Modelling the improved resilience of inshore coral reefs to climate change due to terrestrial water quality improvements

A case study from the Burdekin River catchment

Scott A. Wooldridge

Australian Institute of Marine Science

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Objective

For inshore coral reefs located within the nutrient-enriching ‘footprint’ of the Burdekin River flood plume, model the envelope of future bleaching risks based on a range of land management actions.

Introduction

Previous spatial modelling within the Great Barrier Reef (GBR) has highlighted that inshore coral reefs which are regularly exposed to poor water quality are less *resistant* to thermal stress, such that upon exposure to sub-optimal temperatures (>28°C) they display higher rates of bleaching (and mortality) per unit increase in maximum sea-surface temperature (SST) (Wooldridge and Done 2009). Explanation for this negative impact of poor water quality has centred 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, b). Support for this interpretation is found in the strong quantitative relationship that exists between the upper thermal bleaching limits of inshore corals and the degree of exposure to DIN-enriched flood-plume (terrestrial) waters (Figure 1a; Wooldridge 2009b). The sensitivity of this water quality / bleaching synergism is suggestive of a ~2°C lowering in the upper thermal bleaching thresholds for corals in the most DIN-enriched coastal waters, with the marginal rate of improvement in the bleaching threshold (°C) being significantly higher at the lowest DIN exposure levels, i.e. highest water quality (Figure 1b). 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 algae endosymbiont (‘zooxanthellae’) population to become nitrogen (i.e. growth) limited (Wooldridge and Done 2009).

Significantly, the water quality / bleaching synergism identifies ‘local’ land management actions that lower terrestrial DIN delivery to the reef as a potential adaptive measure to combat the ‘global’ impact of climate change on corals (Wooldridge 2009b). Since mid-range warming scenarios for the GBR have summer maximum SSTs increasing by ~2-3°C by 2100 (Figure 2; Wooldridge *et al.* 2005), the potential may even exist for ‘local’ water quality improvements to significantly offset (near) future heat stress impacts on corals. Initial case-study testing of these ideas focused attention on the relatively small Tully-Murray drainage basin within the Wet Tropics region of the encompassing GBR catchment (Wooldridge 2008). In this case, model simulations demonstrated that land management strategies which lowered end-of-river DIN concentrations by eighty percent could theoretically ‘buy’ the locally-impacted coral reefs an additional 65-70 years of reef-building capacity beyond the current ‘business-as-usual’ projection. Whilst this result is promising, the high levels of DIN reduction needed to achieve meaningful improvement were considered to be due (at least in part) to the comparatively small discharge volume of Tully River flood plume, and its potential dilution and mixing with the DIN-enriched plumes of nearby catchments (e.g. Herbert, Johnson and Burdekin catchments).

In this study, I adopt the modelling simulation framework developed for the Tully-Murray River catchment (see Wooldridge 2008) but focus attention on inshore reef areas that fall under the enriching ‘footprint’ of the much larger Burdekin River flood plume. In particular, for a ‘mid-range’ SST warming scenario on the GBR (Figure 2), I simulate the beneficial influence of a 20%, 40%, 60% and 80% reduction in end-of-river DIN concentrations on the future survival prospects of locally-impacted reefs.

The Burdekin River basin

The Burdekin River basin, located in the Dry Tropics of central Queensland, is the second largest drainage system in area (~130,126 km^2) to discharge into the GBR lagoon, and accounts for ~33% of the total GBR catchment (Figure 3a). Grazing is the most dominant land use (Figure 3b), yet small land areas of intensive fertilised cropping (predominately sugarcane) in the near-coast flood plain contribute disproportionately to the DIN flood plume loads (Brodie *et al.* 2003). Average annual rainfall in the Burdekin River catchment is ~800mm. Widespread heavy rainfall is usually generated by monsoonal depressions and tropical cyclones during summer. Isolated thermal storms in early summer can also deliver considerable and at times intense rainfall to less extensive areas of the catchment. During significant flood events, the large discharge volume from the Burdekin River has the potential to cause plume waters to extend northward to Cairns (~450 km; Wolanski and van Senden 1983). The relatively short wet seasons are typically separated by long dry periods, and drought conditions can often persist for several years.

The inshore coral reefs that fall within the enriching 'footprint' of the Burdekin River plume suffered disproportionately high levels of bleaching / mortality during the 1998 and 2002 bleaching events on the GBR (Berkelmans *et al.* 2004). For example, a long-term photo-transect monitoring study from Pandora Reef (18°48'42''S, 146°26'36''E) highlights the significant drop in hard-coral cover (percent) associated with the 1998 bleaching event, and limited recovery due to the subsequent 2002 event (Figure 4; Done *et al.* 2008).

Projected water quality impact on local bleaching thresholds

The *ChloroSim* decision support model (outlined in Wooldridge *et al*. 2006) enables the enriching impact of the Burdekin River flood plume to be mapped (and varied) as a function of the model 'tuneable' end-of-catchment flood concentration of DIN. For the present study, a thirty-year (1969-1998) ensemble of historical flood plume events (King *et al.* 2002) was used to model the impact of a 20%, 40%, 60% and 80% reduction in end-of-catchment DIN. The simulated lowering in DIN availability within inshore lagoon waters was recorded as a reduction in the annual exceedence probability (AEP) of Chl *a* > 0.9 $\mu g.L^{-1}$, and then transposed into the equivalent improvement in coral bleaching thresholds (as facilitated by the relationship outlined in Figure 1). In this way, the impact of the modeled reductions in end-of-catchment DIN of the Burdekin River was mapped as the equivalent increase in the upper thermal bleaching limit (°C) for the locally-impacted coral reefs (Figure 5).

Projected coral mortality (LD_{50}) till 2100

Mortality thresholds based on 50% mortality of thermally sensitive coral taxa have been proposed by Berkelmans (2008). Analysis of these curves in relation to their bleaching thresholds indicates that for most reef sites on the GBR, thermally sensitive taxa die ~0.5-1.5°C above their bleaching threshold. In this study, a modelled trigger value of 3°C above the bleaching threshold was chosen to represent 50% mortality events (LD_{50}). The higher triggering point endeavours to capture the raised 'reef-wide' average thermal tolerance due to the contribution of more thermally-tolerant coral taxa (e.g. massive *Porites* spp; Marshall and Baird 2000).

Projected increases in summer SSTs for the GBR were based on the global warming rate predicted by the SRES A1T scenario (IPCC 2001). The scenario assumes rapid economic growth and global population that peaks in the middle of the 21st Century with the transition to non-fossil alternative energy sources over the coming century. The scenario is considered an optimistic 'mid-range' warming scenario; causing maximum summer SSTs on the GBR to increase ~2.5°C by 2100 (Figure 2). A dominant feature of the projected warming on the GBR is the proportionately higher rate of warming in the central-southern GBR.

Calculation of the AEP of the LD_{50} threshold (for each level of DIN improvement) at specific time intervals (2010, 2030, 2050, 2070 and 2100) was achieved with a standard normal (z-score) methodology (see Wooldridge (2008) for details). The methodology quantifies the likelihood of projected summer SST exceeding the spatially explicit LD_{50} threshold temperatures (i.e. bleaching threshold + 3°C). A summary of the analysis for a subset of reefs off Townsville (18°48', 146°26') is detailed in Figure 6. To aid interpretation, a five-year average return interval (ARI) is highlighted (red line), which identifies the shortest possible 'inter-disturbance' interval that may still permit a hard coral-dominated reef condition on the GBR (Wakeford *et al.* 2008). Importantly, the model projections demonstrate that an 80% reduction in end-of-catchment DIN has the capacity to prolong the persistence of hard corals (i.e. maintain reef building capacity) at these inshore reefs by an additional ~60 years beyond current projections.

Discussion

The average return interval (ARI) between events that cause catastrophic mortality in reef-building taxa is a key parameter defining a reef's community structure, and hence its visual appearance and habitat values (Done 1997). Long-term field data from the GBR suggest that even in areas of high water quality, an ARI of more than five years between major disturbance events is needed to maintain hard coral-dominated reefscapes (Wakeford *et al.* 2008). It is therefore of major concern that the current trajectory of SST warming is predicted to cause near-annual bleaching events (of similar-to-greater magnitude than the 1998 and 2002 GBR events; Berkelmans *et al.* 2004) across most of the inshore GBR by 2050 (Hoegh-Guldberg 1999; Done *et al.* 2003; Wooldridge *et al.* 2005).

In this study, model simulation was used to demonstrate how reduced delivery of terrestrial DIN into the inshore lagoon waters of the GBR might assist in maintaining the hard-coral dominance of impacted reefs given the threat posed by rapidly rising SSTs. Previous research on the benefits of good water quality in promoting resilient coral communities in the face of climate change impacts has primarily focused on the recoverability side of coral mortality events (see review by Fabricius 2005). In this case, reef waters that are characterised by low sediment and nutrient loads are judged favourably in term of (i) promoting the re-establishment of disturbed reef sites with new coral recruits, principally 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. Whilst this recovery-side aspect of improved reef water quality is a clear (beneficial) aspiration of 'local' management strategies (see McCook *et al.* 2007), it is only partially considered in the present study. Instead, it is the identified role of DIN-enrichment in pre-conditioning the survival prospects of the existing coral communities to thermal stress (see Wooldridge and Done 2009) that is explicitly simulated. In particular, the analysis builds upon the demonstrated synergistic relationship between the upper thermal bleaching limits of inshore corals and the degree of exposure to DIN-enriched flood-plume (terrestrial) waters (Figure 1; Wooldridge 2009b). When applied to the most impacted coral reefs within the nutrient enriching 'footprint' of the Burdekin River flood plume, this relationship suggests that a lowering of end-of-catchment DIN concentrations by 80% could theoretically help to raise the upper thermal bleaching limits by ~2°C beyond current estimates (Figure 5). From the perspective of future SST projections, this raised bleaching tolerance represents the potential for an additional sixty years of reef-building capacity beyond the current 'do-nothing' projection (Figure 6).

In this way, 'local' land management actions which lower the delivery of DIN into the inshore GBR can be understood to 'buy' time for inshore corals in their challenge to adapt to globally-driven warming of ocean surface temperatures. Yet, it is important to note that water quality improvements alone are not 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, it 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 corals 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).

An environmental-economic analysis is presently underway to determine the most efficient land use and land management arrangements needed to achieve specific DIN improvement targets within the Burdekin River basin (Martin van Grieken (CSIRO) in prep). A similar analysis undertaken in the nearby Tully-Murray River basin (Roebeling *et al.* 2007) highlights that for DIN intensive land uses (e.g. sugarcane production), DIN delivery can be reduced by approximately fifteen percent through the adoption of current 'win-win' best management practice in production (e.g. reduced tillage, zero tillage, economic optimum rates of fertilizer application, nitrogen replacement and split nitrogen application). However, in order to achieve reductions in DIN delivery beyond sixty percent, the adoption of 'lose-win' management practices is required (e.g. reduced production area and reduced fertilizer application rates). Such management strategies involve significant economic 'cost' to local farming communities. An integrated socio-economic assessment of the extended ecological services (e.g. tourism, fishing) provided by a healthy inshore reef complex is required to judge whether the imposition of land pollution abatement costs can be justified solely from an economic standpoint. Future work planned for MTSRF Project 2.5i.4 will endeavour to provide insight into these wider considerations.

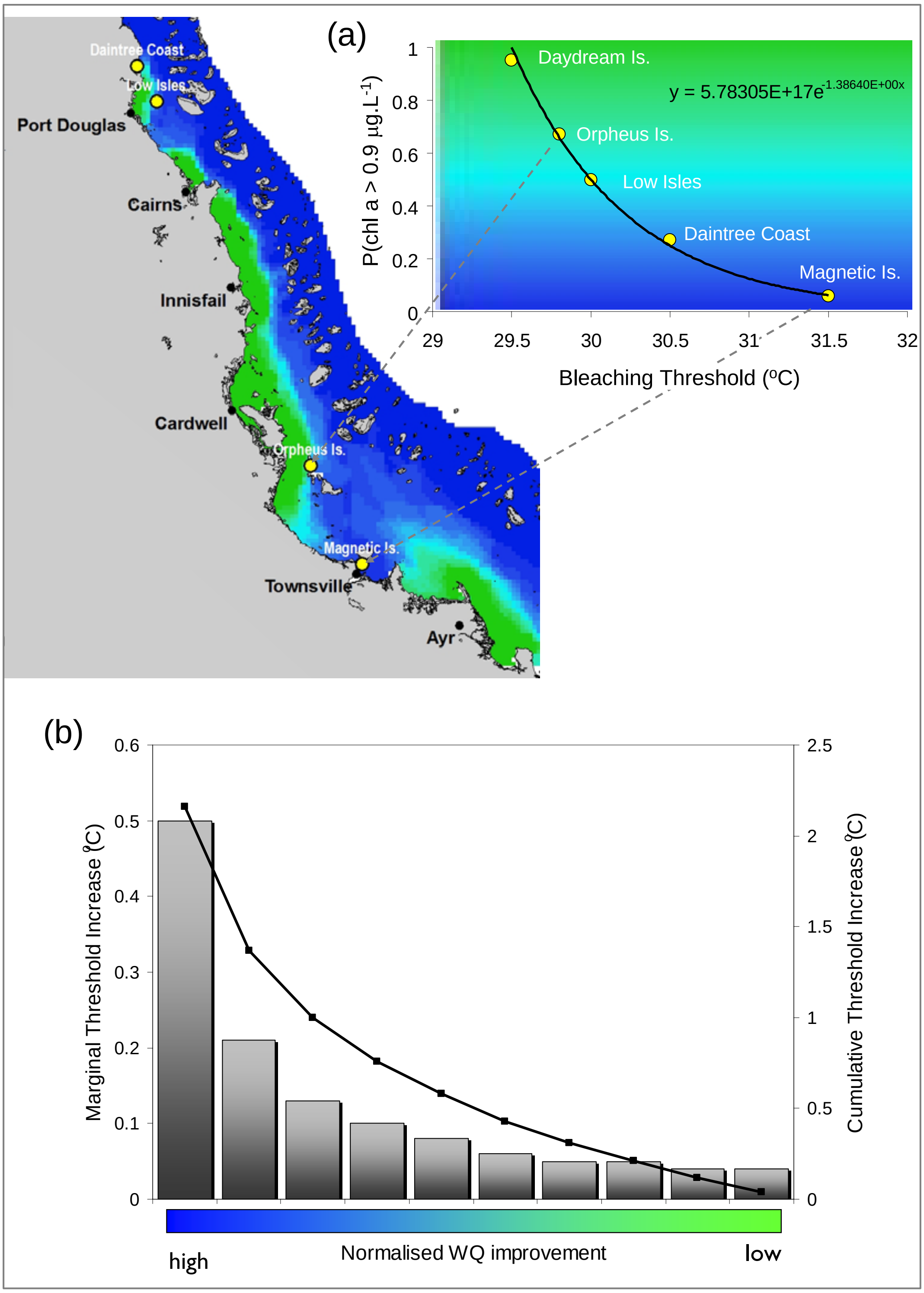

Figure 1: (a) Quantitative linkage between upper thermal bleaching limits (°C) and the degree of exposure to nutrient enriched terrestrial waters. Coastal reef waters with high DIN-enriching impact are characterised by a higher annual exceedence probability (AEP) of Chl *a* > 0.9 µg.L^{-1}. (b) Marginal (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.

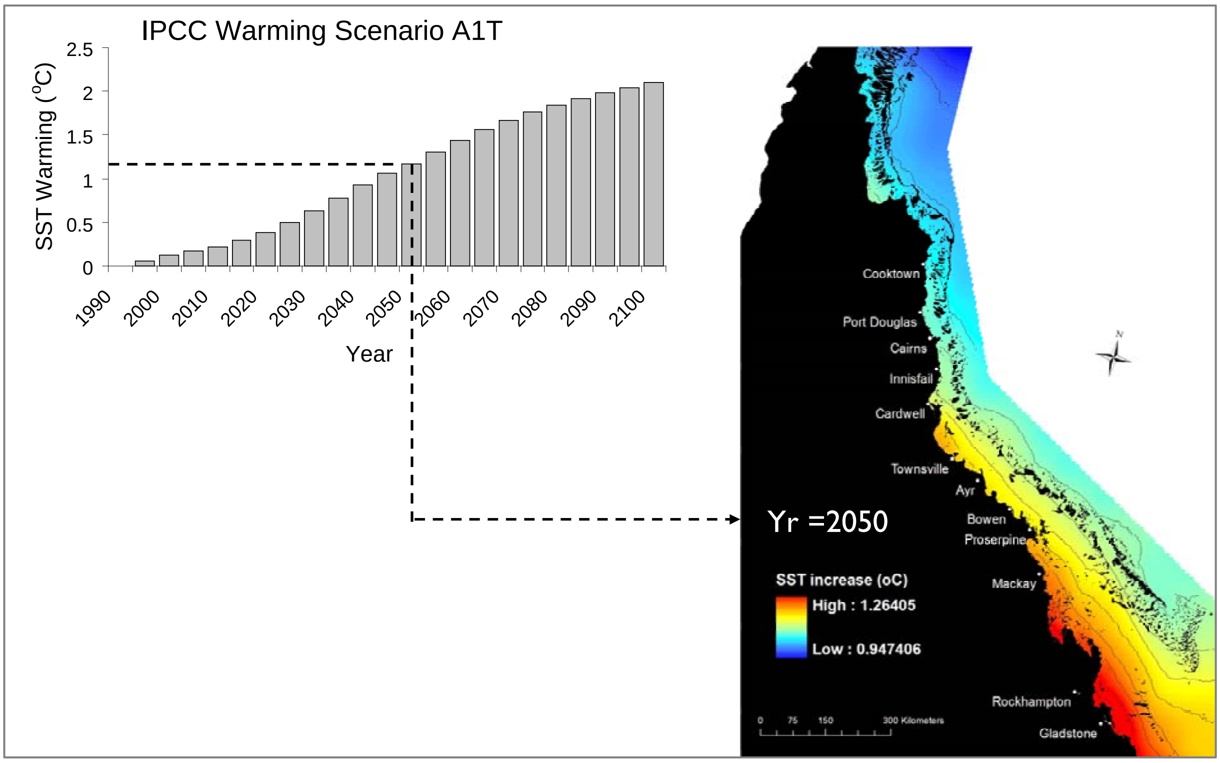

Figure 2: Spatial and temporal predictions of the increase in summer maximum SST (°C) resulting from the IPCC warming scenario A1T.

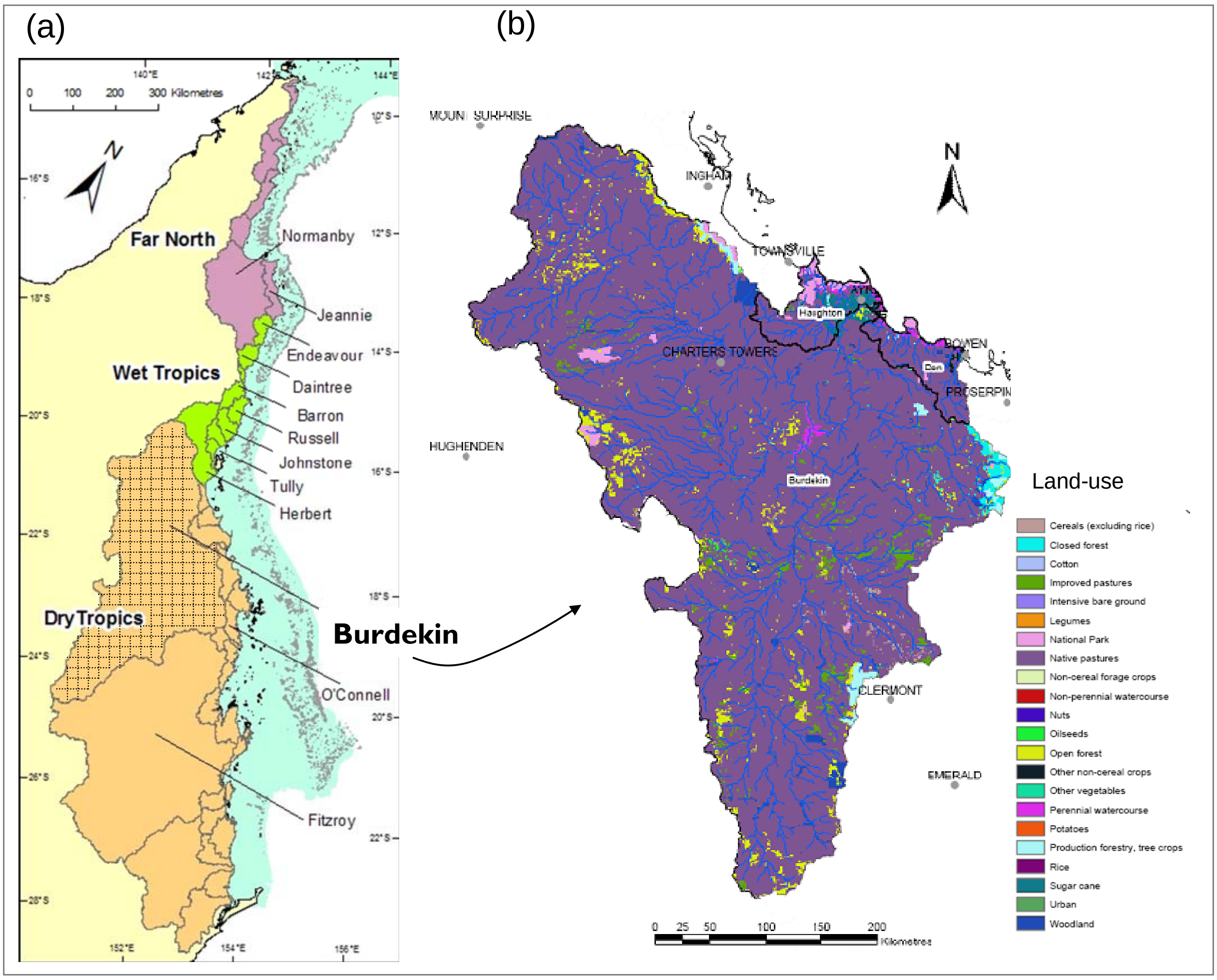

Figure 3: (a) The Great Barrier Reef and its catchments.
(b) Land use in the Burdekin River catchment.

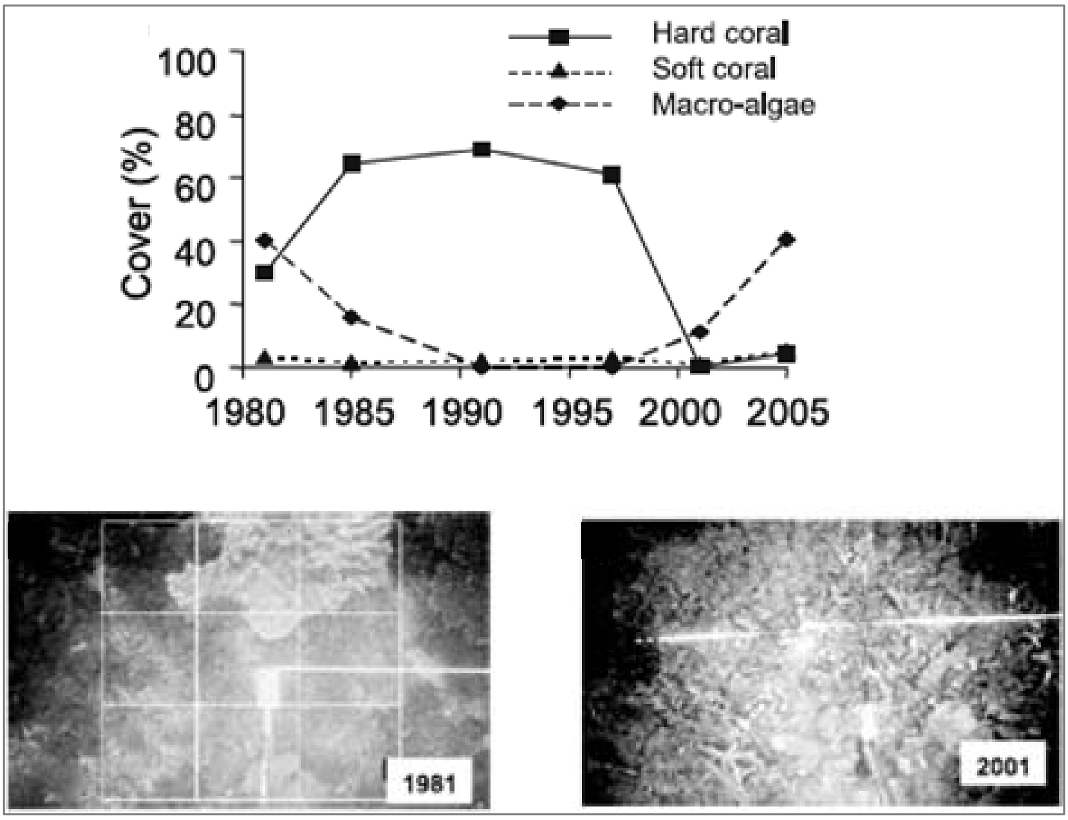

Figure 4: Photo-transect of the shallow fore-reef zone of Pandora Reef detailing the trajectory of hard coral, soft coral and macro-algae cover (percent) during the period 1981-2005 (after Done *et al.* 2008). The significant loss of coral cover due to the 1998 GBR bleaching event has been slow to recover due to the subsequent bleaching event in 2002.

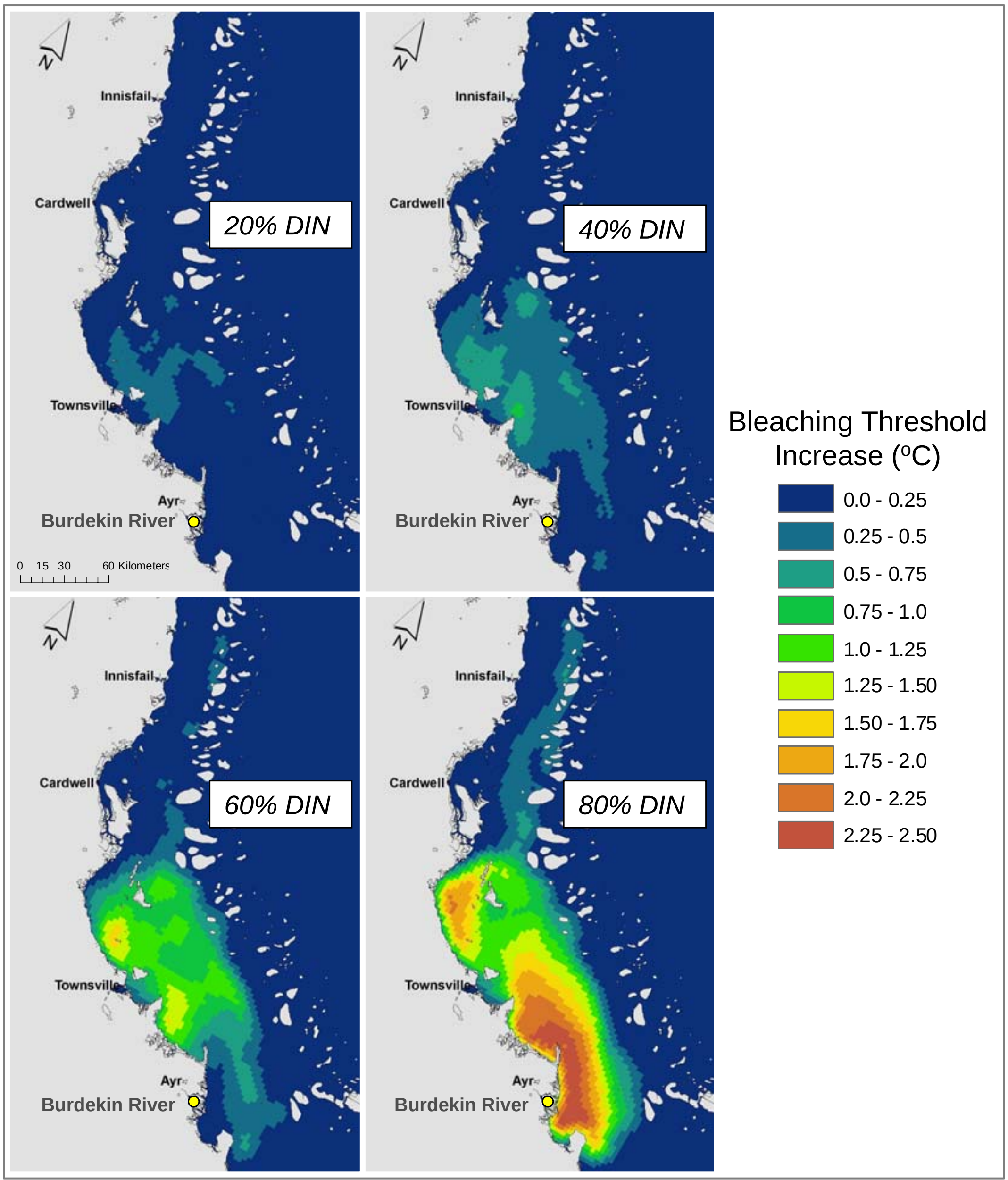

Figure 5: Modelled improvement in upper thermal bleaching threshold (°C) due to a 20%, 40%, 60% and 80% reduction in end-of-river DIN concentration for the Burdekin River catchment.

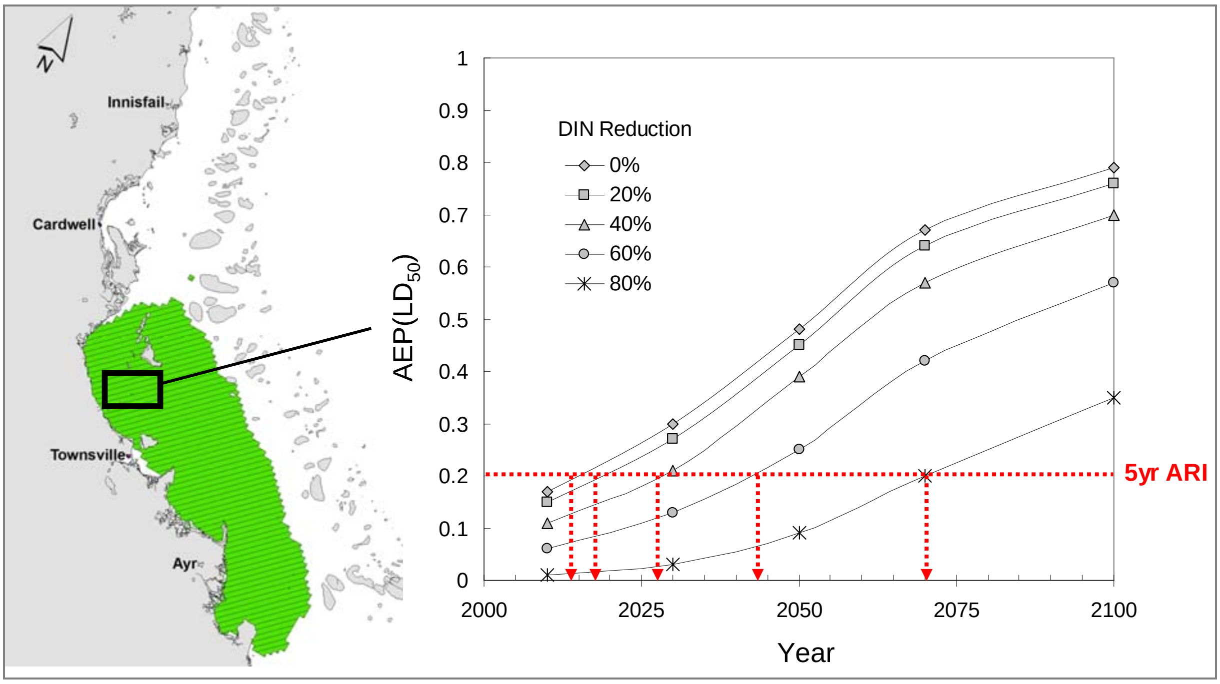

Figure 6: Projected AEP of LD_{50} mortality events given a 20%, 40%, 60% and 80% reduction in end-of-river DIN concentration. The five-year ARI (red line) is indicative of the maximum bleaching disturbance frequency for the continued maintenance of a hard coral-dominated reefscapes on the GBR.

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