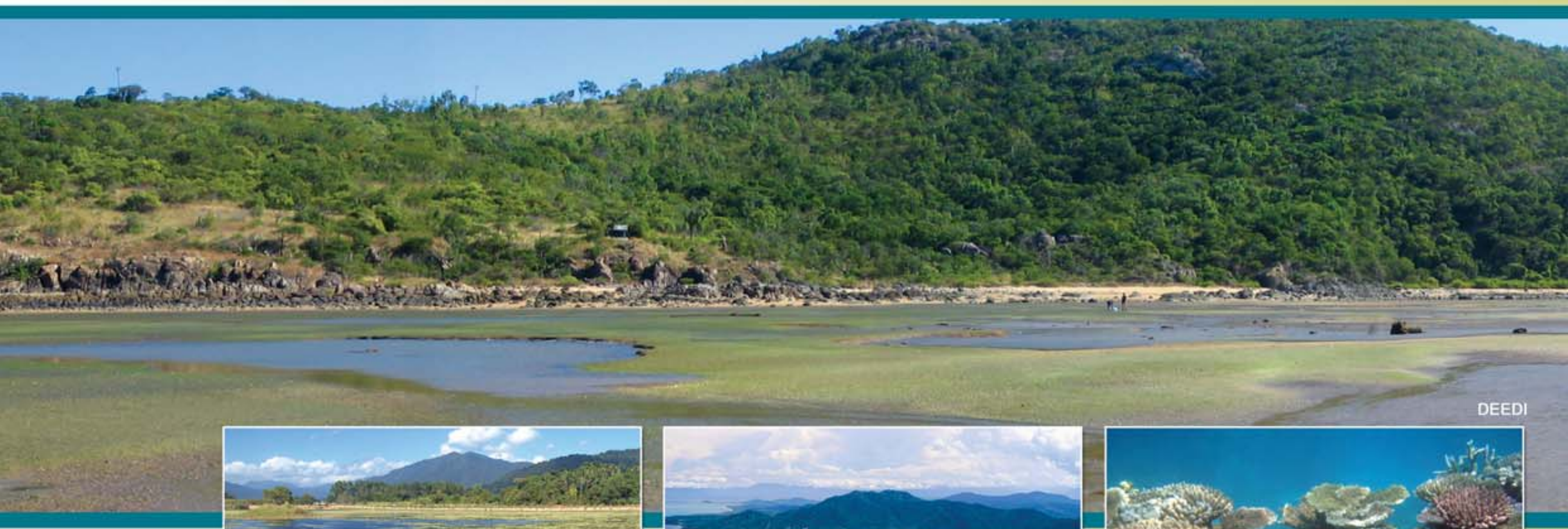
Marine and Tropical Sciences Research Facility

Synthesis Report

Thresholds of major pollutants with regard to impacts on instream and marine ecosystems



Compiled by Jane Waterhouse

Australian Government
Department of the Environment, Water, Heritage and the Arts

Reef & Rainforest Research Centre

Thresholds of major pollutants with regard to impacts on instream and marine ecosystems

Compiled by Jane Waterhouse

coasts | climate | oceans

Australian Government
Department of the Environment, Water, Heritage and the Arts

Supported by the Australian Government's
Marine and Tropical Sciences Research Facility

ISBN 978-1-921359-56-9

This report should be cited as:
Waterhouse, J. (2010) *Thresholds of major pollutants with regard to impacts on instream and marine ecosystems.* Synthesis Report prepared for the Marine and Tropical Sciences Research Facility (MTSRF). Published by the Reef & Rainforest Research Centre Ltd, Cairns (26pp.).

Published by the Reef and Rainforest Research Centre on behalf of the Australian Government's Marine and Tropical Sciences Research Facility.

The Australian Government's Marine and Tropical Sciences Research Facility (MTSRF) supports world-class, public good research. The MTSRF is a major initiative of the Australian Government, designed to ensure that Australia's environmental challenges are addressed in an innovative, collaborative and sustainable way. The MTSRF investment is managed by the Department of the Environment, Water, Heritage and the Arts (DEWHA), and is supplemented by substantial cash and in-kind investments from research providers and interested third parties. The Reef and Rainforest Research Centre Limited (RRRC) is contracted by DEWHA to provide program management and communications services for the MTSRF.

Cover photographs courtesy of Fisheries Queensland (DEEDI) (seagrass meadow, main image); GBRMPA (coastal flood plume); and Suzanne Long (coral reef; wetlands).

This report is available for download from the
Reef and Rainforest Research Centre Limited website:
http://www.rrrc.org.au/publications/synthesis_reports.html

Reef & Rainforest RESEARCH CENTRE

November 2010

Contents

List of Figures

List of Tables

Acronyms used in this report

ACTFR .... Australian Centre for Tropical Freshwater Research

COTS .... Crown-of-Thorns Starfish

DIN .... Dissolved Inorganic Nitrogen

GBR .... Great Barrier Reef

GBRMPA ...... Great Barrier Reef Marine Park Authority

MMP .... Reef Rescue Marine Monitoring Program

MTSRF .... Marine and Tropical Sciences Research Facility

NRM .... Natural Resource Management

PAM .... Pulse-Amplitude-Modulated

SE .... Standard Error

Introduction

Managers of the Great Barrier Reef (GBR) require information on the status of reef ecosystems, relationships between pressures and response, and an understanding of the thresholds of GBR species and ecosystems to these pressures. This information can be used to establish guidelines and targets for management that trigger a strategic management response. Knowledge of catchment and instream ecosystems is also necessary for regionally based natural resource managers, and to refine the understanding of relationships between catchment and marine ecosystems.

In response to these needs, a key focus area of the Australian Government's Marine and Tropical Sciences Research Facility (MTSRF) has been the development of thresholds of pollutants of concern in freshwater, estuarine and marine ecosystems. The outcomes of this research are summarised below, starting with an overview of new knowledge of the impacts of degraded water quality, and outlining how this work has been translated into threshold values and, ultimately in some cases, management guidelines for the GBR.

Impacts of water quality on GBR catchment and marine ecosystems

Marine ecosystem response

Through several years of research, strong links between coral reef health and water quality conditions have been shown at local scales (reviewed in Fabricius, 2005), at regional scales (van Woesik *et al.* 1999; Fabricius *et al.* 2005), and recently at a GBR-wide scale (Fabricius, in press; 2010; De'ath and Fabricius, 2008; 2010). Much of this work, which has been supported through the MTSRF, originated as part of the joint *Catchment to Reef* program of the CRC Reef Research Centre and the Rainforest CRC. The most recent and comprehensive reviews of this work are provided in Fabricius (in press) and Fabricius (2010), with a focus on the impacts of eutrophication on reef ecosystems. These reviews describe how nutrient enrichment directly and indirectly affects corals and other reef-associated organisms, how the ecological balance of coral reef ecosystems changes with nutrient enrichment, light loss and sedimentation, and identifies factors influencing the susceptibility of reefs to eutrophication. A qualitative conceptual model of this knowledge is also presented to describe these relationships.

Abundances of a range of other reef associated organisms have also been shown to change along water quality gradients. A review of existing reef studies identified the main effects of nutrient and sediment related parameters on key coral reef organism groups and found that nutrient enrichment can lead to macroalgal dominance if light levels are sufficient, but lead to dominance by heterotrophic filter feeders if light becomes a limiting factor for macroalgae (Johannes *et al.* 1983; Birkeland, 1988). It also showed that crustose coralline algae, which are essential settlement substratum for coral larvae, are negatively related to sedimentation (Fabricius and De'ath, 2001), as later confirmed by laboratory experiments (Harrington *et al.* 2005).

The distribution and growth of seagrasses is dependent on a variety of factors such as temperature, salinity, nutrient availability, substratum characteristics, and underwater light availability (turbidity) (Waycott and McKenzie, 2010). Terrigenous runoff, physical disturbance, low light and low nutrients, respectively, are the main drivers of each of the four seagrass habitat types found in Queensland, and changes to any or all of these factors may cause seagrass decline (Waycott and McKenzie, 2010). The most common cause of seagrass loss is the reduction of light availability due to 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), or chronic and pulsed increases in suspended sediments and particles leading to increased turbidity (Schaffelke *et al.* 2005). In addition, changes of sediment characteristics may also play a critical role in seagrass loss (Mellors *et al.* 2005).

The key findings of MTSRF research on the impacts of degraded water quality on coral reef and seagrass ecosystems are summarised in Box 1.

Managers also need to understand factors influencing the susceptibility of GBR ecosystems to increased pollutant loads. As an important starting point, Fabricius (2010) established a set of spatial, geophysical and biological properties that predict the exposure, resistance and resilience of coral reefs to degradation by nutrient enrichment (Table 1). In summary, it suggests that degradation from poor water quality is most likely to occur in poorly flushed locations with weak currents, on deeper reef slopes, in places where fish abundances are low, and in regions that are frequently affected by other forms of disturbance. In contrast, reefs with strong currents, well-flushed locations, shallow reef crests surrounded by a deep water body, and reefs inhabited by healthy populations of fishes are likely to have the highest levels of resistance and resilience. Managers can use this information as the basis of a risk assessment to identify priority areas for management.

Box 1: Summary of the impacts of degraded water quality on GBR marine ecosystems.

- Most studies show that high levels of dissolved inorganic nitrogen and phosphorus can cause significant physiological changes in corals, but do not kill or greatly harm individual coral colonies (reviewed in Fabricius, 2005). However, exposure to dissolved inorganic nitrogen can lead to declining calcification, higher concentrations of photo-pigments (affecting the energy and nutrient transfer between zooxanthellae and host; Marubini and Davies, 1996), and potentially higher rates of coral diseases (Bruno *et al.* 2003). In areas of nutrient upwelling or in heavily polluted locations, chronically elevated levels of dissolved inorganic nutrients may so alter the coral physiology and calcification as to cause noticeable changes in coral communities (Birkeland, 1997).
- The main way in which dissolved inorganic nutrients affect corals appears to be by enriching organic matter in the plankton and in sediments (Fabricius, in press).
- Macroalgae and heterotrophic filter-feeders benefit more from dissolved inorganic and particulate organic nutrients than do corals. As a result, corals that can grow at extremely low food concentrations may be out-competed by macroalgae and/or more heterotrophic communities that grow best in high nutrient environments (Fabricius, in press).
- Benthic irradiance is a crucial factor for reef corals. Light limitation, for example from increased turbidity, reduces photosynthesis, leading to slower calcification and thinner tissues (Anthony and Hoegh-Guldberg, 2003; Allemand, in press).
- Sedimentation reduces coral recruitment rates and coral biodiversity, with many sensitive species being under-represented or absent in sediment-exposed communities. High sedimentation rates are related to low abundances of corallines in coral reefs (Kendrick, 1991; Fabricius and De'ath, 2001).
- While adult corals can tolerate prolonged periods of low light, competition with macroalgae and moderate levels of sedimentation, the settlement of coral larvae and the survival of newly settled young and small colonies are extremely sensitive (Fabricius, 2005). Very little settlement occurs on sediment-covered surfaces, and the tolerance of coral recruits to sediment is at least one order of magnitude lower than that of adult corals. Settlement of coral larvae is also controlled by light intensity and spectral composition; reduced light reduces the depth at which larvae settle (Baird *et al.* 2003).
- More frequent outbreaks of Crown-of-Thorns starfish (COTS) are linked to high nutrient levels (Brodie *et al.* 2005; Houk *et al.* 2007). After primary COTS outbreaks have formed in a region with high phytoplankton concentrations, many of their numerous larvae may be transported by currents to remote regions, hence secondary COTS outbreaks may form far away from areas of eutrophication.
- Densities of benthic filter feeders – such as sponges, bryozoans, bivalves, barnacles and ascidians – increase in response to nutrient enrichment (Smith *et al.* 1981; Costa Jr. *et al.* 2000). In high densities some filter feeders such as internal macro-bioeroders can substantially weaken the structure of coral reefs and increase their susceptibility to storm damage.
- Octocorals (soft corals and sea fans), are passive suspension feeders and species richness declines by up to sixty percent along a gradient of increasing turbidity, due to the disappearance of zooxanthellate octocorals (Fabricius and De'ath, 2004).
- Herbicides found in GBR waters have biological effects on coral zooxanthellae at concentrations below 1 µg/L (e.g. Jones and Kerswell, 2003; Jones *et al.* 2003; Jones, 2005; Negri *et al.* 2005; Markley *et al.* 2007; Cantin *et al.* 2007). The long-term effect on ecosystem performance of the continuous presence of such residues is not known, but evidence is emerging that some pesticides not only affect the photosynthesis of the endosymbionts but also coral reproduction (Jones, 2005; Negri *et al.* 2005; Markley *et al.* 2007; Cantin *et al.* 2007).

- Herbicides (principally diuron) have been found in coastal and intertidal seagrasses adjacent to catchments with high agricultural use, at levels shown to adversely affect seagrass productivity (McMahon *et al.* 2005; Haynes *et al.* 2000). For example, diuron toxicity trials on three tropical seagrass species (*Halophila ovalis*, *Cymodocea serrulata* and *Zostera capricorni*) using Pulse-Amplitude-Modulated (PAM) fluorometry indicated that environmentally relevant levels of diuron (0.1-1.0 µg/l) exhibited some degree of toxicity to one or more of the tested seagrass species (Haynes *et al.* 2000).
- In the GBR system, seagrasses are at risk from a wide diversity of impacts, in particular where coastal developments occur (Grech, 2010; Grech *et al.* 2010). Seagrasses require adequate light, nutrients, carbon dioxide and suitable substrate for anchoring, along with tolerable salinity, temperature and pH (Collier and Waycott, 2009; Waycott and McKenzie, 2010).
- Elevated tissue nutrient concentrations in the leaves of seagrasses are indicators of excessive nutrient loads (Dennison *et al.* 1993). The ratio of the major nutrients in seagrass tissues are indicative of the status of plant utilisation of available nutrients – when in excess, the plants are saturated and a tendency for the ecosystem to have excessive algal growth occurs (summarised in Waycott and McKenzie, 2010).

Table 1: Spatial, geophysical and biological properties that predict the exposure, resistance and resilience of coral reefs to degradation by eutrophication. Source: Fabricius, 2010.

Factor	Property	Highest risk, lowest resistance and resilience
Hydrodynamics	Currents and waves determine exposure to pollutants (through dilution, mixing, and removal), and resistance of organisms (growth rates and photosynthesis are high at strong currents)	Weak currents, weak or extreme wave exposure
Connectivity	Connectivity to region with large brood stock determines larval supply and rates of self-seeding	Low connectivity to region with large brood stock and low self-seeding
Location	Downstream distance from source and discharge load of source determines exposure	Near to and downstream of point of discharge
Local topography	Local: steepness of reef slope determines the accumulation or downward transport of settled pollutants	Terraces, gradual slopes
Geomorphology	Geomorphology determines sediment retention vs flushing: retention is greatest in lagoons, embayments and on leeward side of reefs, while sediments and pollutants are flushed away from headlands, channels, or reef flanks	Lagoons, semi-enclosed embayments, leeward areas
Bathymetry	Depth of area, and depth and nature of surrounding seafloor determine the rate of wave re-suspension, removal of sediments and light limitation in turbid water	Lower reef slopes, areas surrounded by shallow sea floor
History	Exposure history facilitates adaptation to local conditions, and determines successional stage	Large and fast changes from historical to present conditions
Ecology	Substrata suitable for coral recruitment	Low coral recruitment success
	Fish abundances balance community structures (herbivores controlling macroalgal biomass, predators controlling invertebrate populations)	High fishing pressure, low abundances of herbivores and predators
	Biodiversity (functional redundancy, presence of more tolerant taxa)	Low biodiversity
	Additional coral disturbances (coral predators, diseases, bleaching, storms) determine cumulative stress	Frequent and severe additional disturbances, synergistic stressors

Estuarine ecosystem response

Estuarine health is not measured as part of any strategic monitoring and evaluation program for the GBR catchment, although some water quality measurements (dissolved oxygen, temperature, pH, conductivity, turbidity, chlorophyll *a*, nitrogen and phosphorus – total and dissolved) are collected monthly in the Fitzroy and Burnett estuarine areas as part of the Reef Water Quality Protection Plan Paddock to Reef Program integrated monitoring, modelling and reporting[1].

As part of the MTSRF, Sheaves and others (see Sheaves *et al.* 2007, 2010; Sheaves and Johnston, 2010; in press) assessed techniques that can be employed to determine the ecosystem health of estuaries and coastal wetlands in Australia's tropical regions, evaluated the sensitivity of those techniques to detect the effects of specific stressors, and evaluated their ability to separate natural variations from deleterious anthropogenic impacts. The study showed that while there is a large amount of information about detecting impacts and measuring ecosystem health in temperate estuaries, the extent to which temperate approaches are transferable to tropical/subtropical systems is unclear. There have been no location-specific studies evaluating the appropriateness of extrapolation from temperate to tropical understanding. In particular, biochemical processes such as toxicity, persistence and accumulation rates are likely to differ between cooler temperate and warmer tropical systems. Contrasts in functioning of tropical compared to temperate estuaries are likely to be compounded by the much higher biological diversity present in tropical estuaries, which potentially leads to more complex ecological processes. High diversity might also equate to high variability, adding another layer of complexity. MTSRF research has aimed to fill some of these knowledge gaps and a range of indicators have been selected, however, the development of response thresholds is a topic for further work.

Catchment and instream ecosystem response

Aquatic ecosystem health has long been regarded as a function of water quality alone – this is certainly more the case for marine waters. Within catchments, water quality is only one of the issues, and not necessarily the most important. Habitat integrity, riparian condition and levels of weed infestation can all have a major bearing, as was the case for Wet Tropics streams (refer to Pearson, 2005; Arthington and Pearson, 2007; Mackay *et al.* 2010), and as may be the case for coastal wetlands in the GBR catchments, in particular, the Tully-Murray wetlands (Pearson et al. 2010a; 2010b). Our understanding of the ecosystem health of GBR waterways has been greatly enhanced by recent reports generated through the *Catchment to Reef* program and MTSRF research on streams of the Wet Tropics (e.g. Arthington and Pearson, 2007; Pearson and Stork, 2007; Connolly *et al.* 2007a, 2007b; Mackay *et al.* 2010; Pusey *et al.* 2007a, 2007b; Faithful *et al.* 2006) and floodplain waterways (Pearson *et al.* 2005; Pearson *et al.* 2010a, 2010b; Wallace *et al.* 2009a, 2009b), and on the riverine waterholes and floodplains of the dry tropics (e.g. Perna and Burrows, 2005; Blanchette, 2010). The key findings are summarised in Box 2.

[1] http://www.reefplan.qld.gov.au/library/pdf/paddock-to-reef.pdf

Box 2: Summary of the impacts of degraded water quality on GBR catchment and instream ecosystems

- Ambient or chronic water quality is of greatest importance to the ecology of rivers and wetlands, as opposed to the short-term events that appear to drive water quality in coastal waters (Arthington and Pearson, 2007). Flood events are typically most important with regard to contaminant exports, while the intervening periods are more important to the ecology of waterways.
- The most serious factors currently affecting health in Wet Tropics streams and wetlands are changes to habitats, including flow modification, invasion by exotic weeds and loss of riparian vegetation, which can cause major changes to waterway morphology, habitat complexity, food availability, gas exchange with the atmosphere and, therefore, biodiversity (Arthington and Pearson, 2007).
- Organic effluents have been shown to cause fish kills and a major decrease in biodiversity as a result of oxygen depletion; and deposition of fine sediments derived from agriculture and other sources reduce biodiversity in streams (Arthington and Pearson, 2007).
- Dry tropics streams and wetlands are affected by similar influences but due to varying land uses and a dominance of cattle grazing, are generally more exposed to issues related to sedimentation. Many Dry Tropics rivers cease to flow in the dry season, contracting to isolated lagoons, which provide refugia for the biota. These lagoons develop their own character depending on their lithology, riparian vegetation, cattle access, etc. (Pusey *et al.* 1998).
- Flow regime has a high influence on fish populations. For example, Godfrey and others (Godfrey, 2009; Godfrey *et al.* 2010) have demonstrated that the relationship between the structure and dynamics of the larval fish assemblage in lowland riverine Wet Tropics habitats and the underlying variability of the habitat and its condition are shaped primarily by the prevailing flow regime.
- The gradient of flow regime from mid Wet Tropics to Dry Tropics is very clearly reflected by their biodiversity, with even the smaller rivers of the Wet Tropics supporting many more fish species than the large Dry Tropics systems of the GBR catchment (Pusey *et al.* 2007a).
- Disturbance of riverbanks is also caused by feral animals, including several species of fish, such as tilapia (Webb, 2006), and pigs, which can severely disturb the sediments and benthic fauna of shallow wetlands.
- The benefits of riparian vegetation to normal ecosystem function are now well documented (e.g. Pusey and Arthington, 2003) and include: habitat and habitat corridors for terrestrial animals and plants; habitat for semi-aquatic animals; shade; filtration mechanisms; organic inputs; bank stability; instream habitat via roots and snags; basking sites for reptiles; and breeding and roosting sites for many partly aquatic species, ranging from insects to birds.
- The dynamics of oxygen (and, incidentally, pH) in catchment waterways are complex and dependent on a range of natural and human-influenced variables (Pearson *et al.* 2003). Natural oxygen status can best be achieved by maintaining normal flow regimes and riparian zones; by curtailing weed growth; by preventing the input of nutrients; and by removing blockages to flow. While the tropical Australian invertebrate and fish fauna appear extremely resilient to low dissolved oxygen status (Pearson *et al.* 2003; Connolly *et al.* 2004), their tolerance thresholds can be breached, as evidenced by the occasional fish kills that occur in floodplain waterways. Prolonged high sediment levels reduce diversity and abundance of stream biota such as fishes (Hortle and Pearson, 1990).

Establishing thresholds of concern and management guidelines

Marine ecosystem guidelines

Coral reefs

While the effects of pollution on coral reefs at local scales are well understood, links at regional scales between increasing sediment and nutrient loads in rivers, and the broadscale degradation of coral reefs have been more difficult to demonstrate (Fabricius and De'ath, 2004). This is due to a lack of large-scale historic data and the confounding effects of other disturbances such as bleaching, cyclones, fishing pressure and outbreaks of the coral eating COTS, and is further complicated by the naturally high variability in monsoonal river flood events. However more recently, relationships between data sets of water quality, and macroalgal cover and the richness of hard corals and phototrophic and heterotrophic octocorals have been investigated at a GBR-wide scale (De'ath and Fabricius, 2008; 2010).

The methods used to undertake the analysis are outlined in De'ath and Fabricius (2010). Water clarity (Secchi disk depth) and water column chlorophyll were used as measures of water quality (Figure 1). The relationships between water quality on four benthic parameters – macroalgal cover, species richness of hard corals, and generic richness of phototrophic and heterotrophic octocorals (soft corals and sea fans) (Figure 2) were considered. The analysis comprised three stages (described further in De'ath and Fabricius, 2010).

1. *Spatial analysis of water clarity and chlorophyll, and four benthic parameters*. Data from each of the six parameters were reef-averaged, and the spatial distribution of each was modelled. The spatial predictors were relative distance across and along the GBR shelf (hereafter across and along), as opposed to the traditional latitude/longitude (Figure 2a).
2. *Modelling each of the four benthic parameters as functions of water clarity, chlorophyll, and across and along.* Since water clarity and chlorophyll were sampled at different sites than the benthic parameters, their values at the benthic sites were predicted using the spatial models of stage one.
3. *Guideline values for water clarity and chlorophyll conditions were determined*, based on mean values of the coastal and inshore waters of the far northern GBR and the outputs from the models relating the four biotic responses to water clarity, chlorophyll, and across and along. All reefs of the GBR exceeding the guidelines were identified, and the boosted regression tree models were used to predict potential changes in the benthic parameters on these reefs should water clarity and chlorophyll concentrations be improved to meet the guidelines.

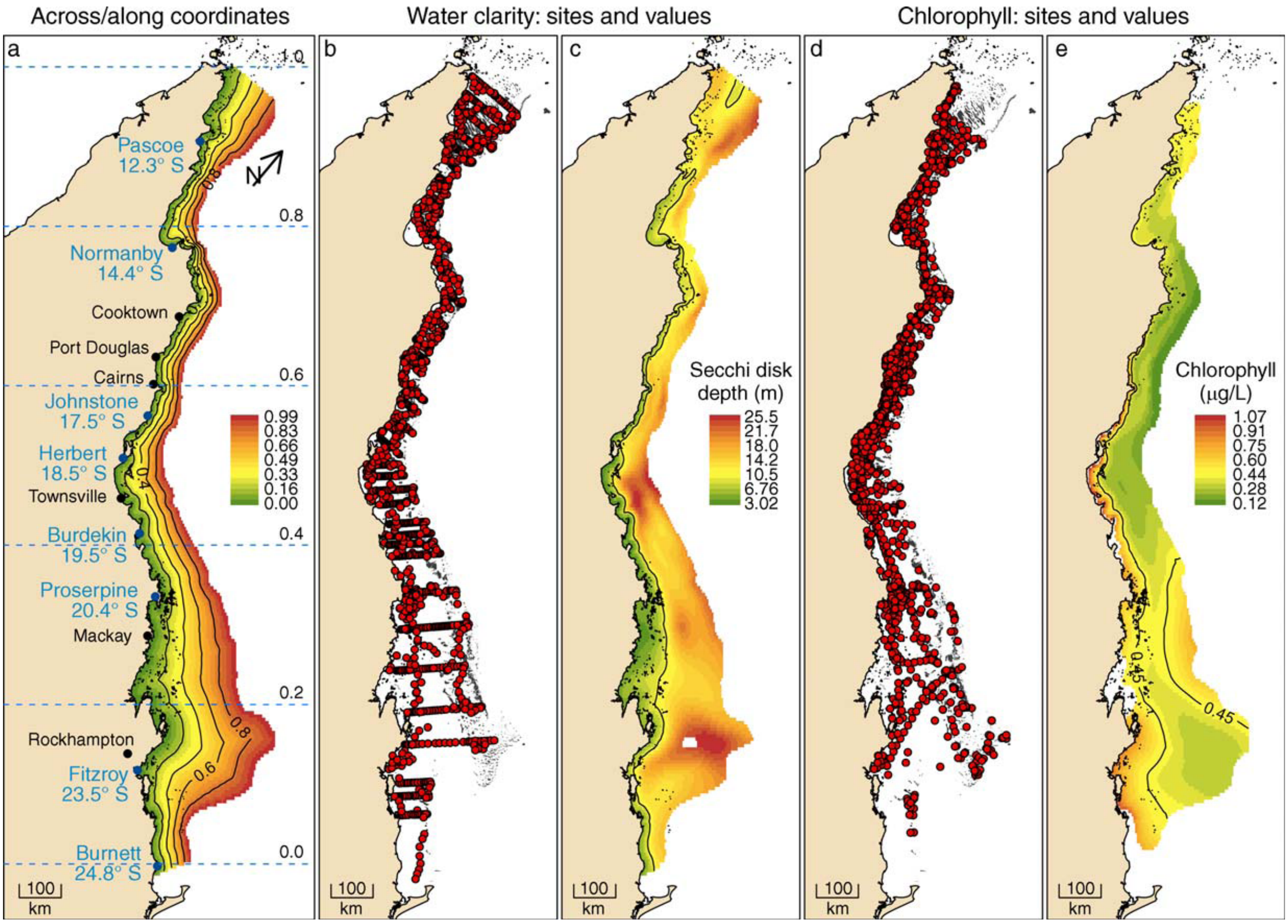


Figure 1: Maps of the Great Barrier Reef, Australia, illustrating, (a) the across/along coordinate system, the spatial distribution of (b) water clarity stations (N = 4067), (c) water clarity values (Secchi disk depth), (d) chlorophyll stations (N = 2058), and (e) chlorophyll values. In (a), the black solid lines are contours for the values of across, the blue dashed horizontal lines are contours for the values of along, and the names blue indicate rivers, with the latitude of their mouths added for reference. Maps of (c) water clarity and (e) chlorophyll values show the critical 10m and 0.45μg/L contours, respectively. Unreliable predictions (>3 mean standard errors of predicted values) were excluded from plots. Maps of the SE of predictions are shown in the Appendix of the source. Source: De'ath and Fabricius, 2010.

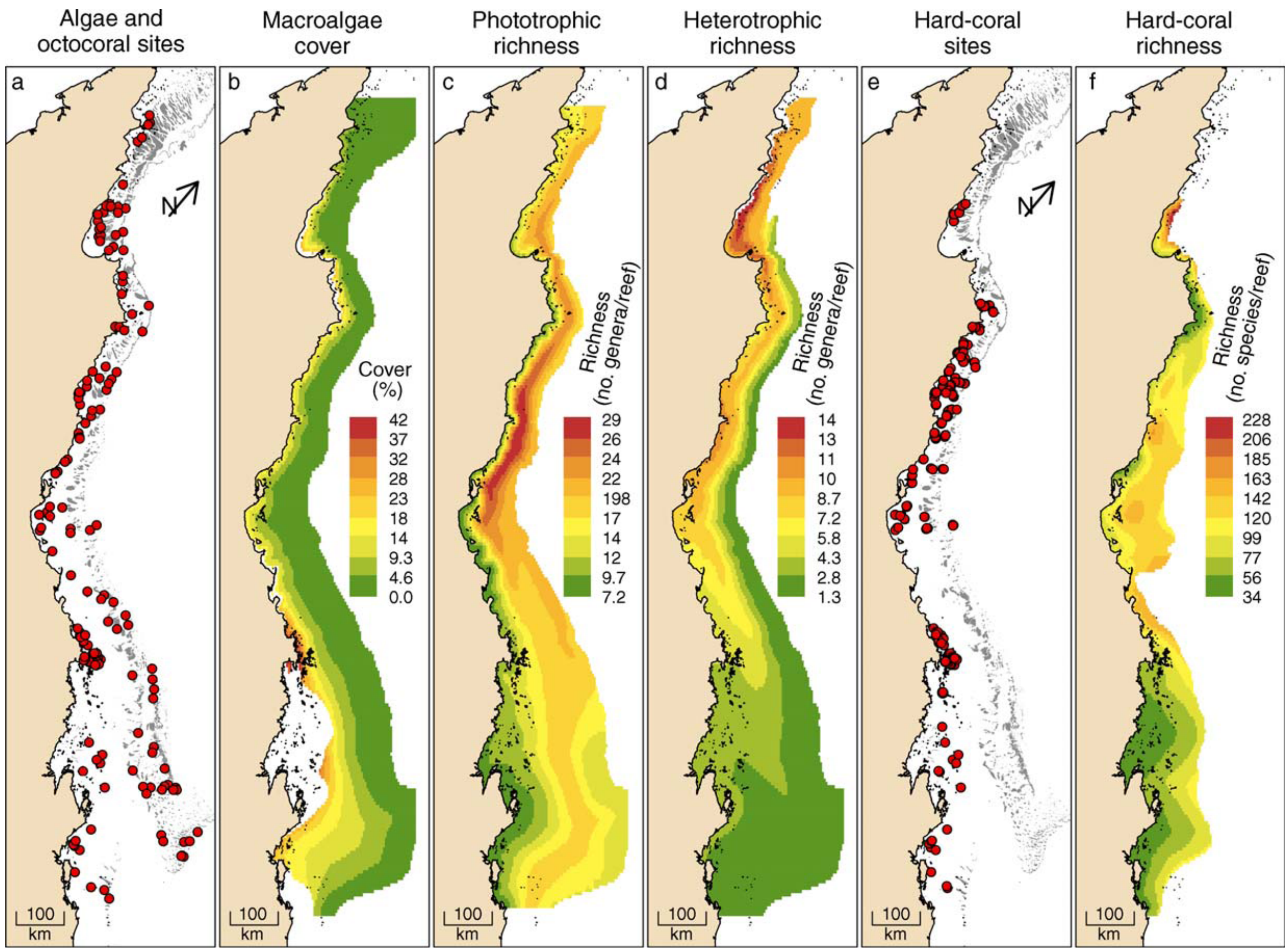


Figure 2: Maps of the Great Barrier Reef illustrating the spatial distribution of (a) macroalgae and octocoral sites (N = 150), (b) macroalgal cover, (c) phototrophic and (d) heterotrophic octocoral richness, (e) hard-coral sites (N = 110), and (f) hard-coral richness. Unreliable predictions (>3 mean SEs of predicted values) were excluded from plots. Maps of the SE of predictions are shown in the Appendix of the source. Source: De'ath and Fabricius, 2010.

The study showed that the four biotic indicators chosen are significantly related to GBR water quality. Macroalgae increased and hard coral richness and the richness of phototrophic octocorals declined with increasing turbidity and chlorophyll, after cross-shelf and long-shore effects were statistically removed (Figure 3). Heterotrophic octocorals benefited slightly from high turbidity. Mean annual values of >10 m Secchi depth and <0.45 g L^{-1} chlorophyll were associated with low macroalgal cover and high richness of phototrophic octocorals and hard corals. The study suggested these values to be useful water quality guideline values. These guidelines are presently exceeded on 650 of the 2,800 gazetted reefs of the GBR. The models showed that compliance with these guideline values by, for example, minimising agricultural runoff would likely reduce macroalgal cover by approximately fifty percent and increase hard coral and octocoral richness by forty and seventy percent, respectively, on these 650 reefs.

This information has been used to inform the development of the Water Quality Guidelines for the Great Barrier Reef Marine Park (GBRMPA, 2009). These guidelines define trigger values that will be used to:

- Support setting targets for water quality leaving catchments;
- Prompt management actions where trigger levels are exceeded;
- Encourage strategies to minimise release of contaminants;
- Identify further research into impacts of contaminants in the Marine Park; and
- Assess cumulative impacts on the GBR ecosystems at local and regional levels.

It is important to note that the levels of contaminants identified in these guidelines are not targets. Instead they are guideline trigger values that, if exceeded, identify the need for management responses.

Two independent approaches were combined to define guideline trigger values for water quality:

1. Modelled relationships between the condition of reef biota and the parameter. Secchi depth and water column chlorophyll concentration were used to identify the highest mean annual chlorophyll and lowest Secchi values that prevented high macroalgal cover and low coral and octocoral richness; and
2. Analyses of the spatial distribution of water quality in Cape York waters. Since Cape York is subject to only minor modification of land use its water quality condition was taken to be consistent with reference sites (European Community, 2005; Environmental Protection Agency, 2006).

There are still many uncertainties in the development and application of these Guidelines. In particular, further work is required to consider what might be achievable targets for ecosystem health given the current state of the system and level of technology. First evidence is emerging that the existence of synergistic effects may have to be carefully considered in estimates of tolerance thresholds (and hence water quality targets). For example, sedimentation effects on crustose coralline algae are significantly worsened when trace concentrations of herbicides occur in the sediments (Harrington *et al.* 2005). Other studies have demonstrated that sedimentation effects on corals worsen with increasing organic enrichment of the sediments (Weber *et al.* 2006) and with enrichment with marine snow (Fabricius *et al.* 2003; Wolanski *et al.* 2003). Studies also show that dissolved inorganic nitrogen (DIN) enrichment enhances bleaching susceptibility (Wooldridge and Done, 2009; Wooldridge, 2009), which is recently supported by similar findings in Florida Keys (Wagner *et al.* 2010). It is also known that DIN enrichment exacerbates the impact of increasing ocean acidification on coral growth (Renegar and Riegl, 2005).

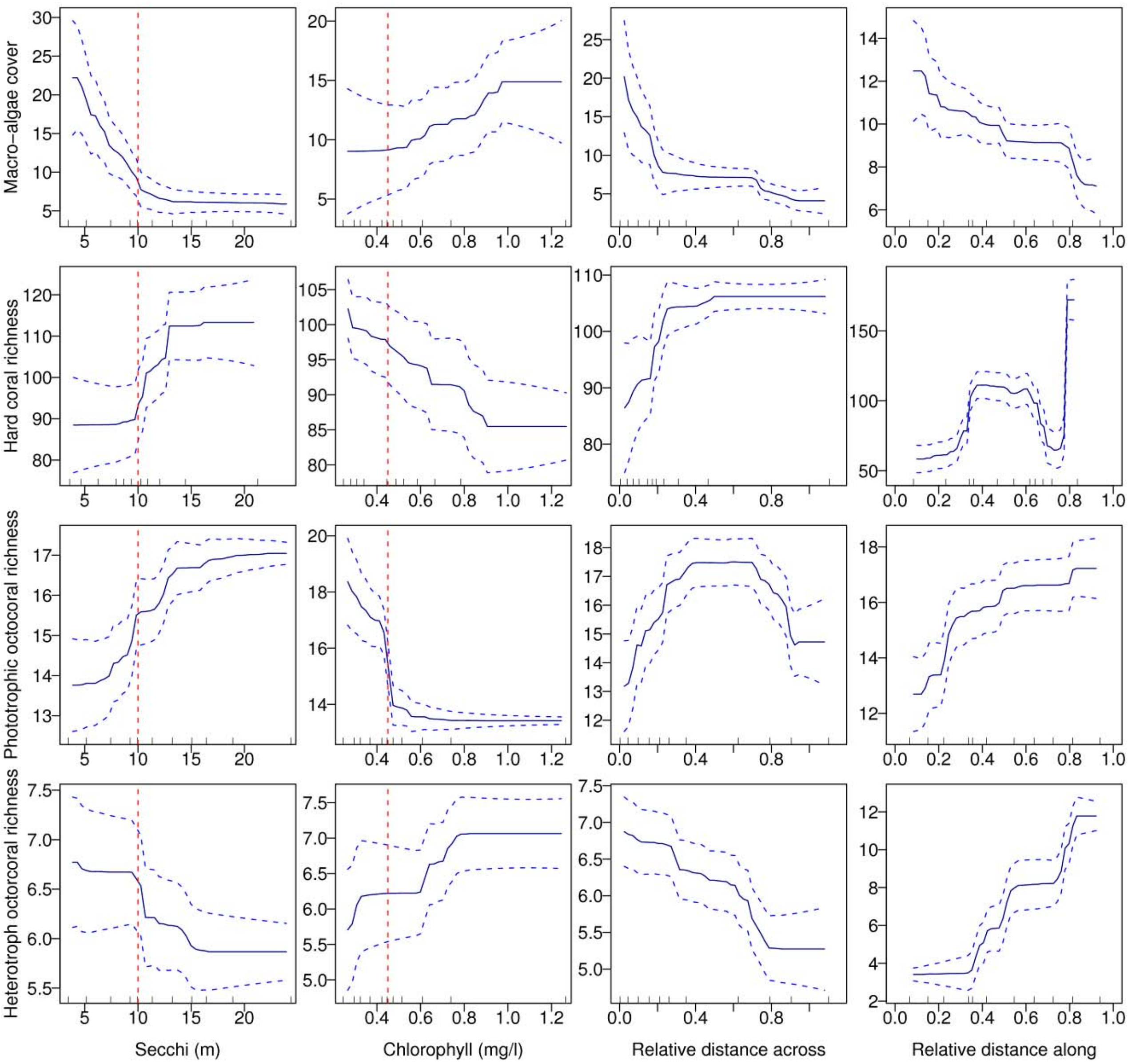


Figure 3: Relationship of macroalgal cover and the taxonomic richness of hard corals, phototrophic and heterotrophic octocorals (soft corals and sea fans with and without zooxanthellae, respectively), along gradients in water clarity (measured as Secchi disk depth) and chlorophyll, while also controlling for relative distance across and along the shelf (from De'ath and Fabricius, 2008). Substantial increases in macroalgal cover and losses in coral biodiversity are being observed at <10 m Secchi disk depth and >0.45 µg L^{-1} chlorophyll. The red lines show the proposed water quality guideline values (10 m Secchi disk depth, and 0.45 µg L^{-1} chlorophyll).

Seagrasses

In the GBR system, seagrasses are at risk from a diverse range of impacts, particularly where coastal developments occur (Grech, 2010; Grech *et al.* 2010). Healthy seagrass meadows in the GBR act as important resources as the primary food for dugong, green turtles, and numerous commercially important fish species and as habitat for a large number of invertebrates, fish and algal species (Carruthers *et al.* 2002). Requirements for the formation of healthy seagrass meadows are relatively clear, as seagrasses are photosynthetic plants that occupy marine habitats. They require adequate light, nutrients, carbon dioxide and suitable substrate for anchoring, along with tolerable salinity, temperature and pH levels (Waycott and McKenzie, 2010). A number of thresholds of these requirements have been established for seagrass communities that are relevant to the GBR, and are summarised here:

N:P ratios: The ratio of N:P is a useful indicator as it is a reflection of the 'Redfield' ratios (Redfield *et al.* 1963), and seagrass with an atomic N:P ratio of 25 to 30 can be determined to be 'replete' (Atkinson and Smith, 1983; Fourqurean *et al.* 1997; Fourqurean and Cai, 2001). N:P values in excess of 30 suggest P-limitation.

C:N ratios: Changing C:N ratios have been found in a number of experiments and field surveys to be related to light levels (Abal *et al.* 1994; Grice *et al.* 1996; Cabaço *et al.* 2007; Collier *et al.* 2009). Experiments on seagrasses in Queensland indicate that an atomic C:N ratio of less than 20 for seagrass may suggest reduced light availability (Abal *et al.* 1994; Grice *et al.* 1996).

C:P ratios: The median seagrass tissue ratio of C:P is approximately 500 (Atkinson and Smith, 1983), therefore deviation from this value is also likely to be indicative of some level of nutrient enriched (lower C:P) or nutrient limited conditions (higher C:P).

Other indicators are more variable and, to date, threshold values have not been established. Further evaluation of the best indicators of seagrass health and water quality conditions has been undertaken by Waycott and McKenzie (2010).

Catchment and instream ecosystem guidelines

Previous work in the Wet Tropics has documented some thresholds for selected species and variables, including dissolved oxygen (Pearson and Penridge, 1987; Connolly *et al.* 2004 – see Figure 4), nutrients (Pearson and Connolly, 2000), ammonia (Økelsrud and Pearson, 2007), substrate disturbance (Rosser and Pearson, 1995), and sediment deposition (Connolly and Pearson, 2007). Recently, a large project undertaken by the Australian Centre for Tropical Freshwater Research (ACTFR) documented critical levels of dissolved oxygen and guidelines for many species of tropical Australian freshwater fish (Butler *et al.* 2007; Butler and Burrows, 2007). This type of work is essential for understanding species' responses and thresholds, and in the case of the ACTFR work, developing guidelines against selected criteria (in this case, dissolved oxygen).

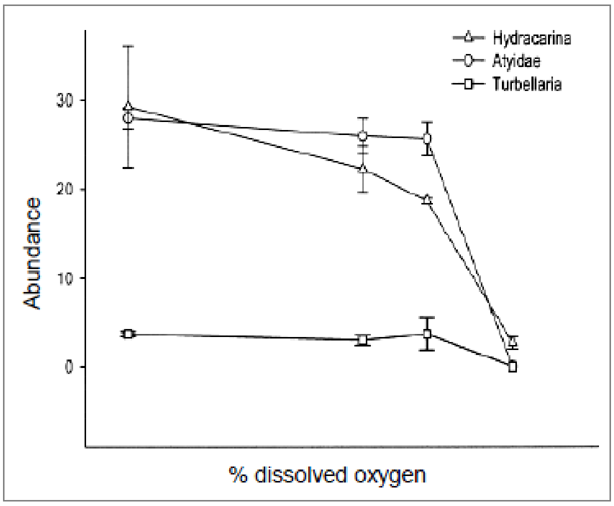


Figure 4: Threshold pattern for dissolved oxygen and several taxa from Wet Tropics streams (from Connolly *et al.* 2004).

As supporting information to the development of thresholds of concern for freshwater ecosystems in the GBR, MTSRF research aimed to measure spatial and temporal variability of biophysical indicators in floodplain lagoons along natural environmental gradients and gradients of disturbance (see Pearson *et al.* 2010a for an overview of this research). In particular, the field study in the Tully-Murray catchment was designed such that stressor-response relationships along gradients of disturbance (supported by data from laboratory trials and the literature) would help to identify thresholds – points along each disturbance gradient where ecological changes of scientific or management concern become apparent.

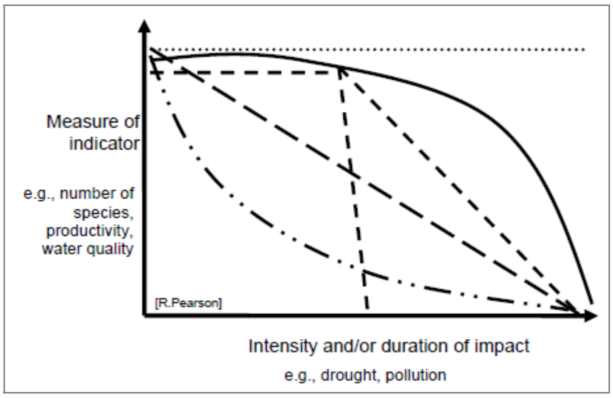


Figure 5: Some alternative threshold patterns for different indicator and pressure variables (from Pearson *et al.* 2010a).

However, in ecosystems there are multiple factors affecting species, some of which act along similar axes, but others of which act independently. Some factors may have no effect while others have a linear or gradual effect such that no clear threshold exists (Figure 5). In the wetland situation, for example, it is possible that light levels have a direct linear effect on plant abundance, but plants will also be

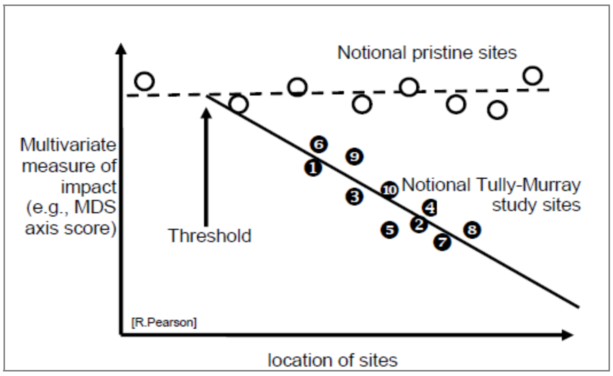


Figure 6: Notional position of Tully-Murray sites on an impact/location gradient (from Pearson et al. 2010a).

affected by changes in habitat, nutrients, in habitat, nutrients, concentration of herbicide, etc., which may have non-linear effects (Mackay *et al.* 2010). In the Tully-Murray many habitat and water quality variables were measured, each of which may have independent effects on each species of plant and animal. Moreover, many variables will act differently on different life stages of the biota, so the end result is a composite response to these multiple effects. In some situations a single variable overrides all others. Dissolved oxygen is one such variable that can control presence or absence of fish (as in Figure 4).

The Tully-Murray analyses indicate, however, that many water quality variables and habitat variables act in concert, such that there were significant relationships between ordination axes and many of the variables. It is thus clear that the multiple responses to multiple variables are expressed quite generally. It is evident that in the Tully-Murray wetlands, as in the Wet Tropics stream study (Arthington and Pearson, 2007) many of the variables that affect the biota can be resolved into 'habitat' and 'water quality' composites. Thus, a gradient of response to a gradient of land-use impact is evident, defined by the variable composites. The fact that response to the various factors measured can be identified indicates that some composite threshold has been crossed. Without reference sites it is difficult to establish where that threshold might be situated (Figure 5). The best guess at sites closest to reference condition are notional lagoons 1 and 6; but in this schema they are somewhat removed from reference (unknown how far). This is how the Tully-Murray wetlands are perceived. The goal in management is to have sites progressively take a trajectory up and beyond the notional 'threshold of concern'.

The research showed that measuring such a threshold in the wetlands is challenging. Some parts of the gradient are entirely natural (e.g. distance from the coast; salinity) although even they may be affected by development (distance to the coast along channels might be greatly reduced by drainage works). Therefore, natural gradients need to be removed from consideration, as done in the stream study (Connolly *et al.* 2007a, 2007b; Pusey *et al.* 2007b). In that study, multiple replicate sites and comparisons between more and less impacted catchments, facilitated analysis and interpretation. In the Tully-Murray wetlands the study was very constrained by the low number of sites available, creating a gradient of sites that was truncated at both pristine and disturbed ends of the spectrum, so the interpretation is necessarily more equivocal. Nevertheless, the results provide a robust set of stressor-response relationships and a substantial benchmark against which improvement in the ecological condition of floodplain lagoons can be evaluated.

Application of the findings

The findings of this MTSRF research are directly relevant to managers of the Great Barrier Reef World Heritage Area and its catchments. The outcomes of the research on thresholds of concern for coral ecosystems (De'ath and Fabricius, 2010) provide the basis for the Water Quality Guidelines for the Great Barrier Reef Marine Park (GBRMPA, 2009). These Guidelines are used for assessment of the annual results of the Reef Rescue Marine Monitoring Program (RRMMP), for assessing annual status and relative change between monitoring periods. Remote sensing techniques that have evolved through development and testing in the RRMMP enable broad-scale assessment of chlorophyll, turbidity and coloured dissolved organic matter concentrations against these Guidelines. The thresholds that are suggested for tissue nutrients in seagrasses are currently used to assess the seagrass monitoring results in the same program.

The findings of the catchment and instream health research can be used to assess the condition of Wet Tropics streams and wetlands, which is of interest to the Queensland Government and regional Natural Resource Management (NRM) groups. Where thresholds were not able to be established due to considerable local and regional differences and/or insufficient datasets, the assessment provides a robust set of stressor-response relationships and a substantial benchmark against which improvement in the ecological condition of streams and floodplain lagoons can be evaluated.

References

Note: All references generated through MTSRF Program research are indicated by an asterisk (*).

Abal, E.G., Loneragan, N.R., Bowen, P., Perry, C.J., Udy, J.W. and Dennison, W.C. (1994) Physiological and morphological responses of the seagrass *Zostera capricorni* Aschers, to light intensity. *Journal of Experimental Marine Biology and Ecology* 178: 113-129.

Allemand, D. (in press) Eutrophication. In: Hopley, D. (ed.) *Encyclopedia of modern coral reefs*. Springer.

Anthony K.R.N. and Hoegh-Guldberg O. (2003) Variation in coral photosynthesis, respiration and growth characteristics in contrasting light microhabitats: an analogue to plants in forest gaps and understoreys? *Functional Ecology* 17: 246-259.

* **Arthington**, A.H. and Pearson, R.G. (eds.) (2007) *Indicators of Ecosystem Health in Wet Tropics Streams*. Final Report, Task 3, Catchment to Reef Research Program. Cooperative Research Centre for Tropical Rainforest Ecology and Management and Cooperative Research Centre for the Great Barrier Reef (247pp.).

Atkinson, M.J. and Smith, S.V. (1983) C:N:P ratios of benthic marine plants. *Limnology and Oceanography* 28: 568-574.

Baird A.H., Babcock R.C. and Mundy C.P. (2003) Habitat selection by larvae influences the depth distribution of six common coral species. *Marine Ecology Progress* Series 252: 289-293.

Birkeland, C. (1988) Geographic comparisons of coral-reef community processes. In: Choat, J.H. *et al.* (eds.). *Proceedings of the Sixth International Coral Reef Symposium*, Townsville, pp. 211-220.

Birkeland C. (1997) Geographic differences in ecological processes on coral reefs. In: Birkeland C. (ed.) *Life and death of coral reefs*. Chapman and Hall, New York, pp. 273-287.

* **Blanchette**, M. (2010) *Dynamics of macroinvertebrate assemblages and trophic relationships in dry tropical rivers of the Upper Burdekin catchment*. Confirmation Report. Thesis Due 2010, James Cook University.

Brodie, J., Fabricius, K., De'ath, G. and Okaji, K. (2005) Are increased nutrient inputs responsible for more outbreaks of crown-of-thorns starfish? An appraisal of the evidence. *Marine Pollution Bulletin* 51: 266-278.

Bruno J., Petes L.E., Harvell D. and Hettinger A. (2003) Nutrient enrichment can increase the severity of coral diseases. *Ecology Letters* 6: 1056-1061.

Butler, B. and Burrows, D.W. (2007) *Dissolved oxygen guidelines for freshwater habitats of northern Australia*. Version 1.0. ACTFR Report No. 07/32. Australian Centre for Tropical Freshwater Research (ACTFR), James Cook University, Townsville (http://cms.jcu.edu.au/idc/groups/public/documents/technical_report/jcudev_017880.pdf)

Butler, B., Burrows, D.W. and Pearson, R.G. (2007) *Providing Regional NRM with Improved Aquatic Health Risk Assessment and Monitoring Tools: the Nationally Significant Indicator – Dissolved Oxygen.* ACTFR Report No. 07/31. Australian Centre for Tropical Freshwater Research (ACTFR), James Cook University, Townsville (http://cms.jcu.edu.au/idc/groups/public/documents/technical_report/jcudev_017879.pdf)

Cantin, N.E., Negri, A.P. and Willis, B.L. (2007) Photoinhibition from chronic herbicide exposure reduces reproductive output of reef-building corals. *Marine Ecology Progress Series* 344: 81-93.

Carruthers, T.J.B., Dennison, W.C., Longstaff, B.J., Waycott, M., Abal, E.G., McKenzie, L.J. and Lee Long, W.J. (2002) Seagrass habitats of north east Australia: models of key processes and controls. *Bulletin of Marine Science* 71: 1153-1169.

* **Collier** C. and Waycott, M. (2009) *Drivers of change to seagrass distributions and communities in the Great Barrier Reef*. 2009 Annual Conference of the Marine and Tropical Sciences Research Facility (MTSRF), Townsville.

* **Collier**, C., Lavery, P.S., Ralph, P.J. and Masini, R.J. (2009) Shade-induced response and recovery of the seagrass *Posidonia sinuosa*. *Journal of Experimental Marine Biology and Ecology* 370: 89-103.

* **Connolly** N.M. and Pearson, R.G. (2007) The effect of fine sedimentation on tropical stream macroinvertebrate assemblages: a comparison using flow-through artificial stream channels and recirculating mesocosms. *Hydrobiologia* 592: 423-438.

* **Connolly**, N.M., Pearson, B., Loong, D., Maughan, M. and Pearson, R.G. (2007a) Hydrology, Geomorphology and Water Quality of Four Wet Tropics Streams with Contrasting Land-use Management. In: Arthington, A.H. and Pearson, R.G. (eds.) *Biological Indicators of Ecosystem Health in Wet Tropics Streams*. Final Report, Task 3, Catchment to Reef Research Program. Cooperative Research Centre for Tropical Rainforest Ecology and Management and Cooperative Research Centre for the Great Barrier Reef, pp. 14-78.

* **Connolly**, N.M., Pearson, B. and Pearson, R.G. (2007b) Macroinvertebrates as Indicators of Ecosystem Health in Wet Tropics Streams. In: Arthington, A.H. and Pearson, R.G. (eds.) *Biological Indicators of Ecosystem Health in Wet Tropics Streams*. Final Report, Task 3, Catchment to Reef Research Program. Cooperative Research Centre for Tropical Rainforest Ecology and Management and Cooperative Research Centre for the Great Barrier Reef, pp. 128-175.

* **Connolly**, N.M., Crossland, M.R. and Pearson, R.G. (2004) Effect of low dissolved oxygen on survival, emergence and drift in tropical stream macroinvertebrate communities. *Journal of the North American Benthological Society* 23: 251-270.

Costa Jr., O.S., Leao, Z.M., Nimmo, M. and Attrill, M.J. (2000) Nutrification impacts on coral reefs from northern Bahia, Brazil. *Hydrobiologia* 440: 370-415.

* **De'ath**, G. and Fabricius, K.E. (2010) Water quality as a regional driver of coral biodiversity and macroalgal cover on the Great Barrier Reef. *Ecological Applications* 20: 840-850.

* **De'ath**, G. and Fabricius, K.E. (2008) *Water Quality of the Great Barrier Reef: Distributions, Effects on Reef Biota and Trigger Values for the Protection of Ecosystem Health*. Research Publication No. 89. Great Barrier Marine Park Authority, Townsville, 104 pp.

Dennison, W.C., Orth, R.J., Moore, K.A., Stevenson, C., Carter, V., Kollar, S., Bergstrom, P.W. and Batiuk, R.A. (1993) Assessing water quality with submersed aquatic vegetation: habitat requirements as barometers of Chesapeake Bay health. *BioScience* 43: 86-94.

European Community (2005) Water Framework Directive (WFD). Proposal for a Directive of the European Parliament and of the Council establishing a Framework for Community Action in the field of Marine Environmental Policy (Marine Strategy Directive) [SEC(2005) 1290], Brussels, 24 October 2005.

Environmental Protection Agency (2006) *Queensland Water Quality Guidelines*. The State of Queensland, Environmental Protection Agency (http://www.derm.qld.gov.au/register/p01414aa.pdf)

* **Fabricius**, K.E. (in press) Eutrophication. In: Hopley D (ed.): *Encyclopedia of modern coral reefs*. Springer.

* **Fabricius**, K.E. (2010) Factors determining the resilience of coral reefs to eutrophication: A review and conceptual model. In: Dubinski, Z. (ed.) *Corals and Coral Reefs*. Springer.

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

Fabricius, K.E. and De'ath, G. (2001) Biodiversity on the Great Barrier Reef: Large-scale patterns and turbidity-related local loss of soft coral taxa. In: Wolanski, E. (ed.) *Oceanographic Processes of Coral Reefs: Physical and Biological Links in the Great Barrier Reef*. CRC Press, London, pp. 127-144.

Fabricius, K.E., and De'ath, G. (2004) Identifying ecological change and its causes: a case study on coral reefs. *Ecological Applications* 14: 1448-1465.

Fabricius, K., De'ath, G., McCook, L., Turak, E. and Williams, D. (2005) Changes in algal, coral and fish assemblages along water quality gradients on the inshore Great Barrier Reef. *Marine Pollution Bulletin* 51: 384-398.

Fabricius, K.E., Wild, C., Wolanski, E. and Abele, D. (2003) Effects of transparent exopolymer particles, muddy sediments and muddy marine snow on the survival of hard coral recruits. *Estuarine, Coastal and Shelf Science* 57: 613-621.

* **Faithful** J.W., Brodie, J., Hooper, A., Leahy, P., Henry, G., Finlayson, W. and Green, D. (2006) *Plot-Scale Runoff of Nutrients and Sediments under Varying Management Regimes on Banana and Cane Farms in the Wet Tropics, Queensland, Australia*. Project Report, Task 1, Catchment to Reef Program. ACTFR Report No 05/03. Australian Centre for Tropical Freshwater Research (ACTFR), James Cook University, Townsville, 37 pp.

Fourqurean, J.W. and Cai, Y. (2001) Arsenic and phosphorus in seagrass leaves from the Gulf of Mexico. *Aquatic Botany* 71: 247-258.

Fourqurean, J.W., Moore, T.O., Fry, B. and Hollibaugh, J.T. (1997) Spatial and temporal variation in C:N:P Ratios, δ^{15}N and δ^{13}C of eelgrass *Zostera marina* as indicators of ecosystem processes, Tomales Bay, California, USA. *Marine Ecology Progress Series* 157: 147-157.

* **Godfrey**, P. (2009*) Influence of flow seasonality on the recruitment ecology of riverine fishes from lowland Wet Tropics rivers.* PhD Thesis, James Cook University.

* **Godfrey**, P., Arthington, A.H., Pearson, R.G., Karim, F. and Wallace, J.S. (2010) *Fish ecology, movement patterns and hydrological connectivity in the Tully-Murray floodplain*. Presentation to 'Impacts and Achievements of the MTSRF', 2010 Annual Conference of the Marine and Tropical Sciences Research Facility (MTSRF), 18-20 May, Cairns (http://www.rrrc.org.au/news/downloads/paul_godfrey_day1_catchmenttoreef.pdf)

GBRMPA (2009) Water Quality Guidelines for the Great Barrier Reef Marine Park. Great Barrier Reef Marine Park Authority (GBRMPA), Townsville (http://www.gbrmpa.gov.au/corp_site/key_issues/water_quality/water_quality_guidelines)

* **Grech**, A. (2010) *Spatial models and risk assessments to inform marine planning at ecosystem-scales: dugongs and seagrasses as a case study*. PhD. School of Earth and Environmental Sciences, James Cook University, Townsville.

* **Grech**, A., Coles, R., Waycott, M., Rasheed, M. and McKenzie, L. (2010) Risk assessment for coastal seagrass habitats of the Great Barrier Reef World Heritage Area. Outputs from the risk assessment working group. In: Waycott, M. and McKenzie, L.J. (eds.) *Final Report to the Marine and Tropical Sciences Research Facility: Project 1.1.3 – Condition, trend and risk in coastal habitats: Seagrass indicators, distribution and thresholds of potential concern*. Reef and Rainforest Research Centre Limited, Cairns, Australia.

* **Grice**, A.M., Loneragan, N.R. and Dennison, W.C. (1996) Light intensity and the interactions between physiology, morphology and stable isotope ratios in five species of seagrass. *Journal of Experimental Marine Biology and Ecology* 195: 91-110.

Harrington, L., Fabricius, K., Eaglesham, G. and Negri, A. (2005) Synergistic effects of diuron and sedimentation on photosynthesis and survival of crustose coralline algae. *Marine Pollution Bulletin* 51: 415-427.

Haynes, D., Ralph, P., Prange, J. and Dennison, W. (2000) The Impact of the Herbicide Diuron on Photosynthesis in Three Species of Tropical Seagrass. *Marine Pollution Bulletin* 41: 288-293.

Hortle, K.R. and Pearson, R.G. (1990) The fauna of the Annan River, north Queensland, with reference to the effects of tin mining. *Australian Journal of Marine and Freshwater Research* 41(6): 677-694.

Houk, P., Bograd, S. and van Woesik, R. (2007) The transition zone chlorophyll front can trigger *Acanthaster planci* outbreaks in the Pacific Ocean: Historical confirmation. *Journal of Oceanography* 63: 149-154.

Johannes, R.E., Wiebe, W.J. and Crossland, C.J. (1983) Three patterns of nutrient flux in a coral reef community. *Marine Ecology Progress Series* 12: 131-136.

Jones, R. (2005) The ecotoxicological effects of photosystem II herbicides on corals. *Marine Pollution Bulletin* 51: 495-506.

Jones, R.J. and Kerswell, A.P. (2003) Phytotoxicity of photosystem II (PSII) herbicides to coral. *Marine Ecology Progress Series* 261: 149-159.

Jones, R.J. Müller, J. Haynes, D. and Schreiber, U. (2003) Effects of herbicides diuron and atrazine on corals of the Great Barrier Reef, Australia. *Marine Ecology Progress Series* 251: 153-167.

Kendrick, G.A. (1991) Recruitment of coralline crusts and filamentous turf algae in the Galapagos archipelago: Effect of simulated scour, erosion and accretion. *Journal of Experimental Marine Biology and Ecology* 147: 47-63.

Mackay, S.J., James, C. and Arthington, A.H. (2010) Macrophytes as indicators of stream condition in the wet tropics region, Northern Queensland, Australia. *Ecological Indicators* 10: 330-340.

Marubini F. and Davies P.S. (1996) Nitrate increases zooxanthellae population density and reduces skeletogenesis in corals. *Marine Biology* 127: 319-328.

McMahon, K., Bengtson Nash, S., Eaglesham, G., Müller, J.F., Duke, N. C. and Winderlich, S. (2005) Herbicide contamination and the potential impact to seagrass meadows in Hervey Bay, Queensland, Australia. *Marine Pollution Bulletin* 51: 325-334.

Mellors, J., Waycott, M. and Marsh, H. (2005) Variation in biogeochemical parameters across intertidal seagrass meadows in the central Great Barrier Reef region. *Marine Pollution Bulletin* 51: 335-342.

Negri, A. Vollhardt, C. Humphrey, C. Heyward, A. Jones, R. Eaglesham, G. Fabricius, K. (2005) Effects of the herbicide diuron on the early life history stages of coral. *Marine Pollution Bulletin* 51: 370-383.

Økelsrud, A. and Pearson, R.G. (2007) Acute and post-exposure effects of ammonia toxicity to juvenile barramundi (*Lates calcarifer* [Bloch]). *Archives of Environmental Contamination and Toxicology* 53: 624-631.

Pearson, R.G. (2005) Biodiversity of the freshwater fauna of the Wet Tropics region of north-eastern Australia: patterns and possible determinants. In: E. Bermingham, C.W. Dick and C. Moritz (eds.) *Tropical Rain Forests: Past, Present and Future*. University of Chicago Press, Chicago and London (1004 pp.).

* **Pearson**, R.G. and Stork, N.E. (2007) Catchment to Reef: Water Quality and Ecosystem Health. Chapter 45. In: Stork, N. and Turton, S. (eds.) *Living in a Dynamic Tropical Forest Landscape*. Blackwell Publishing.

Pearson, R.G. and Connolly, N. (2000) Nutrient enhancement, food quality and community dynamics in a tropical rainforest stream. *Freshwater Biology* 43: 31-42.

Pearson, R.G. and Penridge, L.K. (1987) The effects of pollution by organic sugar mill effluent on the macro-invertebrates of a stream in tropical Queensland. *Australian Journal of Environmental Management* 24: 205-215.

* **Pearson**, R.G., Arthington, A.H., Godfrey P.C., Wallace J., Karim, F. and Ellison, M. (2010a) *Ecosystem Health of Wetlands of the Great Barrier Reef Catchment: Tully-Murray Floodplain Case Study*. Final Report to the Marine and Tropical Research Facility. Project 3.7.3. James Cook University, Townsville.

* **Pearson**, R.G., Arthington, A.H., Godfrey P.C., Wallace J. and Karim, F. (2010b) Wetlands and floodplains: Drivers and indicators of ecosystem health. Presentation to 'Impacts and Achievements of the MTSRF', 2010 Annual Conference of the Marine and Tropical Sciences Research Facility (MTSRF), 18-20 May, Cairns (http://www.rrrc.org.au/news/downloads/richard_pearson_day1_catchmenttoreef.pdf)

* **Pearson**, R.G., Crossland, M., Butler, B. and Manwaring, S. (2003) Effects of cane-field drainage on the ecology of tropical waterways. Three volumes. Report on SRDC Projects JCU016 and JCU024. ACTFR Report No. 3/04-1-3. Australian Centre for Tropical Freshwater Research (ACTFR), James Cook University, Townsville.

Perna, C. and Burrows, D.E. (2005) Improved dissolved oxygen status following removal of exotic weed mats in important fish habitat lagoons of the tropical Burdekin River floodplain, Australia. *Marine Pollution Bulletin* 51: 138-148.

Pusey, B.J. and Arthington, A.H. (2003) Importance of the riparian zone to the conservation and management of freshwater fish: a review. *Marine and Freshwater Research* 54: 1-16.

* **Pusey**, B.J., Kennard, M.J. and Arthington, A.H. (2007a) Origins and maintenance of freshwater fish biodiversity in the Wet Tropics region. Chapter 9. In: Stork, N. and Turton, S. (eds.) *Living in a Dynamic Tropical Forest Landscape*. Blackwell Publishing.

* **Pusey**, B.J., Kennard, M.J. and Arthington, A.H. (2007b) Freshwater Fish as Indicators of Ecosystem Health in Wet Tropics Streams. In: Arthington, A.H. and Pearson, R.G. (eds.) *Biological Indicators of Ecosystem Health in Wet Tropics Streams*. Final Report, Task 3, Catchment to Reef Research Program. Cooperative Research Centre for Tropical Rainforest Ecology and Management and Cooperative Research Centre for the Great Barrier Reef, pp. 177-233.

Pusey, B.J., Arthington, A.H. and Read, M.G. (1998) Freshwater fishes of the Burdekin River, Australia: biogeography, history and spatial variation in assemblage structure. *Environmental Biology of Fishes* 53: 303-318.

Redfield, A.C., Ketchum, B.H. and Richards, F.A. (1963) The influence of organisms on the composition of sea-water. In: Hill MN (ed.) *The Sea*. Volume 2. Interscience, New Your, pp 26-77.

Renegar, D.A. and Riegl, B.M. (2005) Effect of nutrient enrichment and elevated CO_2 partial pressure on growth rate of Atlantic scleractinian coral *Acropora cerviconis*. *Marine Ecology Progress Series* 293: 69-76.

Rosser, Z. and R.G. Pearson (1995) Responses of rock fauna to physical disturbance in two Australian tropical rainforest streams. *Journal of the North American Benthological Society* 14: 183-196.

Schaffelke, B., Mellors, J. and Duke, N.C. (2005) Water Quality in the Great Barrier Reef Region: Responses of mangrove, seagrass and macroalgal communities. *Marine Pollution Bulletin* 51: 279-296.

* **Sheaves**, M. and Johnston, R. (2010) Implications of Spatial Variability of Fish Assemblages for Monitoring of Australia's Tropical Estuaries. *Aquatic Conservation Marine and Freshwater Systems* 20: 348-356.

* **Sheaves**, M., Connolly, R. and Johnston, R. (2010) *Assessment of estuarine indicators in tropical ecosystems.* Project 3.7.1 Report to the Australian Government's Marine and Tropical Sciences Research Facility, Cairns.

* **Sheaves**, M., Connolly, R. and Johnston, R. (2007) *Assessment of techniques for determining the health of tropical estuarine ecosystems*. Report to the Australian Government's Marine and Tropical Sciences Research Facility, Cairns (34pp.).

Smith, V.S., Kimmerer, W.J., Laws, E.A., Brock, R.E. and Walsh, T.W. (1981) Kaneohe Bay sewage diversion experiment: perspectives on ecosystem responses to nutritional perturbation. *Pacific Science* 35: 279-340.

van Woesik, R., Tomascik, T. and Blake, S. (1999) Coral assemblages and physico-chemical characteristics of the Whitsunday Islands: evidence of recent community changes. *Marine and Freshwater Research* 50: 427-440.

Wagner, D.E., Kramer, P. and van Woesik, R. (2010) Species composition, habitat and water quality influence coral bleaching in southern Florida. *Marine Ecology Progress Series* 408: 65-78.

* **Wallace**, J.S., Hawdon, A., Keen, R. and Stewart, L. (2009a) The role of coastal floodplains in generating sediment and nutrient fluxes to the Great Barrier Reef lagoon in Australia. *International Journal of Ecohydrology and Hydrobiology* 8: 183-194.

* **Wallace**, J.S., Hawdon, A., Keen, R. Stewart, L. and Kemei, J. (2009b) Flood water quality and marine sediment and nutrient loads from the Tully and Murray catchments in north Queensland, Australia. *Marine and Freshwater Research* 60: 1123-1131.

* **Waycott**, M., Longstaff, B. and Mellors, J. (2005) Seagrass population dynamics and water quality in the Great Barrier Reef Region: A review and future research directions. *Marine Pollution Bulletin* 51: 343-350.

* **Waycott**, M., and McKenzie, L. (2010) Indicators and thresholds of concern for seagrass ecosystem health for the Great Barrier Reef. Projects 1.1.3 and 3.7.1 Final Report to the Marine and Tropical Sciences Research Facility. Reef and Rainforest Research Centre Limited, Cairns (56 pp.).

Weber, M., Lott, C. and Fabricius, K.E. (2006) Different levels of sedimentation stress in a scleractinian coral exposed to terrestrial and marine sediments with contrasting physical, geochemical and organic properties. *Journal of Experimental Marine Biology and Ecology* 336: 18-32.

Wolanski, E., Richmond, R., McCook, L. and Sweatman, H. (2003) Mud, marine snow and coral reefs. *American Scientist* 91: 44-51.

* **Wooldridge**, S.A. (2009) Water quality and coral bleaching thresholds: formalising the linkage for the inshore reefs of the Great Barrier Reef (Australia). *Marine Pollution Bulletin* 58: 745-751.

* **Wooldridge**, S.A. and Done, T.J. (2009) Improved water quality can ameliorate effects of climate change on corals. *Ecological Applications* 19: 1492-1499.