AIMS has been collecting transect and manta tow data since the establishment of the marine park, and other institutes and universities conduct more specific studies. The repetition of these techniques across cross-shelf and latitudinal gradients, as well as through time, allows quantifiable trajectories indicating trends reef health. The spatial and temporal links allow the inference of the extent, persistence, and even cause of a potential problem.

Another central objective of management, and essential to its enforcement, is monitoring of human compliance with relevant regulations. GBRMPA took public comment, recreational and commercial uses into consideration during the RAP in order to minimise conflict between the needs for preservation and people. Major activities in the marine park in need of monitoring include fishing (commercial and recreational), tourism, and shipping (including consequent port development and maintenance). Fisheries Queensland utilises GBRMPA's zonation for spatial restriction of fishing activity, but also enacts limits on gear type, bag limits, maximum and minimum size of caught fish to be kept, and target species restrictions. It requires extensive reporting within daily catch and effort logbooks by fishing vessels. Information on recreational fishing is gathered by surveys in major population centers (or ports where fishermen set out from), and during fisheries patrols (Fisheries Queensland, 2014).

Successful co-ordination is crucial for establishment of specific and broad-scale, yet practical management objectives. Every five years, a synthesis of the monitoring programs is compiled and released by GBRMPA. This Outlook Report, it summarises the state of the resilience and value, the extent of uses within, and threats to the ecosystems within the park (GBRMPA 2014).

The adaptive aspect of GBR management is key to continued success, particularly with intensifying impacts to the ecosystem (discussed in the following section). GBRMPA's regular Outlook reports identify and prioritise threats for management action. Action can then be taken by the relevant agency, such as the reporting, decision, and outcome network resulting in water quality protection plans described in detail by Bennett et al. (2005). This example aims to manage land use and agricultural activities to reduce pesticides, suspended sediments, and nutrients in river effluent where land use practices are constantly changing. The Outlook reports also provide future projections on ecosystem use and health, so management can be proactive and better informed when approached with major development permits.

There are several methods of enforcement used by GBRMPA and Queensland Governments. Fisheries Queensland requires fishery-specific permits, gear restrictions (including the required use of bycatch-reduction devices), quotas, and detailed catch reporting. Each vessel is required to carry a GPS-based locator, which automatically relays the position of the vessel. Daily catch reporting must be made. Patrol boats also conduct random inspections of both commercial and recreational fishermen. Aircraft also patrol areas, checking for compliance of no-entry zones and poaching of no-take zones. All agencies also encourage public reporting of regulation offenders. Due to lacking staff, budget, and the immense size of the marine park, enforcement largely depends upon deterrence by random inspections and heavy fines.

Inter-agency collaboration is a central theme to effective monitoring, enforcement, and ultimately adaptive management. Partitioning of responsibility within monitoring of the GBR Marine Park, and coastal influences to relevant agencies maximises the specialisation and resources applied to each aspect. The consideration of public and industry input allows for an environment of increased voluntary compliance and reduced conflict, while still protecting the vast majority of management objectives.

Outlook 2014 and Threats to the Great Barrier Reef

Globally, coral reefs are under significant threat from climate change and local pressures. They may interrupt feedback mechanisms maintaining coral dominance (e.g. overfishing of functionally important herbivores), or enhance de-stabilising feedbacks. Threats also alter connective processes between reefs, and to other habitat types. Ultimately, these threats endanger ecosystem health, resilience of coral dominance, and their inhabitant biodiversity, and may lead to a shift from coral dominance to algal dominated structures (Hughes et al. 2007). With increasing effects of climate change and coastal populations, these threats have become more apparent in recent decades, even prompting concern from the UNESCO World Heritage

Committee for the future of the GBR. The increased pressures and state of the reef were summarised within the Great Barrier Reef Outlook Report 2014 (GBRMPA 2014), and will be discussed here along with other supporting research and background information.

Global climate change introduces complicated and synergistic problems for coral reefs. Increasing sea surface temperature anomalies are driving up frequencies of coral bleaching events (Baker et al. 2008), the frequency and intensity of destructive storms (Wilkinson 1999), and sea level rise (Buddemeier et al. 1988). Increasing partial pressure of CO2 within the atmosphere is shifting the oceans towards more acidic conditions and threatening coral reef structure (Doney et al. 2009), inhabitant animals (Orr et al. 2005, Dixson et al. 2010), and the coral – algal competitive balance (Diaz-Pulido et al. 2011). Oceans are extremely dynamic systems where no one effect can be considered in isolation. Unfortunately, the majority of climate change effects upon corals and reefs do not consider these interdependencies (Hoegh-Guldberg et al. 2007). However, some studies provide some hope for the abilities of coral species to overcome these threats (Ware et al. 1996, Stanley & Fautin 2001).

As apocalyptic as the expectations from climate change look, the preeminent drivers of phase shifts come from local pressures (Bellwood et al. 2004). Overfishing of functionally important herbivores, eutrophication, and increased sediment input are all relevant to coastal reefs, including the Great Barrier Reef (Hughes et al. 2007). Nutrient input from coastal development and agricultural runoff are a significant problem for the GBR. Devastating COTS outbreaks are enhanced by excessive nitrogenous input from agricultural fertilisers (GBRMPA 2014). Perhaps more threatening is the input of sediment-laden water from river effluent and port dredging projects. Additional major port expansions have been proposed in recent years, prompting heavy public and scientific concern for reef health (Grech et al. 2013). This sediment smothers corals directly, decreases light availability to photosynthetic corals, increases incidence of coral disease, and makes algae more resilient to herbivory (Fabricius 2005, Goatley & Bellwood 2012).

According to Outlook 2014, threat culpability belongs to economic growth, population growth, and global greenhouse gas emissions. Although various organs of management have been successful recently in mitigating these threats somewhat, the Great Barrier Reef is in poor condition, and continuing to deteriorate. These threats cannot be sufficiently mitigated under current management. This poor outlook, combined with the UNESCO World Heritage Committee's concerns, prompted federal and state governments to conduct a "comprehensive strategic assessment" of the current state of management. Knowledge and management gaps were identified for the improvement of GBR management.

The Reef 2050 Long-Term Sustainability Plan

Based on the status identified in the Outlook 2014 and management gaps identified by the comprehensive strategic assessment, the joint governments prepared the Reef 2050 Long-term Sustainability Plan (Commonwealth of Australia, 2015). The foundation of this plan is a series of outcomes expected to be achieved by 2050. In the short term (within five years), so-called SMART (Specific Measureable Achievable Realistic and Time-bound) targets look to move toward medium-term objectives. Proposed management changes include direct actions, enhanced co-operation with other governmental and non-governmental agencies, and amendments to legislation.

Direct actions by Australian and Queensland Governments during the development of the plan have been taken. Standards set by the World Heritage Committee are to be incorporated more strongly into Queensland Government legislation. Including increased penalties for violation of the Environmental Protection Act and the ban on disposal of dredge material within the GBR marine park. Funding is promised for research investigating knowledge gaps regarding response of GBR habitats and fauna to aforementioned threats. An emphasis was placed on enhanced co-operation between governmental, NGO, community organisations, and industry for an iterative, transparent process of improvement.

SMART targets and immediate actions outlined by the plan aim towards the achievement of medium-term (by 2020) objectives under seven themes: water quality, ecosystem health, biodiversity, heritage, economic benefits, community benefits, and governance.

Poor water quality is addressed via the Reef Water Quality Protection Plan 2013 for continued management and monitoring of runoff, dredging, sewage outfalls, and industrial contaminants. Targets are outlined to achieve a ten year improvement through co-operation of relevant stakeholders. The ecosystem health theme is centered on the principle of avoidance, mitigation, or at least offsetting of impacts. This theme also contains targets to improve mapping and modelling of important ecosystems within the GBR World Heritage Area to better inform management. Biodiversity objectives rely on monitoring indicator species, and protection of turtles, marine mammals, and seabirds. Targets involve the improvement of coral trout sticks (an important target species for commercial and recreational fisheries) and turtle, marine mammal, and seabird populations. Human heritage areas are to be continued to be identified and protected, including those important to the Indigenous peoples. Through socio-economic monitoring, and GBRMPA’s Recreation Management Strategy and Reef Guardian Stewardship program, community benefits from the reef are expected to be enhanced and preserved. For continued economic growth, economic indicators will be incorporated into the new Integrated Monitoring Reporting Program (discussed below) and development will follow the Queensland Government's Queensland Plan and Queensland Ecotourism Plan. Continued adaptive management, production of Outlook Reports every five years, and the Paddock to Reef program will be key to achieving these goals.

The plan's vision is to stop the deteriorating state of the GBR ecosystem, maintaining Outstanding Universal Value (and other concurrent criteria to be maintained with World Heritage Area status), while allowing "sustainable development" of coastal communities, agriculture, and ports.

Discussion

The Great Barrier Reef is one of the largest networks of marine reserves in the world, and perceived globally as a great management "success story." Significant infrastructure, generally good interagency co-operation, and a relatively compliant user base are all important ingredients to the success here. The agencies responsible for managing the marine park and catchments have access to immense amounts of scientific work (and can conduct much of it themselves) by in situ institutions and these same agencies also have legal powers to enforce regulations imposed. By understanding the underlying connectivity of reefs, and other habitats, this science can be used to inform modelling to ultimately forecast potential and actual reef health threats.

The marine park contains some of the most pristine reefs (in the northern sector); while so many other areas within the Indo-Pacific are under serious, unyielding pressure (Graham et al. 2013). Much of those same pressures are present within the GBR, albeit with different circumstances. Threats to coral reefs from global climate change affect reefs everywhere, but it is the local pressures that determine a reef's ability to maintain resilience. Poor water quality is a local pressure prevalent within the GBR marine park that is increasing in intensity and posing a very serious risk to almost two thirds of the reefs (GBRMPA 2014). Declining coral cover and recent approvals of large-scale, controversial capital dredging projects have prompted concern from many groups, not the least of which are the scientific community and the UNESCO World Heritage Committee.

The Reef 2050 Long-Term Sustainability Plan details the past successes and strengths of past and contemporary GBR management, while acknowledging the deteriorating state of the reef identified by the Outlook 2014 report, and threats posed by approval of large dredging projects within the region. The impetus for the Report's creation was concern from the World Heritage Committee on the state of management, and its capability to deal with forecasted threats. However, the majority of the 2050 Plan relies on Plans, targets, and actions already within the scope of management. Little new actions are introduced, and the controversial dredging projects are apparently slotted into a technical loophole. Action WQA6 states: "Prohibit dredging within and adjoining the Great Barrier Reef World Heritage Area, for the development of new, or the expansion of existing port facilities outside priority port development areas, for the next 10 years." The proposed dredging projects are all within "priority port development areas," and the dredging proposed would occur within the World Heritage Area (approved by GBRMPA with some restrictions, GBRMPA 2015).

Within the biodiversity theme of the 2050 Plan, the focus lies on marine mammal, seabird, turtle, and populations of one commercially important fish species. The actual biodiversity of reefs, or any other habitat type within the marine park, is not mentioned. Also not mentioned is any of the species that could serve as indicators for supporting biodiversity (e.g. coral cover, herbivorous fishes, etc.). Even the actions put in place to monitor and protect the charismatic megafauna do not seem to take into account underlying causes. Turtle and dugong populations have been declining due to a loss of seagrass beds. It would seem much more effective to monitor seagrass beds as indicators, continue to enforce the use of bycatch reduction devices in fisheries, and protect critical spawning habitat during breeding season. Rather than just looking at a particular population of animals, connectivity needs to be taken into better account to recognise higher priority of areas over others, as in the case of vulnerable seagrasses (Coles et al. 2015).

Understanding connective processes and feedback between biological and physical systems within the Great Barrier Reef and its catchment are what makes management there such a "gold standard." By understanding underlying principles, monitoring indicators through can advise as to the state and trajectory of change within connective processes, and validate modelling. Modelling is then used to anticipate future outlooks for the area, as well as informed assessment of expectations to changes in local pressures. Monitoring, modelling these pressures can be a feedback loop in itself, informing management to improve monitoring indicator choice and enforcement efficiency with limited resources. Although such a shining example of management, there remains much room for improvement of incorporation of this connectivity into management.

Appendix: References

Alongi DM, McKinnon AD (2005) The cycling and fate of terrestrially-derived sediments and nutrients in the coastal zone of the Great Barrier Reef shelf. Marine Pollution Bulletin, 51:239-252

Baker AC, Glynn P, Riegl B (2008) Climate change and coral reef bleaching: An ecological assessment of long-term impacts, recovery trends and future outlook. Estuarine, Coastal and Shelf Science, 80:435-471

Ball I, Possingham H (2000) MarXan (V1.2) Marine reserve design using spatially explicit annealing. A manual. University of Queensland, Brisbane.

Bellwood DR, Hughes TP, Folke C, Nystrom M (2004) Confronting the coral reef crisis. Nature, 429:827-833

Bennett J, Lawrence P, Johnstone R, et al. (2005) Adaptive management and its role in managing Great Barrier Reef water quality. Marine Pollution Bulletin, 51:70-75

Brodie J, Christie C, et al (2001) Catchment management and the Great Barrier Reef. Water Science and Technology, 43:203-211

Buddemeier RW, Smith SV (1988) Coral reef growth in an era of rapidly rising sea level: predictions and suggestions for long term research. Coral Reefs, 7:51-56

Coles RG, Rasheed MA, et al. (2015) The Great Barrier Reef World Heritage Area seagrasses: Managing this iconic Australian ecosystem resource for the future. Estuarine, Coastal and Shelf Science, 153:A1- A12

Commonwealth of Australia (2015) Reef 2050 Long-Term Sustainability Plan, 111pp.

Day J, et al (2002) The Representative Areas Program for protecting biodiversity in the Great Barrier Reef World Heritage Area. In: (Moosa MK, ed.) Proceedings of the 9th international coral reef symposium. Ministry of the Environment, Indonesian Institute of Sciences, International Society for Reef Studies, Jakarta, pp. 687-696

De'ath G, Fabricius KE, Sweatman H, Puotinen M (2012) The 27-year decline of coral cover on the Great Barrier Reef and its causes. PNAS, 109:17995-17999

Diaz-Pulido G, Gouezo M, Tilbrook B, Dove S, Anthony KRN (2011) High CO2 enhances the competitive strength of seaweeds over corals. Ecology Letters, 14:156-162

Dixson DL, Munday PL, Jones GP (2010) Ocean acidification disrupts the innate ability of fish to detect predator olfactory cues. Ecology Letters, 13:68-75

Doney SC, Fabry VJ, Feely RA, Kleypas JA (2009) Ocean acidification: the other CO2 problem. Annual Reviews of Marine Science, 1:169-192

Evans RD, Russ GR, Kritzer JP (2008) Batch fecundity of Lutjanus carponotatus (Lutjanidae) and implications of no-take marine reserves on the Great Barrier Reef, Australia. Coral Reefs, 27:179-189

Fabricius KE (2005) Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. Marine Pollution Bulletin, 50:125-146

Fernandes L, Day J, Lewis A, et al (2005) Establishing representative no-take areas in the Great Barrier Reef: Large-scale implementation of theory on marine protected areas.

Conservation Biology, 19:1733-1744

Fisheries Queensland (2014) www.daff.qld.gov.au/fisheries (accessed 26 March 2015)

Gacia E, Duarte CM (2001) Sediment retention by a Mediterranean Posidonia oceanica meadow: the balance between deposition and resuspension. Estuarine, Coastal and Shelf Science, 52:505-514

GBRMPA (2014) Great Barrier Reef Outlook Report 2014. Great Barrier Reef Marine Park Authority, Townsville, 328pp.

GBRMPA (2015) Great Barrier Reef Marine Park Authority, www.gbrmpa.gov.au (accessed 29 March 2015)

Goatley & Bellwood (2012) Sediment suppresses herbivory across a coral reef depth gradient. Biology Letters, 8:1016-1018

Graham NAJ, Bellwood DR, Cinner JE, et al. (2013) Managing resilience to reverse phase shifts in coral reefs. Frontiers in Ecology and the Environment, 11:541-548

Granek EF, Compton JE, Phillips DL (2009) Mangrove-exported nutrient incorporation by sessile coral reef invertebrates. Ecosystems, 12:462-472

Grech A, Bos M, et al. (2013) Guiding principles for the improved governance of port and shipping impacts in the Great Barrier Reef. Marine Pollution Bulletin, 75:8-20

Haapkyla J, Unsworth RKF, Flavell M, et al. (2011) Seasonal rainfall and runoff promote coral disease on an inshore reef. PLoS ONE, 6:e16893

Harrison HB, Williamson DH, Evans RD, et al. (2012) Larval export from marine reserves and the recruitment benefit for fish and fisheries. Current Biology, 22:1023-1028

Hoegh-Guldberg O, Mumby PJ, Hooten AJ, et al. (2007) Coral reefs under rapid climate change and ocea acidification. Science, 318:1737-1742

Hoey AS, Bellwood DR (2008) Cross-shelf variation in the role of parrotfishes on the Great Barrier Reef. Coral Reefs, 27:37-47

Hoey AS, Bellwood DR (2010) Cross-shelf variation in browsing intensity on the Great Barrier Reef. Coral Reefs, 29:499-508

Hughes TP, Rodrigues MJ, Bellwood DR, Ceccarelli D, Hoegh-Guldberg O, McCook L, Moltschaniwskyj N, Pratchett MS, Steneck RS, Willis B (2007) Phase shifts, herbivory, and the resilience of coral reefs to climate change. Current Biology, 17:1-6

Jones GP, Milicich MJ, Emslie MJ, Lunow C (1999) Self-recruitment in a coral reef fish population. Nature, 402:802-804

Kerry JT, Bellwood DR (2012) The effect of coral morphology on shelter selection by coral reef fishes. Coral Reefs, 31:415-424

Larcombe P, Costen A, Woolfe KJ (2001) The hydrodynamic and sedimentary setting of nearshore coral reefs, central Great Barrier Reef shelf, Australia: Paluma Shoals, a case study. Sedimentology, 48:811-835

Lewis S, Brodie J, Ledee E, Alewijnse (2006) The spatial extent of delivery of terrestrial materials from the Burdekin Region in the Great Barrier Reef lagoon. Australian Centre for

Tropical Freshwater Research, Report No. 06/02, Townsville, 102pp.

McCook LJ (2001) Competition between corals and algal turfs along a gradient of terrestrial influence in the nearshore central Great Barrier Reef. Coral Reefs, 19:419-425

McCook LJ, Ayling T, Cappo M, et al. (2010) Adaptive management of the Great Barrier Reef: a globally significant demonstration of the benefits of networks of marine reserves. PNAS, 107:18278-18285

Mumby PJ, Edwards AJ, Arias-Gonzalez JE, et al. (2003) Mangroves enhance the biomass of coral reef fish communities in the Caribbean. Nature, 427:533-536

Orr JC, Fabry VJ, Aumont O, et al. (2005) Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. Nature, 437:681-686

Sale PF, Van Lavieren H, Ablan Lagman MC, et al. (2010) Preserving Reef Connectivity: A Handbook for Marine Protected Area Managers (Benedetti L, ed.). Connectivity Working Group, Coral Reef Targeted Research & Capacity Building for Management Program, UNU-INWEH, Melbourne, 80pp.

Stanley Jr. GD, Fautin DG (2001) The origins of modern corals. Science, 291:1913-1914

Stobutzki IC, Bellwood DR (1997) Sustained swimming abilities of the late pelagic stages of coral reef fishes. Marine Ecology Progress Series, 149:35-41

Ware JR, Fautin DG, Buddemeier RW (1996) Patterns of coral bleaching: modelling the adaptive bleaching hypothesis. Ecological Modeling, 84:199-214

Welsh JQ, Bellwood DR (2012) How far do schools of roving herbivores rove? A case study using Scarus rivulatus. Coral Reefs, 31:991-1003

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

Williams DB (1982) Patterns in the distribution of fish communities across the central Great Barrier Reef. Coral Reefs, 1:35-43