Managing local water quality to help combat climate change impacts on the Great Barrier Reef, Australia

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Acronyms Used In This Report

AEP............... Annual exceedance probability
AIMS............. Australian Institute of Marine Science
CO_2............... Carbon dioxide (chemical formula)
DIN................ Dissolved inorganic nitrogen
DIP................ Dissolved inorganic phosphorous
GBR.............. Great Barrier Reef
IPCC............. Intergovernmental Panel on Climate Change
LUF............... Land use factor
MODIS.......... Moderate-resolution Imaging Spectroradiometer
MPA.............. Marine Protection Area
SST(s)........... Sea-surface temperature(s)
UTBT............ Upper thermal (coral) bleaching threshold

Acknowledgements

I thank Ray Berkelmans (AIMS) for making available the data that underpins the time-integrated bleaching thresholds for the inshore reefs of the Great Barrier Reef (see Figure 4a).

Introduction

The waters of the Great Barrier Reef (GBR) are warming and are predicted to continue to do so at an accelerating rate throughout the 21st Century (Figure 1; IPCC 2001). The rising temperatures are predicted to cause increased coral bleaching, coral mortality and biodiversity depletion that will have serious consequences for reef biodiversity, ecology, appearance and dependent recreational use and economic activity (Hoegh-Guldberg 1999; Done *et al.* 2003; Hoegh-Guldberg and Hoegh-Guldberg 2004; Wooldridge *et al.* 2005). The severity of the problem is highlighted by predictions that the inshore reef areas of the central GBR may be severely set back or even transformed to a non-coral dominated state by as early as 2030 (Wooldridge *et al.* 2005).

As a general rule, coral bleaching is triggered when sea surface temperatures (SSTs) exceed the 'normal' mean summer maximum temperatures by 1-2°C for more than a few days (Hoegh-Guldberg 1999). For most tropical shallow-water coral reefs this results in an upper thermal bleaching threshold (UTBT) of ~30°C. However, emerging research highlights the fact that the UTBT for most corals is far from static (Figure 2). In particular, it has been demonstrated that corals which regularly experience poor water quality are less 'resistant' to thermal stress, such that upon exposure to sub-optimal temperatures (>28°C) they display higher bleaching sensitivity (per unit increase in SST) (Figure 3; Wooldridge and Done 2009). Explanation for the negative impact of poor water quality has centered on the potential for elevated levels of dissolved inorganic nitrogen (DIN) to enhance the damaging cellular processes that underpin the thermal bleaching process (Wooldridge 2009a; Wooldridge and Done 2009). Support for this interpretation is found in the strong quantitative relationship that exists between the UTBT of inshore corals on the GBR and the degree of exposure to DIN-rich flood-plume (terrestrial) water (Figure 4a; Wooldridge 2009b). In this case, the variable water quality regime spans ~2°C variation in the UTBT, with the marginal rate of increase (°C) being significantly higher at the lowest DIN exposure levels, i.e. highest water quality (Figure 4b). This empirical result aligns well with the theoretical prediction that the physiological tolerance of symbiotic corals to thermal stress is maximal when external seawater DIN availability falls to levels that cause the intracellular algal symbiont ('zooxanthellae') population to become nitrogen (i.e. growth) limited within the coral host (Wooldridge and Done 2009).

The synergistic linkage between water quality and coral bleaching thresholds provides concrete evidence for the oft-expressed belief that improved coral reef management will increase regional scale resilience of coral reefs to global climate change (Bellwood *et al.* 2004; Marshall and Schuttenberg 2006; McCook *et al.* 2007). Moreover, the linkage enables a modelling framework to be outlined for the inshore reefs of the GBR in which the envelope of future bleaching risks can be mapped as a function of 'local' land management imperative and 'global' warming scenarios (Figure 5; Wooldridge 2009b). In this case, alternative catchment management strategies can be tested for their attendant level of benefit in offsetting future SST increases. The potential ~2°C improvement in UTBT for the most-disturbed inshore GBR reef sites appears significant given that mid-range warming scenarios have SSTs on the GBR increasing by ~2-3°C by 2100 (Figure 1; IPCC 2001).

It has been estimated that the post-European development of the GBR catchment has resulted in an approximate 4-10 fold (average) increase in DIN loads entering the GBR lagoon (Furnas 2003; Wooldridge *et al.* 2006). The majority of this DIN is sourced from intensely fertilised agricultural lands (viz. sugarcane, banana plantations) that tend to be located within close proximity of the coast (Figure 6; Furnas 2003; Brodie *et al.* 2003). Since excessive fertiliser application rates and poor land-use practices dominate the increasing DIN response, landscape nutrient budget models highlight the significant capacity for effective management initiatives to aid remediation; albeit at considerable social and economic costs to local farming communities (Armour *et al.* 2007; Roebeling *et al.* 2007).

In this report, I endeavor to simulate the beneficial impact of end-of-catchment DIN reductions (10%, 30%, 50% and 70%) in raising the bleaching resistance (i.e. the UTBT, °C) of inshore reefs between Townsville and Cooktown. Such regional-scale information is vital for helping to identify management strategies that delay, possibly even prevent, the imminent mortality risk and loss in resilience that currently characterises these inner to mid-shelf reefs of the GBR.

Study site

The reefs and other ecosystems of the GBR are embedded on a shallow coastal shelf that varies in width from 50 km in the north to over 200 km in the south (Figure 7). Water depths increase across the shelf to a maximum of 100 m before the shelf break and average about 35 m. The matrix of reef structures on the outer margins of the shelf creates an incomplete barrier to the deep oceanic waters of the Coral Sea. The open water body contained between this outer barrier and the coast is commonly known as the GBR lagoon. The shallowness and width of the GBR lagoon plays an important role in the retention of imported material; distinguishing the GBR system from many other Indo-Pacific coral reefs surrounded by deeper water. The nutrients and sediments held and recycling in the inner-shelf region of the GBR lagoon are dominated by terrestrial sources (Furnas *et al.* 1995; Furnas 2003). The numerous rivers systems that drain the 423,000 km^2 catchment adjoining the GBR lagoon provide the primary delivery mechanism for this terrestrial material (Furnas 2003; Brodie *et al.* 2003).

In general, areas in the northern parts of the GBR catchment remain relatively undisturbed, with limited cropping and low cattle stocking rates (Furnas 2003; Brodie *et al.* 2003). As such, the dissolved nutrient and particulate matter concentrations in coastal waters of the far northern GBR are generally regarded as representative of water quality under minimally altered conditions. The central and southern regions of the GBR catchment, however, are characterised by high catchment-wide cattle stocking rates and intensive cropping activities on the coastal floodplains. River discharges from these developed catchments have elevated dissolved nutrient and particulate matter concentrations, for example, DIN concentrations in flood flow for these rivers are up to thirty times that of rivers in the northern undeveloped catchments (140-1400 $\mu g.L^{-1}$ compared to 14-70 $\mu g.L^{-1}$) (Furnas 2003).

In this study, particular attention is given to the region between Townsville and Cooktown, which includes the Burdekin, Herbert, Tully, Johnstone, Russell, Barron, Daintree, Endeavour, Jeannie and Normanby river systems. The hydrologic characteristics of these river systems (as for most of the larger GBR river systems) is defined by a sharp division between a summer wet season state, lasting a short period annually (one to eight weeks) and a prolonged dry season condition. In the dry season, little or no freshwater discharge occurs and the estuaries behave as tidal inlets with a sharp division between freshwater (salinity 0 psu) and seawater (salinity 36 psu). In the wet season, estuaries are totally river dominated with the 'estuarine' mixing zone (where the salinities range from 0 to 36 psu) lying outside the river mouth on the continental shelf. A salt wedge exists but lies outside the river itself as the river flushes fresh throughout its depth profile to the sea. Hydrodynamic simulations demonstrate that after leaving the river, the 'flood plume' mixing zone is generally advected northwards due to a combination of coriolis force and barotropic hydrodynamics (Wolanski and van Senden 1983; King *et al.* 2001, 2002). The extent of cross-shelf dispersion associated with a particular flood event is affected by both discharge volume and the prevailing wind conditions.

The frequency with which the inner-shelf areas of the GBR lagoon experience plume water varies greatly with location along the GBR coast (Devlin *et al.* 2001); reflecting the likelihood of high intensity rainfall falling on the adjacent coast. Plumes occur in inner-shelf waters of the Wet Tropics coast (Herbert to Daintree Rivers) at least annually and often twice a year; the Dry Tropics coast, which includes the Burdekin River, produces significant plumes approximately at three- to four-year intervals; the Endeavour to Normanby Rivers on the far northern coast produce significant plumes at approximately two- to three-year intervals. The historical record shows that for large (typically monsoon-related) rainfall events, the individual river plumes often merge together and stretch over large portions of the inner-shelf areas; but rarely exceed more than 30 km from the coast (Figure 7). These large flood plumes bath inshore and some mid-shelf reef habitats in nutrient-rich water for periods of several weeks (Devlin *et al.* 2001; Devlin and Brodie 2005).

The initial fate of the terrestrial material that is delivered to the GBR lagoon can be understood from the flood plume sampling of Devlin *et al.* (2001). In the initial mixing zone, water velocity is reduced and changes in pH and salinity promote flocculation of particulate matter. Most of the river-derived particulate matter initially settles from the plume in this zone (Devlin and Brodie 2005). A remotely-sensed image (MODIS) of the 2005 summer flood event for the central GBR clearly demonstrates this depositional effect around the Burdekin River mouth (Figure 8a). Representative measurements that have previously been sampled across this depositional zone (see Devlin *et al.* 2001; Rodhe *et al.* 2005) are also plotted, demonstrating that particulate concentrations (in this case phosphorus) drop to very low levels only a few kilometres from the river mouth at salinities of 5-10 psu. Dissolved fractions in the river runoff are transported far further than the particulate fractions. For example, typical plots of DIN (and DIP) in relation to salinity within the GBR lagoon in a flood plume (Figure 8b) suggest an essentially conservative dilution process (Devlin *et al.* 2001; Rodhe *et al.* 2005). This conservative mixing behaviour for the dissolved nutrient fractions means that their range of influence may extend across hundreds of kilometres from river mouths.

Important from a biological context, the enriching impact of summer runoff events typically coincides with the period of annual maximum SSTs. Given the shallow shelf depth, and limited intrusion of cool offshore oceanic waters, the inshore SSTs of the central-northern GBR are some of the highest observed across the entire GBR; with monthly averaged summer values ~28°C (Wooldridge and Done 2004).

Modelling the beneficial impact of catchment management in *lowering* the enriching impact of flood plume waters on inshore reefs

Measures of phytoplankton biomass usually provide a better indicator of the nutrient status of reef waters than actual measured nutrient concentrations, since fast growing phytoplankton populations quickly respond to, and subsequently deplete, all available stocks of bio-available nutrients, resulting in localised 'blooms' in population densities (Edwards *et al.* 2003; Furnas *et al.* 2005). The concentration of the photosynthetic pigment Chlorophyll *a*, [Chl *a*], is the most commonly used measure of phytoplankton biomass, and hence is also oft- reported as an indicator of the eutrophication status of coastal reef waters.

Within the GBR lagoon, there exists a strong relationship between [Chl *a*] and the flood-plume delivery of terrestrial DIN (Wooldridge *et al.* 2006), which reflects the understanding that DIN-availability usually limits summer phytoplankton biomass in the coastal waters of the GBR (Furnas *et al.* 2005). As highlighted by Figure 8b, during the initial (several days) period before biological uptake-rates becomes significant, the concentration of DIN is directly related to the salinity of the plume water, reflecting the degree of dilution by low-nutrient shelf waters (Devlin and Brodie 2005). Recently, Wooldridge *et al.* (2006) utilised this *conservative* mixing attribute of DIN to infer the enriching impact of runoff events from the various river systems that drain the GBR catchments – the rationale being that a given runoff:seawater dilution ratio, and broad-scale differences in [Chl *a*] observed between river systems, could be attributed to the end-of-catchment concentration of DIN in the discharging runoff. In this way, a decision support model (viz. *ChloroSim*) was developed that enables the enriching impact of river-specific flood plumes to be mapped (and varied) as a function of their (model 'tuneable') end-of-catchment flood concentration of DIN.

For the present study, the *ChloroSim* decision support model was used to map the impact of 10%, 30%, 50% and 70% reductions in end-of-catchment DIN for the Burdekin, Herbert, Tully, Johnstone, Russell, Barron, Daintree, Endeavour, Jeannie and Normanby river systems. Rather than considering the differences arising from a single event, the simulation was run across an historic thirty-year archive (1969-1998) of runoff events (King *et al.* 2002); the ensemble of results enabling the spatial mapping (2 km pixel resolution) of the annual exceedence probability (AEP) of specific [Chl *a*] threshold levels (e.g. 0.9 μg.L^{-1}, see following section).

Modelling the beneficial impact of catchment management in ***raising*** the upper thermal bleaching thresholds of inshore reefs

Previous analysis for the inshore reefs of the GBR demonstrates a strong quantitative relationship between an AEP ([Chl *a*] > 0.9 μg.L^{-1}) and their upper thermal bleaching threshold (Figure 4a; Wooldridge 2009b). In this study, I utilised this quantitative relationship to transpose simulated improvements in inshore water quality (viz. lowered AEP ([Chl *a*] > 0.9 μg.L^{-1})) into the equivalent improvement in coral bleaching thresholds. In this way, the impact of a 10%, 30%, 50% and 70% reduction in end-of-catchment DIN was mapped as an equivalent increase (gain) in the upper thermal bleaching threshold (°C) of impacted reefs (Figure 10).

Results and discussion

The model simulations indicate that 'local' reductions in end-of-catchment DIN have the potential to raise the bleaching resistance of the most disturbed inshore reefs by ~2°C in SST equivalence. However, this level of improvement is conditional on relatively high levels (> 30-70%) of DIN reduction. The simulations highlight that the greatest initial gains are made on the fringes of the high DIN-enrichment areas, which reflects the higher marginal rates of improvement in bleaching resistance (°C) at the lower DIN exposure levels, i.e. areas of higher water quality (see Figure 4b). Although the successive improvement in bleaching resistance due to the each level of DIN reduction is self evident, some care is needed in the interpretation of the results, since the uniform reductions (percent) in end-of-river DIN concentrations are based on pre-existing river (flood) loads. For example, to achieve a thirty percent reduction in the end-of-river DIN concentration from a nutrient-rich river system requires a substantially larger absolute reduction in DIN (in terms of μg L^{-1}) than a thirty percent reduction from a nutrient-poor river system. Countering this fact however, is the understanding that the required effort to achieve DIN improvements becomes more difficult (and economically costly) the cleaner the river system (see e.g. Roebeling *et al.* 2007).

In terms of the enriching footprint of terrestrial runoff intrusions, it is important to note that the initial impact will be experienced as a short-term (days to weeks) pulse of high nutrient water, as opposed to a continuing diffuse source. However, the recycling of inorganic nutrients through pelagic food webs (e.g. via nitrification) ensures a longer-term (weeks to months) persistence of the initial enriching impact (Alongi and McKinnon 2005). Generally speaking, this ensures that the period of nutrient enrichment coincides with annual maximum (summer)

SSTs. Because phytoplankton in the water column is a strong competitor for excess DIN (Furnas *et al.* 2005), brief periods in which phytoplankton growth is limited are important ‘ecological windows’ for the maximum (deleterious) enrichment of benthic organisms by DIN. These windows include: (i) the early (several days) stages of a flood plume when high plume turbidity limits the light (intensity) levels needed to support rapid phytoplankton growth (Turner *et al.* 1990; Dagg *et al.* 2004; Devlin and Brodie 2005), and (ii) periods of extreme temperature that exceed optimal growth limits for the ‘bulk’ phytoplankton population, for example, in 1998 when seawater temperature was extremely high and coral bleaching occurred, low [Chl *a*] was observed at Sesoko Island (Okinawa, Japan) despite high concentrations of DIN; the result being explained by a temperature-dependent decrease in the growth rate of the picoplankton size fraction (Tada *et al.* 2003). In this way, the annual co-occurrence of flood plumes and maximum SSTs on the GBR can be understood to enhance the likelihood of dynamic nutrient enrichment of inshore coral populations.

Terrestrial runoff is not the only source of DIN that impacts upon the GBR, with periodic upwelling of deep (nutrient-rich) oceanic water often a dominating feature on the outer-shelf reefs (Andrews and Gentien 1982). Whilst field observations from elsewhere around the world confirm that reefs which are exposed to nutrient upwelling are subject to differentially enhanced thermal bleaching impacts (D’Croz *et al.* 2001; D’Croz and Mate 2004), the oceanic source of this DIN means that its impact remains largely outside the realm of management. It is thus important to reinforce that any perceived management influence is most strictly related to inner-shelf reef areas for which terrestrial nutrients sources are most often the dominating influence (Furnas 2003). However, a better understanding of the spatio-temporal dynamics of DIN loading across the entire GBR is necessary for identifying those areas most vulnerable to heat stress. Within the GBR, DIN loading is typically highest at coastal locations that are exposed to terrestrial runoff, lowest at mid-shelf locations, and moderate at offshore (upwelling) locations (see e.g. Sammarco *et al.* 1999). All things being equal, it is thus predicted that the mid-shelf reefs of the GBR should display the highest resistance to heat stress. It follows that the design of a marine protected area (MPA) network that aims to spread the risk of future bleaching impacts (sensu Done 2001; Wooldridge and Done 2004; Game *et al.* 2008) should differentially favour the selection of mid-shelf reefs.

Previous consideration of the role of water quality in promoting resilient (healthy) coral communities has primarily focused on the recoverability side of coral mortality events (see review by Fabricius 2005). In this case, reef locations which regularly experience good water quality (i.e. low sediment and nutrient loads) are judged favourably in term of: (i) promoting the re-establishment of disturbed reef sites with new coral recruits, due to enhanced success in the chancy process of larval arrival, settlement, post-settlement survival, and growth; and (ii) limiting the potential for faster growing seaweeds to out-compete the recovery of the surviving (remnant) corals and new coral recruits. Importantly, this recovery-side aspect of water quality complements the bleaching resistance process outlined in this study. In this way, ‘local’ management actions leading to lower DIN enrichment levels are predicted to benefit *both* coral survivorship and recovery in response to thermal stress (bleaching) events.

Yet, whilst promising as a beneficial mitigation (adaptation) strategy, water quality improvements alone are <u>not</u> the ‘silver bullet’ needed to ensure the long-term survival prospect of the inshore reefs of the GBR given the threat of climate change. Instead, they must be considered alongside ‘global’ strategies that aim to lower ocean warming rates via reduction in greenhouse gas emissions (particularly CO_2). Simple logic suggests that in order to be effective, future warming of SSTs must not exceed the potential 1-2°C gain in a coral’s thermal tolerance due to water quality improvements. Current ‘business-as-usual’ SST trajectories appear to be headed well beyond this 2°C envelope (IPCC 2001). Future work by research supported by MTSRF Project 2.5i.4 funding is aimed at identifying the envelope of ‘global’ and ‘local’ management imperative needed to maintain a healthy inshore reef complex on the GBR.

Concluding comments

This study highlights that a major water quality program effective in reducing ambient DIN loadings could decrease bleaching probability across the whole range of temperatures predicted for the inshore GBR by the year 2100. Indeed, for the most ‘at risk’ inshore areas, the potential magnitude of this improvement has been shown to be equivalent to ~2.0°C in relation to the upper thermal bleaching threshold; though in this case, a potentially cost-prohibitive reduction in end-of-river DIN of > 30-70% would be required. Integrated socio-economic modelling will be required to understand (optimise) the alternate tradeoffs that the new modelling framework facilitates. Whereas there is hope, if not confidence, that adaptation of the coral zooxanthellae partnership or composition shifts towards a more thermally-tolerant suite of coral species could keep coral reef ‘resistance’ ahead of rising temperatures, regional-scale reductions in ambient DIN loads are amenable to management, and therefore represent a rational strategy for ameliorating climate change effects on coral reefs. Importantly, this fact reinforces the crucial role of ‘local’ land management strategies to ‘buy time’ for the coral-zooxanthellae endosymbiosis and the numerous goods and services for which it is directly (or indirectly) responsible.

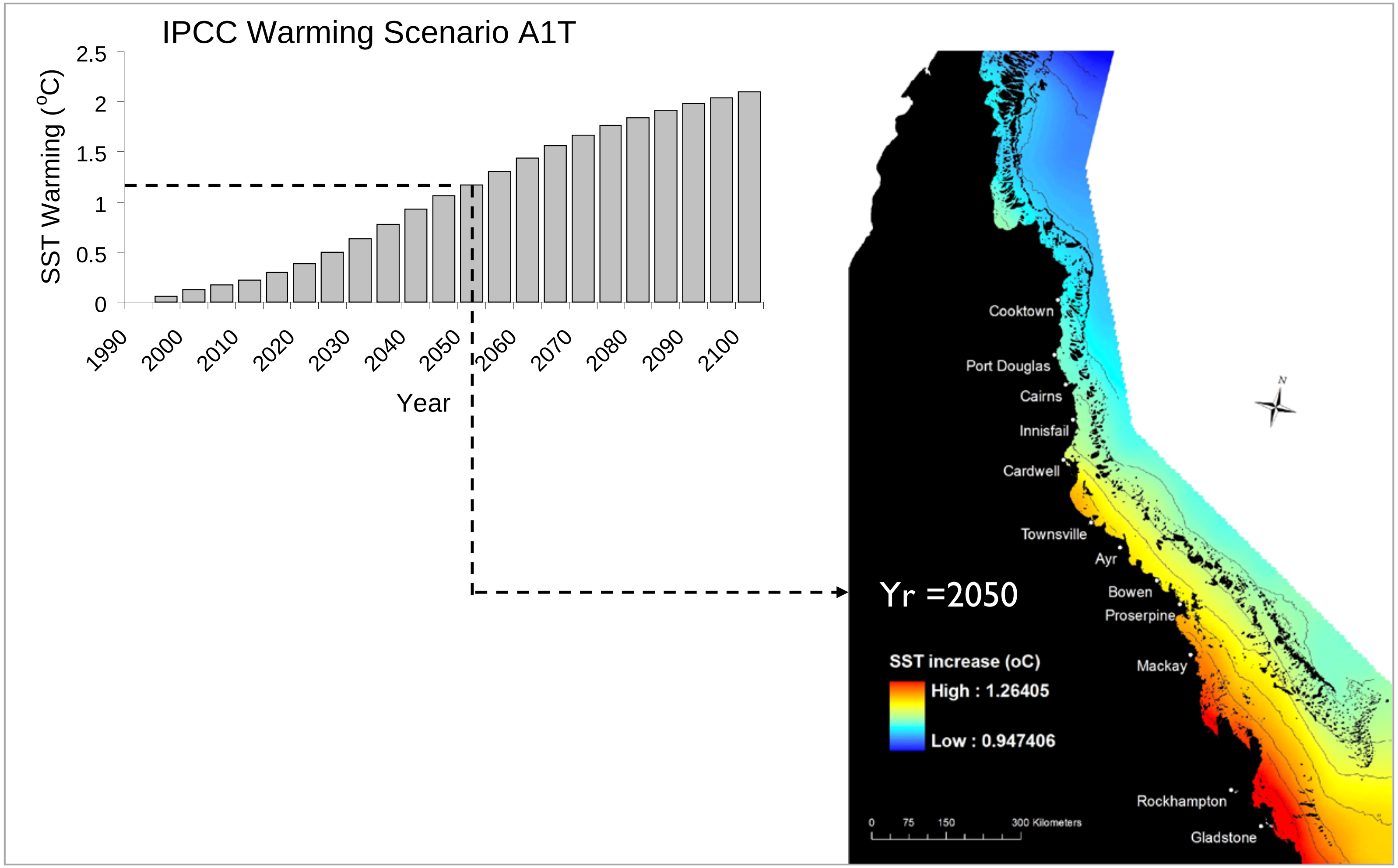

Figure 1: Predicted increase in SST (°C) for the Great Barrier Reef in response to a 'mid-range' IPCC warming scenario.

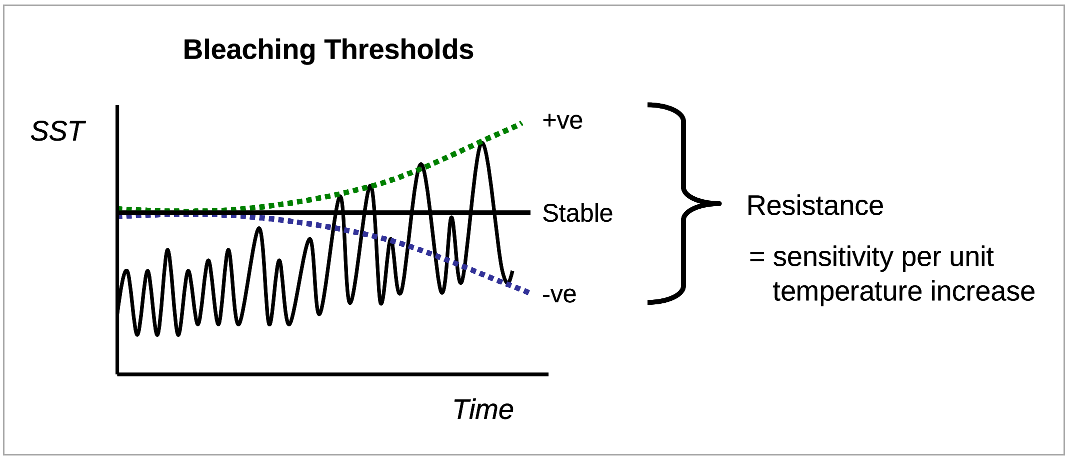

Figure 2: Schematic representation of trends in sea temperatures (solid line) and 'resistance' to coral bleaching (dotted lines). Anthropogenic pressures tend to reduce resistance through time (falling dotted line). Prospective mechanisms that could increase resistance (rising dotted line) include: (i) endosymbiont reshuffling (Berkelmans and van Oppen 2006), (ii) community composition shifts towards corals that can counter the bleaching response via access to stored tissue reserves (Loya *et al.* 2001) or heterotrophic energy sources (Borell and Bischof 2008), (iii) region-scale amelioration of poor water quality (Wooldridge and Done 2009; Wooldridge 2009b).

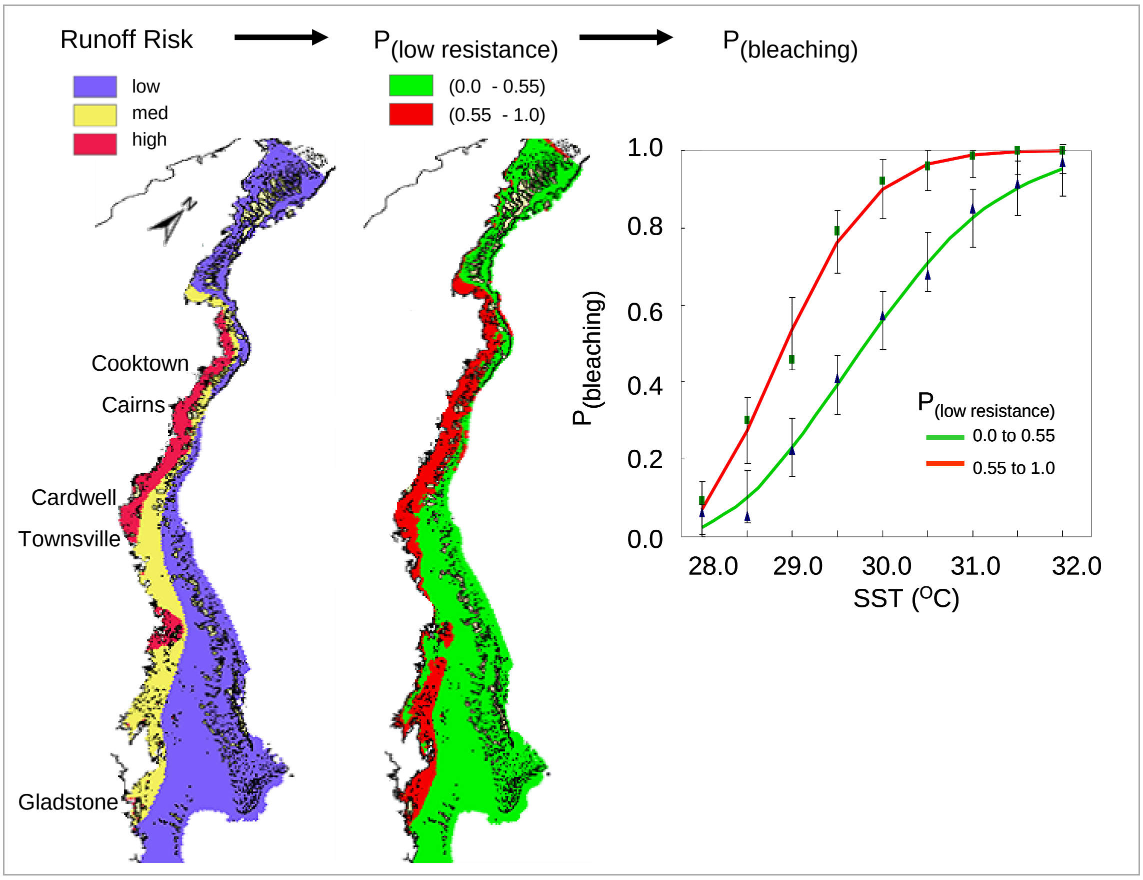

Figure 3: Regional-scale coral bleaching analysis on the GBR (after Wooldridge and Done 2009). Inshore coral reef areas with high runoff exposure risk are shown to correspond (in a probabilistic sense) with reefs that displayed a lower *resistance* to thermal stress (red zone) during the 1998 and 2002 mass bleaching events. Accumulated reef responses (observed) from within the low *resistance* (red zone) areas confirm the increased *risk* of bleaching (per unit increase in SST), and reflect an averaged lowering in upper thermal bleaching threshold of ~1.0-1.5°C.

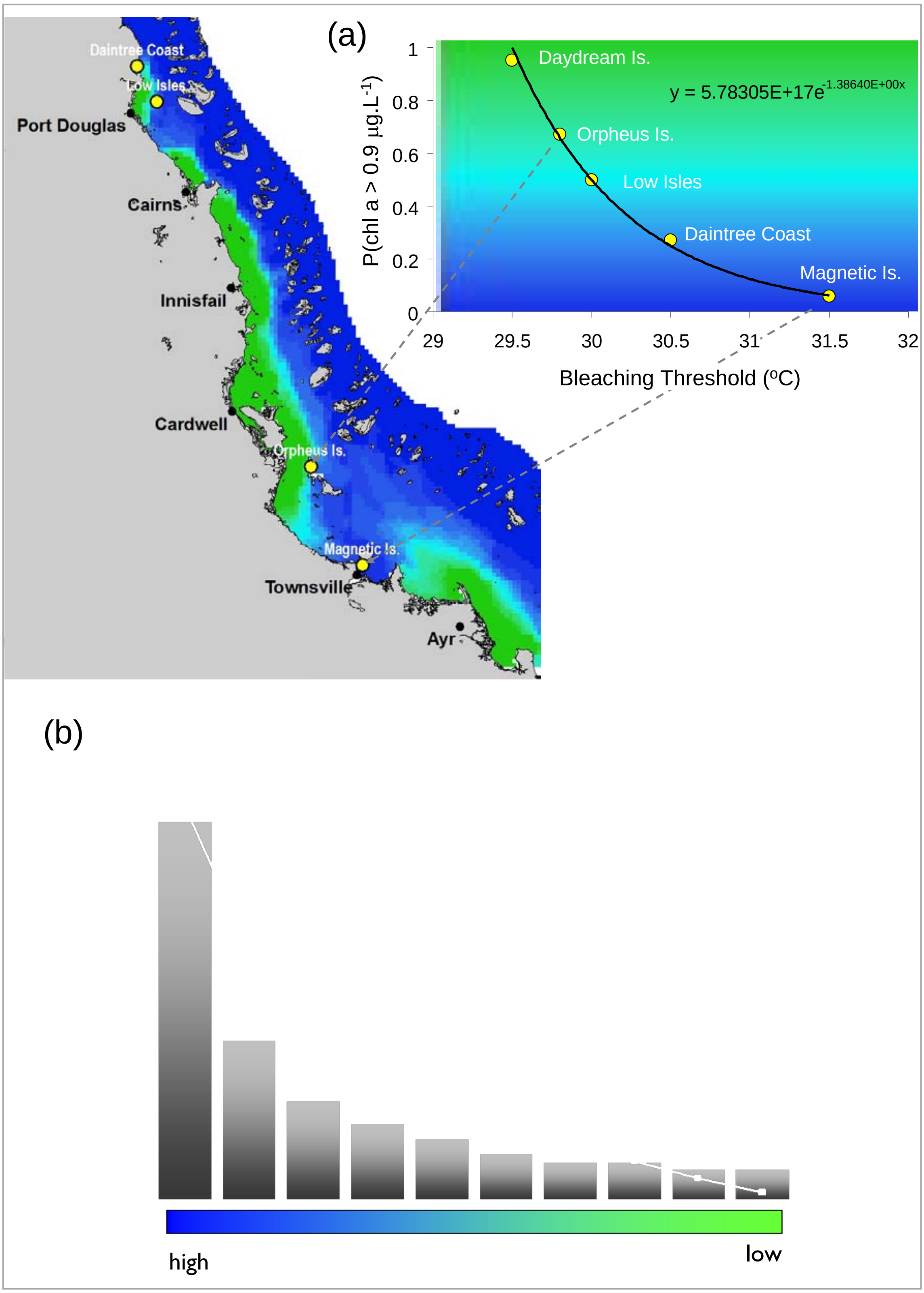

Figure 4: (a) Quantitative linkage between upper thermal bleaching limits (°C) and the degree of exposure to nutrient enriched terrestrial waters. Coastal reef waters with high DIN-enriching impact are characterised by a higher annual exceedence probability (AEP) of [Chl *a*] > 0.9 µg L^{-1}. (b) Marginal (bar) and cumulative (line) increase in coral bleaching threshold (°C) across the (normalised) inshore DIN-enrichment gradient. The relationship links the greatest opportunity for improvement with the highest levels of terrestrial water quality improvement.

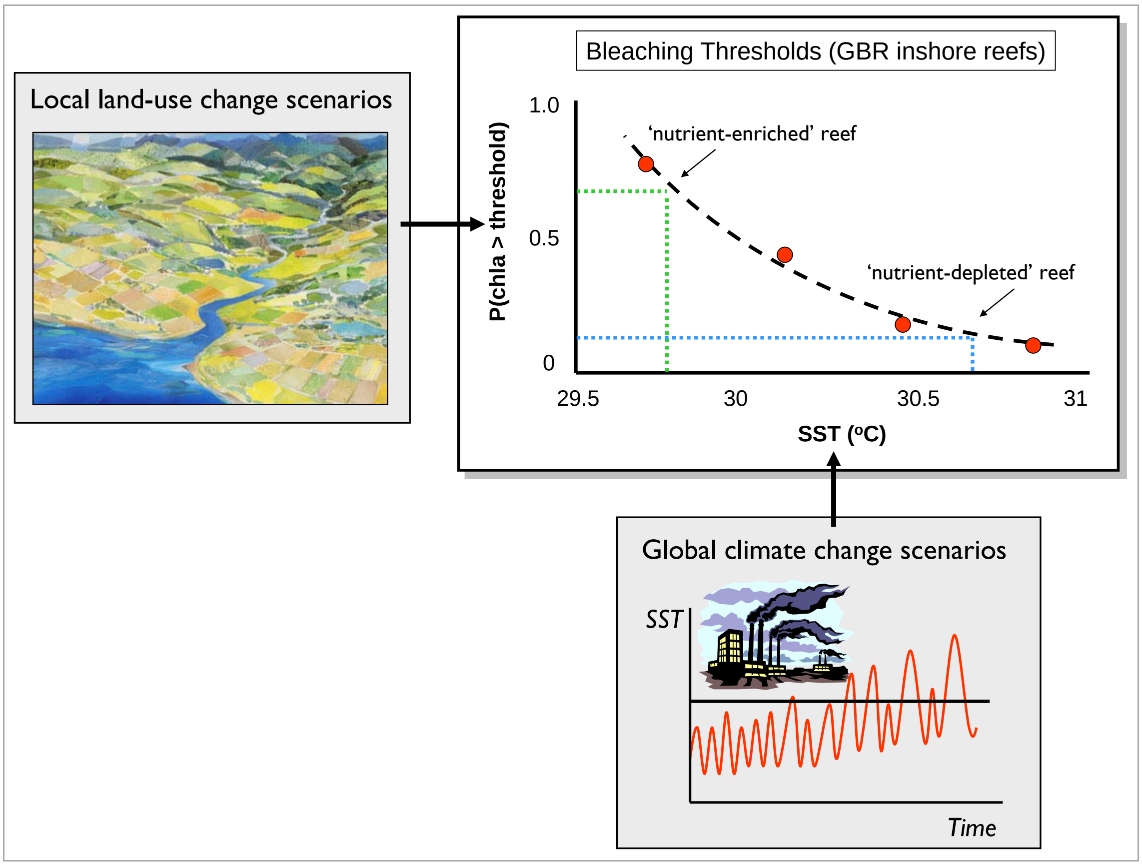

Figure 5: Conceptual modelling framework that enables the impact of 'local' (viz. water quality) and 'global' (viz. CO_2 / temperature reduction) management strategies to be assessed in terms of their *joint* (conditional) potential to reduce the future likelihood of mass coral bleaching on the Great Barrier Reef.

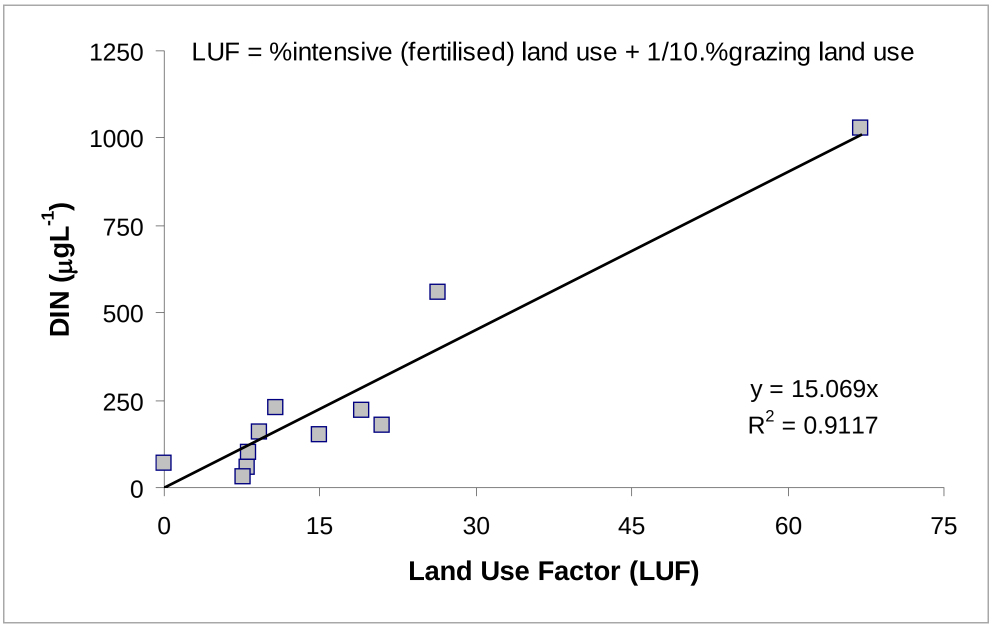

Figure 6: DIN export concentrations as a function of the proportion of fertilised land-use (LUF) in selected GBR catchments (after Wooldridge *et al.* 2006). The assumption that grazing lands contribute only one-tenth of the DIN export per area compared to fertilised cropping lands is based on a number of comparison studies summarised in Brodie and Mitchell (2005).

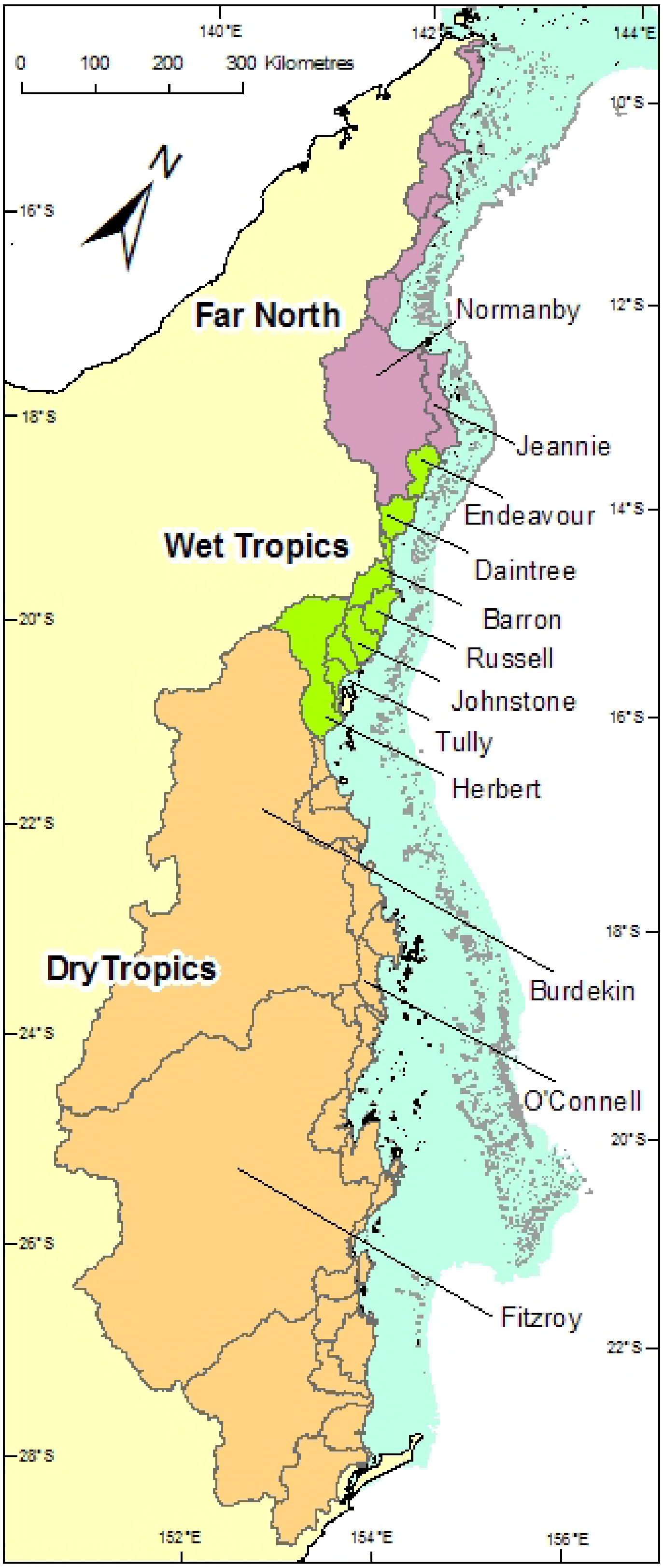

Figure 7: The Great Barrier Reef and its catchments.

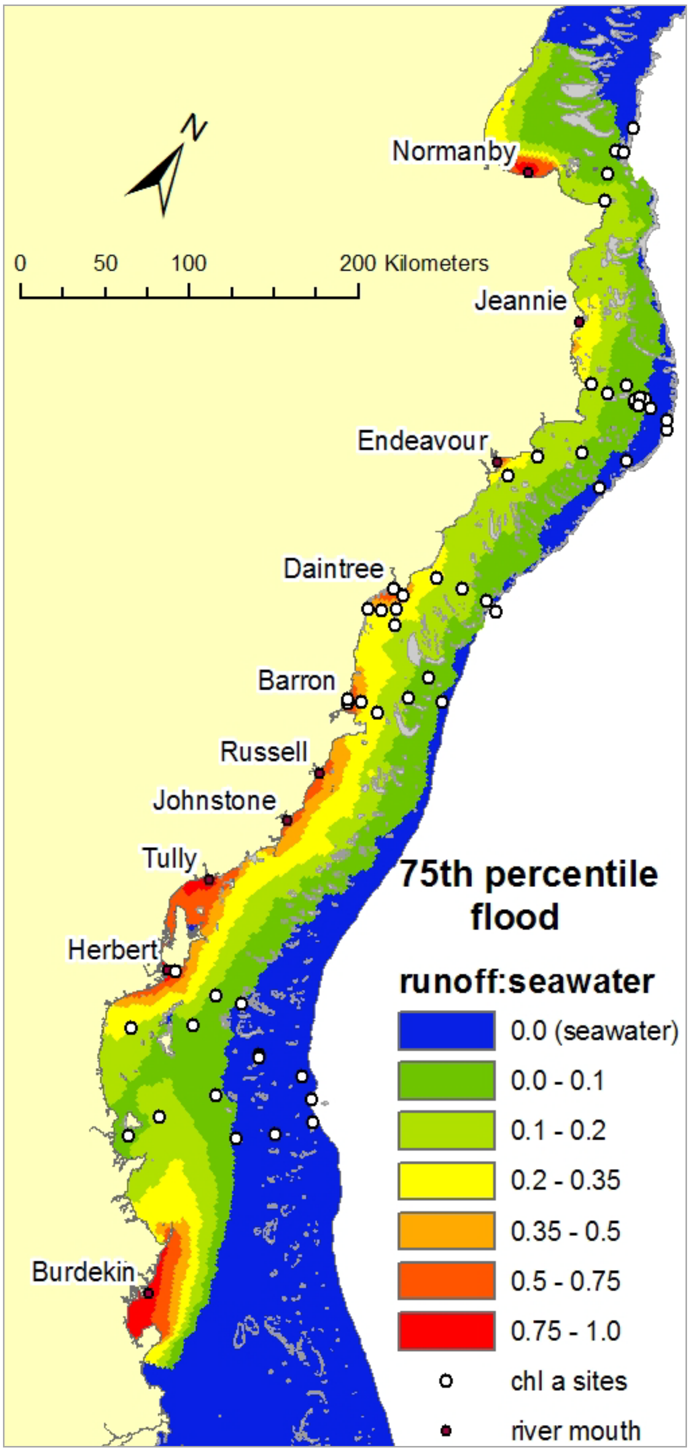

Figure 8: Flood plume (runoff:seawater) dilution rates within the GBR lagoon for a 75th percentile flood event.

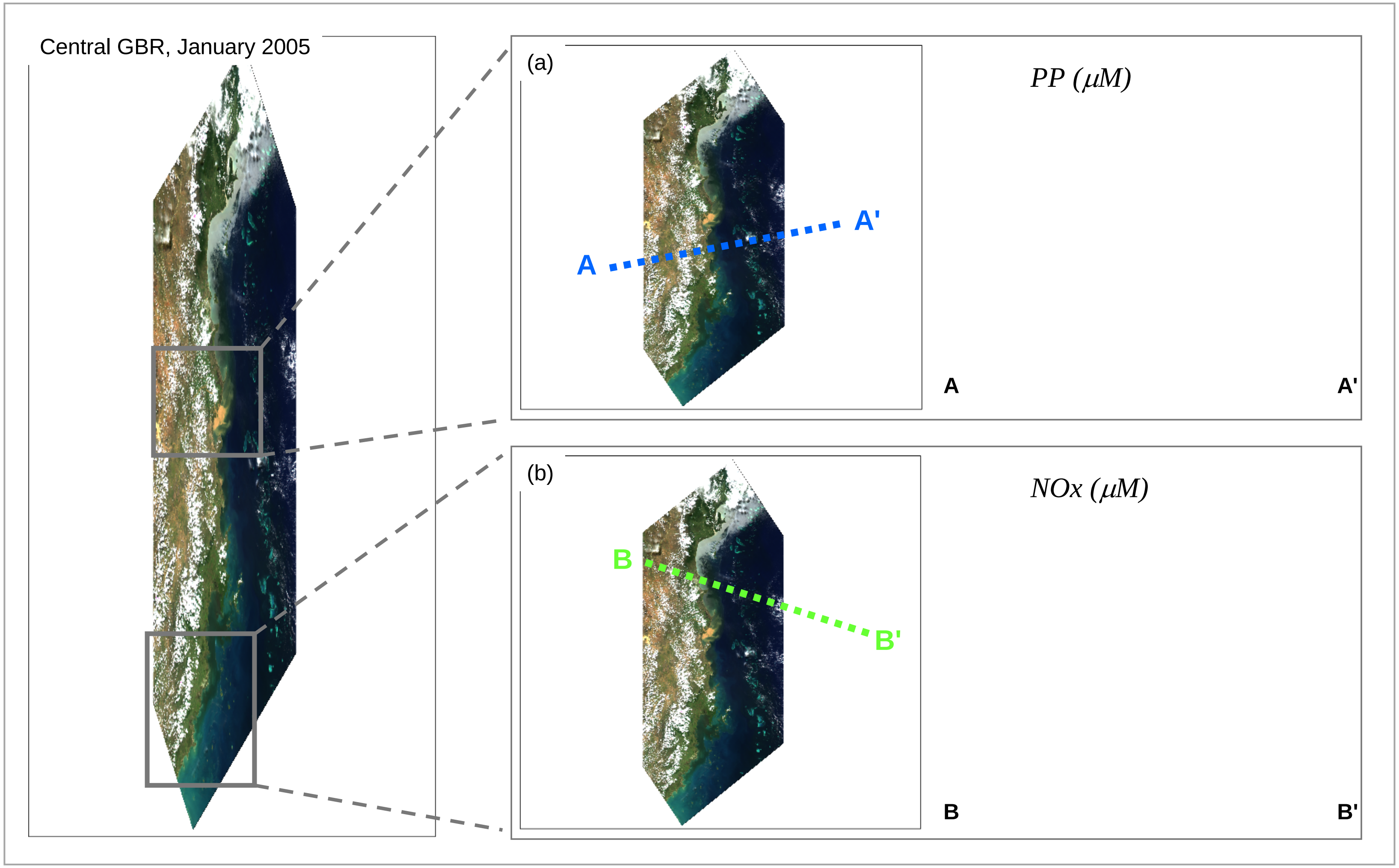

Figure 9: MODIS image of the 2005 summer flood event on the central GBR with representative water quality measurements as previously sampled by Devlin *et al.* 2001. (a) Deposition of particulate material from the Burdekin River plume. (b) Extensive phytoplankton bloom in response to the flood plume load of dissolved inorganic nutrients from the Proserpine, O'Connell and Pioneer Rivers.

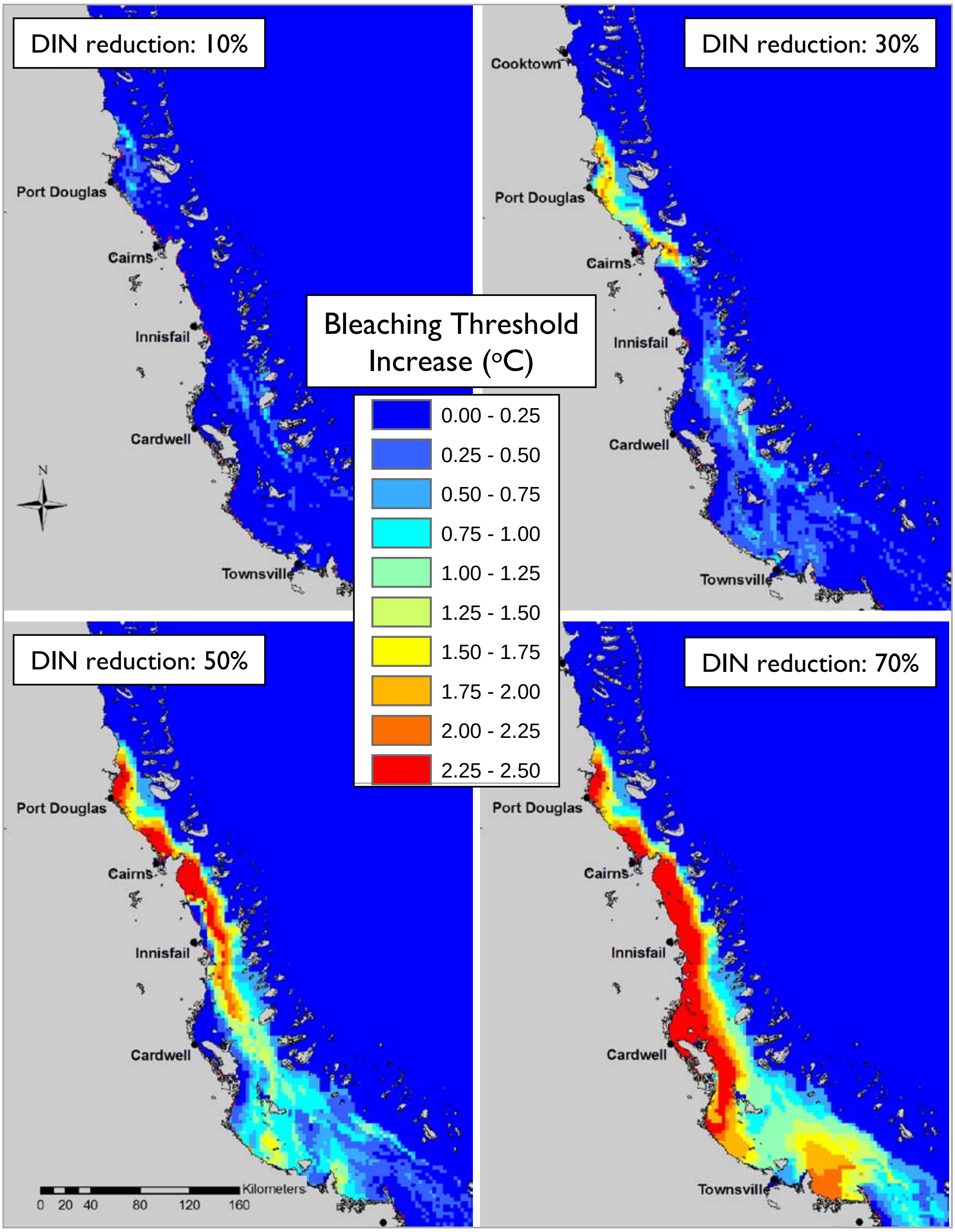

Figure 10: Simulated increased in the upper thermal bleaching limits (°C) of inshore corals due to specified (uniform percentage) reductions in end-of-river DIN loading for the numerous basins that drain the GBR catchment.

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