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

A case study from the Tully-Murray River catchment, North Queensland

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Acronyms Used In This Report

AEP .... Annual exceedance probability
AIMS .... Australian Institute of Marine Science
ARI .... Average return interval
CO_2 .... Carbon dioxide (chemical formula)
DIN .... Dissolved inorganic nitrogen
GBR .... Great Barrier Reef
IPCC .... Intergovernmental Panel on Climate Change
GBR .... Great Barrier Reef
SD .... Standard deviation
SRES .... Special Report on Emissons Scenarios (IPCC)
SST(s) .... Sea-surface temperature(s)

Introduction

The objective of this study is to model the envelope of future bleaching risks to inshore coral reefs that are under the influence of the Tully-Murray flood plume, based on a range of optimised land management actions.

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 increasing temperatures are predicted to lead to increased levels of 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; 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 on the GBR when sea surface temperatures (SSTs) exceed the 'normal' mean summer maximum temperatures by 1-2°C for more than a few days (Berkelmans 2002, 2008). This means that most parts of the GBR are characterised by an upper thermal bleaching threshold of ~30°C. Additional environmental factors can, however, act to synergistically lower bleaching thresholds. For example, excessive solar radiation levels that typically accompany rising SSTs can lower upper thermal bleaching thresholds (Brown 1997). It has also recently been demonstrated that corals 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 (Figure 2a) and mortality (Figure 2b) per unit increase in maximum SST (Wooldridge and Done 2009). Explanation for the 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; Wooldridge and Done 2009). Indeed, for the inshore reefs of the GBR, a strong quantitative relationship exists between upper thermal bleaching thresholds and the degree of exposure to DIN-enriched terrestrial flood-plume waters (Figure 3; Wooldridge 2009b). In this case, the potential sensitivity of the water quality impact is equivalent to ~2°C in relation to the upper thermal bleaching limit. This attendant improvement in thermal tolerance appears significant given that mid-range warming scenarios have SSTs on the GBR increasing by ~2-3°C by the year 2100 (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 (Furnas 2003; Brodie *et al.* 2003). Since 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 (Roebeling *et al.* 2007).

In light of: (i) the 'elevated' ambient DIN loads, (ii) the existence of effective remediation strategies, and (iii) the 'high' sensitivity of the identified DIN-bleaching linkage, it's tempting to suggest that a major water quality improvement program within the GBR catchment could aid the ability of corals to resist the deleterious impacts of future SST warming. In this study, I endeavour to test the utility of this suggestion by developing a modelling framework that permits the envelope of future bleaching risks to be mapped as a function of land management imperative and global warming scenarios. In a case-study application based on a 265,000 Ha agriculture-dominated GBR drainage catchment, it is demonstrated that land management strategies which lower end-of-river DIN concentrations by eighty percent can theoretically 'buy' the locally-impacted coral reefs an additional 65-70 years of reef-building capacity beyond the 'do nothing' projection. It is concluded that the addition of this 'local' management response alongside 'global' strategies that lower future warming rates may considerably delay, possibly even prevent, the imminent mortality risk and loss in resilience that currently characterises the inner to mid-shelf coral reefs of the GBR.

Study site

Numerous river systems discharge into the GBR lagoon along its ~1,500km length (Figure 4a; Wooldridge *et al.* 2006). In this study, I specifically consider the enriching impact of the Tully-Murray River flood plume on nearby inshore and mid-shelf coral reef habitats. The Tully-Murray catchment is dominated by agricultural land uses that are characterised by high fertiliser application rates (e.g. sugarcane, banana plantations, cattle-grazing) (Figure 4b; Brodie *et al.* 2003). As a consequence, the DIN load of the Tully-Murray flood plume is up to thirty times higher than from other rivers that drain from less developed areas of the GBR catchment (140-1400 μg L^{-1} compared to 14-70 μgL^{-1}; Furnas 2003; Brodie *et al.* 2003). Being located in the Wet Tropics, the Tully-Murray catchment receives the bulk of its annual (2,000-4,000 mm) rainfall during the monsoonal (summer) wet period. The large rainfall events during this period lead to a characteristic annual flooding period, wherein the 'estuarine' mixing zone lies outside the river mouth on the continental shelf. The resulting flood plumes baths inshore and some mid-shelf reef habitats in nutrient-rich water for periods of several weeks (Devlin *et al.* 2001; Devlin and Brodie 2005). Importantly, this enriching impact coincides with the period of maximum (summer) SSTs. Given the shallow shelf depth, and limited intrusion of cool offshore oceanic waters, the SSTs in this region are some of the highest observed across the entire GBR; with monthly averaged summer values ~28.5°C (Wooldridge and Done 2004).

Landscape nutrient budget models for the Tully-Murray catchment have been used to explore how altered land use and land management arrangements may help to reduce end-of-catchment DIN loads by 20%, 40%, 60% or 80% (Roebeling *et al.* 2007). Economic costing of the various management strategies, including reductions in fertiliser application rates and land-use replacement, demonstrate that it becomes increasing expensive to achieve the larger rates of DIN water pollution abatement (Figure 5).

Flood plume enrichment of reef waters

Hydrodynamic model simulations demonstrate that the Tully-Murray flood plume is generally advected in a northwards direction, with the extent of cross-shelf dispersion affected by both the discharge volume and the prevailing wind conditions (King *et al.* 2001; 2002). Not surprisingly, DIN concentrations are greatest near the river mouth in undiluted flood plume waters. As the plumes spread, mix and age, DIN concentrations decline as a result of dilution and biological uptake. In the initial period (several days) before biological uptake-rates becomes significant, DIN concentrations are 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 for a given runoff:seawater dilution ratio, and broad-scale differences in the photosynthetic pigment Chlorophyll *a* [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 tool 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. Here, I utilise this decision support tool to map the impact of a 20%, 40%, 60% and 80% reduction in end-of-catchment DIN on the localised enriching 'footprint' of the Tully-Murray flood plume. Rather than considering the differences arising from a single event, the simulation was run for an historic thirty-year archive (1969-1998) of runoff events; 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 $\mu g.L^{-1}$, see next).

Water quality impact on bleaching thresholds

Previous analysis for the inshore reefs of the GBR demonstrates a strong quantitative relationship between an AEP for [Chl *a*] > 0.9 $\mu g.L^{-1}$ and the upper thermal bleaching limit (Figure 3; Wooldridge 2009b). In this study, I utilised this quantitative relationship to transpose simulated improvements in lagoonal water quality (viz. lowered AEP for [Chl *a*] > 0.9 $\mu g.L^{-1}$) into the equivalent improvement in coral bleaching thresholds. In this way, the impact of a 20%, 40%, 60% and 80% reduction in end-of-catchment DIN was mapped as an equivalent thermal increase in the upper coral bleaching threshold (°C) (Figure 6).

Projected coral mortality (LD_{50}) to 2100

Mortality thresholds based on fifty percent mortality of thermally sensitive coral taxa have been proposed by Berkelmans (2008). An analysis of these curves in relation to their bleaching thresholds indicates that at most of these sites 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 fifty percent mortality events (LD_{50}). The higher triggering point endeavours to represent the raised 'reef-wide' average thermal tolerance due to the contribution of more thermally-tolerant coral taxa (e.g. *Porites* spp.; Marshall and Baird 2000). This reef-average mortality threshold compares favourably with the ~3°C difference between field-measured bleaching (BD_{50}) and mortality (LD_{50}) observations during the 1998 mass bleaching event on the GBR (Figure 2).

Calculation of the AEP of the LD_{50} threshold (for each level of DIN improvement) was achieved with a standard normal (*z*-score) methodology. In this case, at specific time intervals (2010, 2030, 2050, 2070, 2100), the downscaled SST projections from eight global climate models (Table 1) were used to develop a normal distribution of daily summer SST projections for each 10 km grid cell that constitutes the GBR model domain (for further details, see Wooldridge 2007). With the *z*-score approach, the likelihood of exceeding the spatially explicit LD_{50} threshold can be conceptualised as the area under the curve in excess of the threshold, *z* (Figure 7). The standard deviation (SD) of this distribution for each grid cell was calculated based on a twelve-year remotely-sensed climatology (AIMS SST web atlas; Skirving *et al.* 2002) of maximum SST during the summer (December to March) period. These SD estimates were temporally updated based on the assumption that the coefficient of variation of SST was stationary in time.

In the present study, the projected SST estimates were based on the global warming rate predicted by the SRES A1T (IPCC) 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. This scenario is considered an optimistic 'mid-range' warming scenario; causing maximum summer SSTs on the GBR to increase ~2.5°C by 2100 (Figure 1). A dominant feature of the projected warming on the GBR is the proportionately higher rate of warming in the central-southern GBR.

The quantitative outworking of the modelling framework in relation to the Tully-Murray catchment is summarised by Figure 8, which highlights the potential levels of improvement in the AEP of LD_{50} events for a subset of impacted mid-shelf reefs given the simulated improvement (20%, 40%, 60% and 80%) in end-of-catchment DIN concentrations. To aid interpretation, a five-year average return interval (ARI) is highlighted (red line), which provides and estimate of the lowest possible ARI estimate for maintaining a resilient, coral-dominated reef condition (see Discussion). Importantly, the model projections demonstrate that an eighty percent reduction in DIN permits the maintenance of the coral-dominated reef state by an additional 65-70 years beyond current projections (Figure 9).

Discussion

Maintenance of reef framework and reef-building capacity are key determinants of ecologically resilient (healthy functioning) coral reefs (Done 1995; Done *et al.* 1996). Indeed, the long-term attribute of *net* reef accretion underpins the majority of ecological services that reefs provide, such as fisheries habitats and destinations for tourism and recreational use. A key parameter in defining reef-building capacity is the average return interval (ARI) between events that cause catastrophic mortality in reef-building taxa (Done 1997). Whilst episodic disturbance and population turnover in corals and associated communities are normal aspects of ecological dynamics in coral reefs, this study supports earlier findings in demonstrating that global climate change has made the previously infrequent 'coral bleaching' disturbance commonplace. By substantially decreasing the life expectancy of coral colonies, the more frequent bleaching mortality episodes will have detrimental effects on the age/size structure of coral colonies and the associated extent of bottom coral cover; potentially even triggering the transition towards non-coral dominated reefscapes (Done 1999; Wooldridge *et al.* 2005). Indeed, an analysis of long-term field responses from the GBR suggests that an ARI between major disturbance events of not less than five years is critical for maintaining coral-dominated reefscapes (Wakeford *et al.* 2008).

In this study, it has been demonstrated how improved water quality (viz. lower DIN) can act to raise the upper thermal bleaching limits of coral reefs (Figure 6), and thereby assist in maintaining the ARI of future projected catastrophic bleaching mortality events above the identified five-year (coral-dominated) threshold (Figure 8). Indeed, land management strategies which lower end-of-river DIN concentrations by eighty percent helped to 'buy' the locally-impacted coral reef system an additional 65-70 years of reef-building capacity beyond the 'do nothing' projection (Figure 9). This projected level of improvement in reef resilience may be reasonably expected to be extended by similar water quality improvement in adjacent catchments, since the flood plumes of many of the river that drain into the GBR lagoon often merge into a single plume with 'averaged' DIN concentrations (Wooldridge *et al.* 2006).

It is important to note that previous consideration of the role of water quality in promoting resilience coral communities 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 terms 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. Whilst this recovery-side aspect of improved reef water quality is a beneficial aspiration of water quality management strategies, it is only partially considered in the present study. Instead, it is the identified role of DIN in pre-conditioning the survival prospects of the existing coral communities to thermal stress that is explicitly simulated. Indeed, an implicit assumption in the present study is that the inter-disturbance recovery rate was independent of DIN loads;

thereby enabling a consistent interpretation to the five-year ARI threshold. The central findings of this study are thus strengthened by the intuitive likelihood that reef waters with lowered DIN levels will assist *both* coral survivorship and recovery in response to thermal stress events.

As with many environmental pollution abatement problems, in the present case-study the greatest marginal gain for reef health and resilience is achieved at the highest levels of DIN reduction (Figure 9), which also corresponds with the highest marginal increases in remediation cost (Figure 5). For the present Tully-Murray catchment study, an estimated $50 million per year is needed to 'buy' the additional 65-70 years of reef-building capacity; a cost that is exclusively imposed on local farming communities in the first instance. An economic assessment of the ecological services (e.g. tourism, fishing) provided by the impacted reefs is required to judge whether this on-going pollution abatement cost can be justified from a purely economic standpoint.

Clearly, improved 'local' land management strategies leading to improved reef water quality is not a panacea for the long-term survival prospect of the inshore to mid-shelf reefs of the GBR. Instead, it must be considered alongside 'global' CO_2 emission reduction strategies that aim to lower future warming rates. Simple logic suggests that in order to be effective, the future warming of SSTs must not exceed the potential 1-2°C gain in upper thermal bleaching limits due to water quality improvements. Future work is planned to expand upon the sensitivity of these suggestions.

Table 1: Model runs used to produce SST change patterns.

Centre	Model	Emission Scenario	Features	Years
CSIRO, Australia[1]	Mark3	SRES A2	SRES sulphates	1961-2100
CSIRO, Australia[2]	DARLAM 125 km	IS92a equivalent CO_2	Nested in CSIRO Mk2	1961-2100
Canadian CCMA[3]	CGCM1	1% CO_2 pa	No sulphates	1900-2100
Canadian CCMA[4]	CGCM2	1% CO_2 pa	No sulphates	1900-2100
Hadley Centre, UK[5]	HADCM2	1% CO_2 pa	No sulphates	1861-2100
Hadley Centre, UK[6]	HADCM3	1% CO_2 pa	No sulphates	1861-2100
DKRZ/MPI, Germany[7, 8]	ECHAM4/OPYC3	IS92a	No sulphates	1860-2099
DKRZ/MPI, Germany[7]	ECHAM3/LSG	IS92a	No sulphates	1880-2085

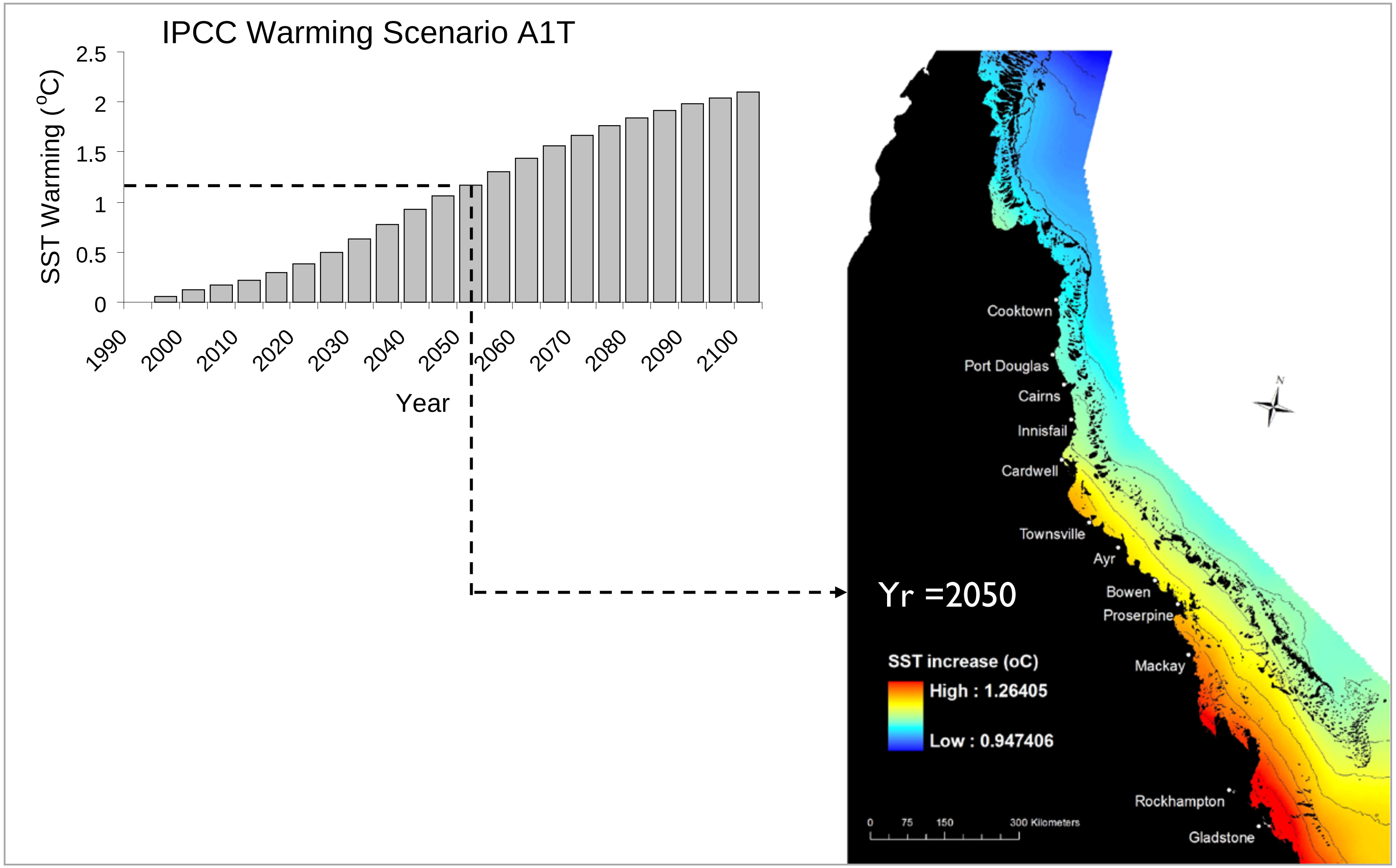

Figure 1: Spatial and temporal predictions of the increase of SST (°C) resulting from the IPCC warming scenario A1T.

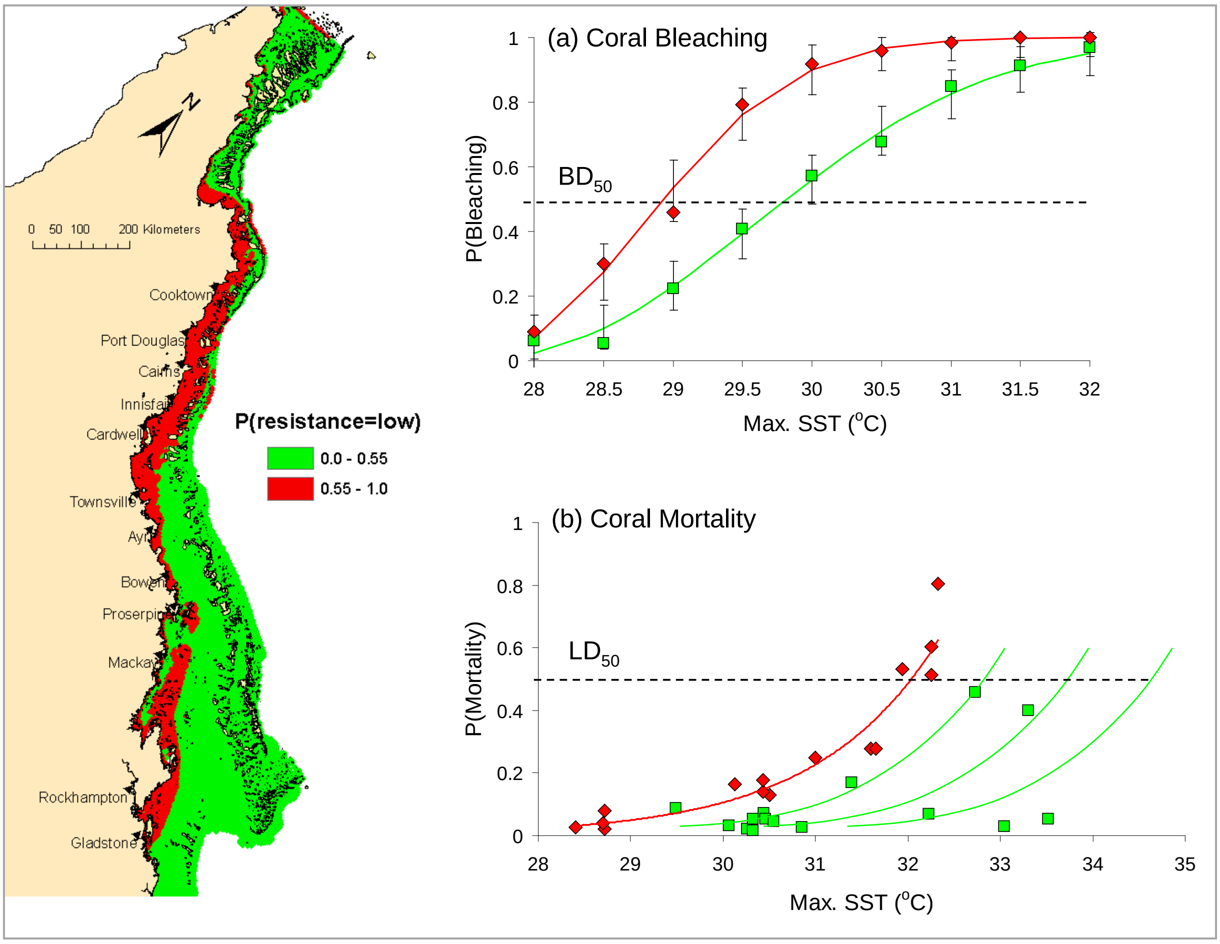

Figure 2: Regional-scale coral bleaching analysis on the GBR (after Wooldridge and Done 2009). Inshore coral reef areas that are regularly exposed to high DIN flood loads are shown to lower *resistance* to thermal stress, as evidenced by an increase risk of (a) bleaching, and (b) mortality (per unit increase in SST).

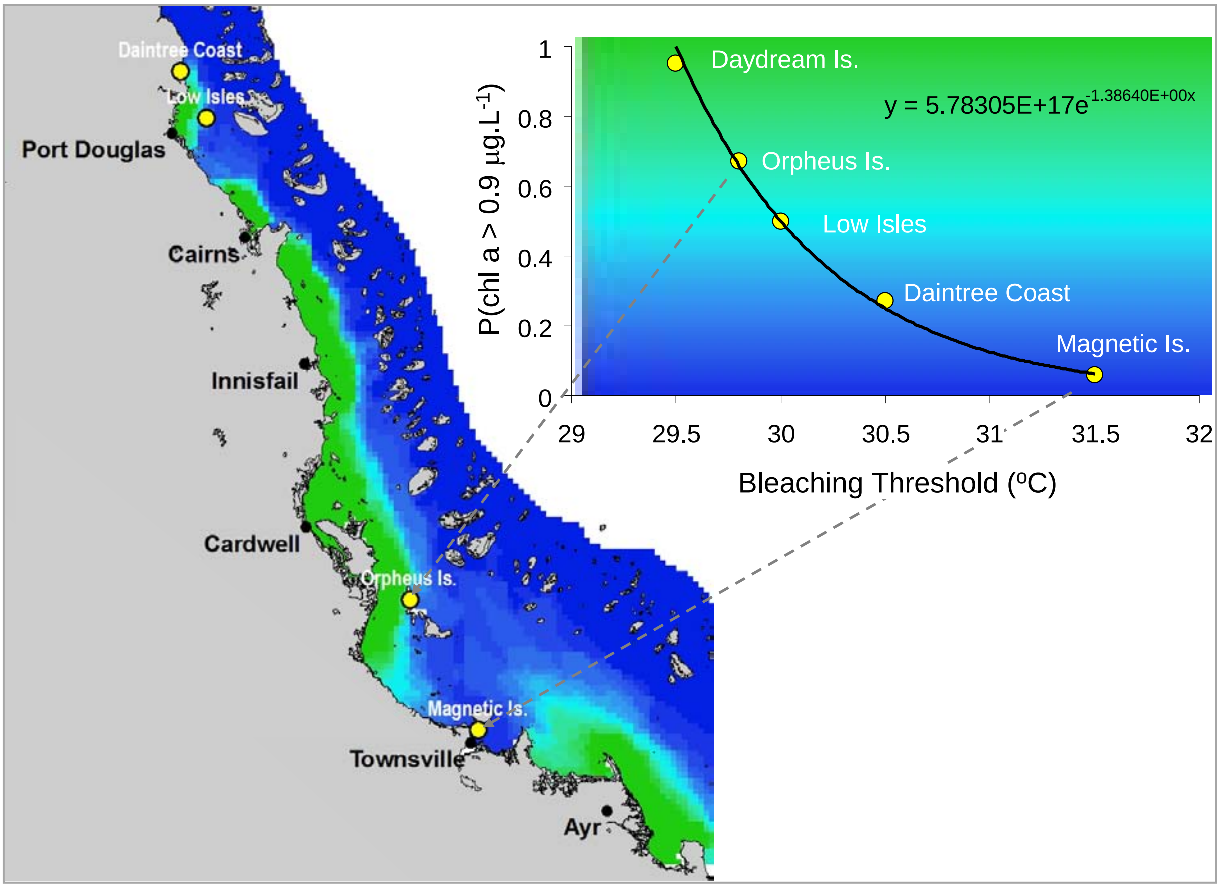

Figure 3: Quantitative spatial linkage between upper thermal bleaching limits and the degree of exposure to nutrient enriched terrestrial waters. Reef waters with high DIN enriching impact are characterised by a higher annual exceedence probability (AEP) of [Chl *a*] > 0.9 $\mu g.L^{-1}$.

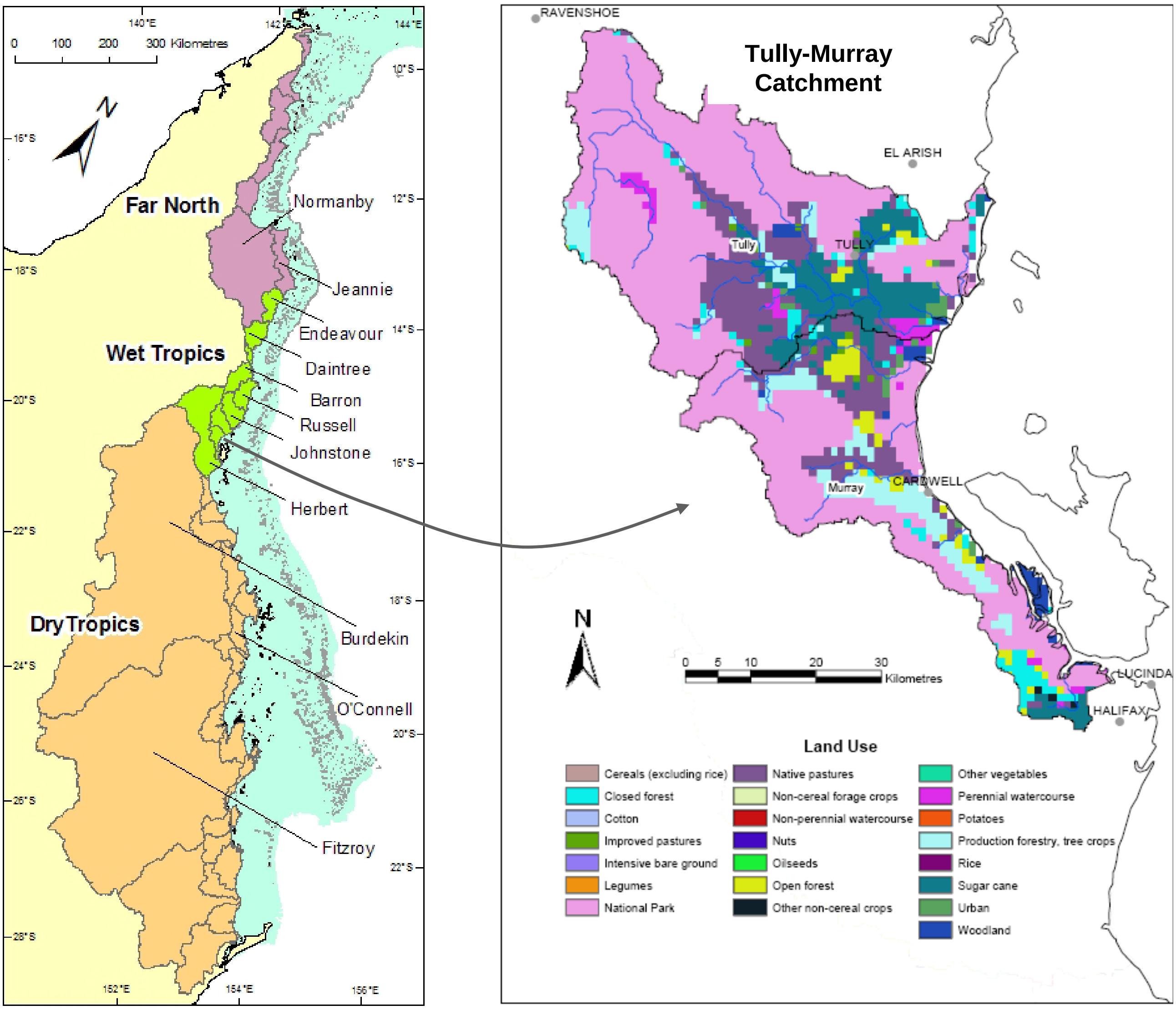

Figure 4: (a) The Great Barrier Reef and its catchments; (b) Land use in the Tully-Murray catchment.

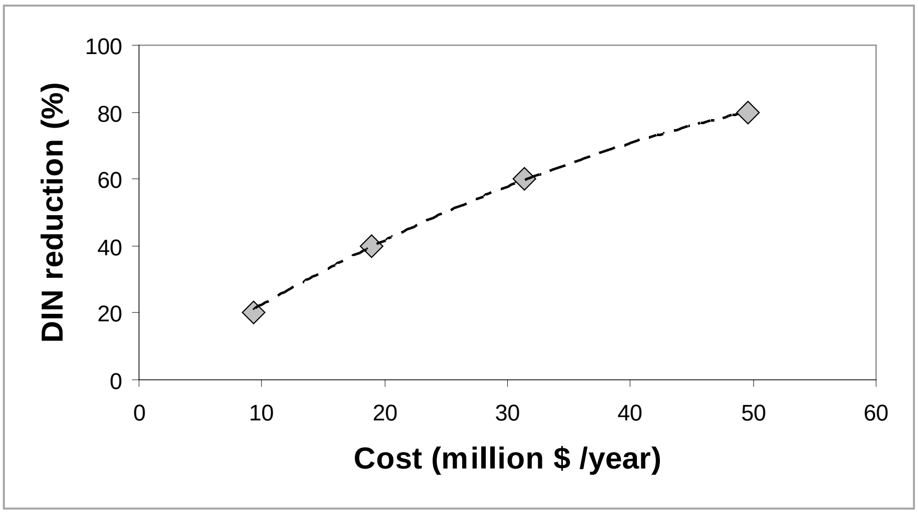

Figure 5: DIN pollution abatement costs for the Tully-Murray catchment.

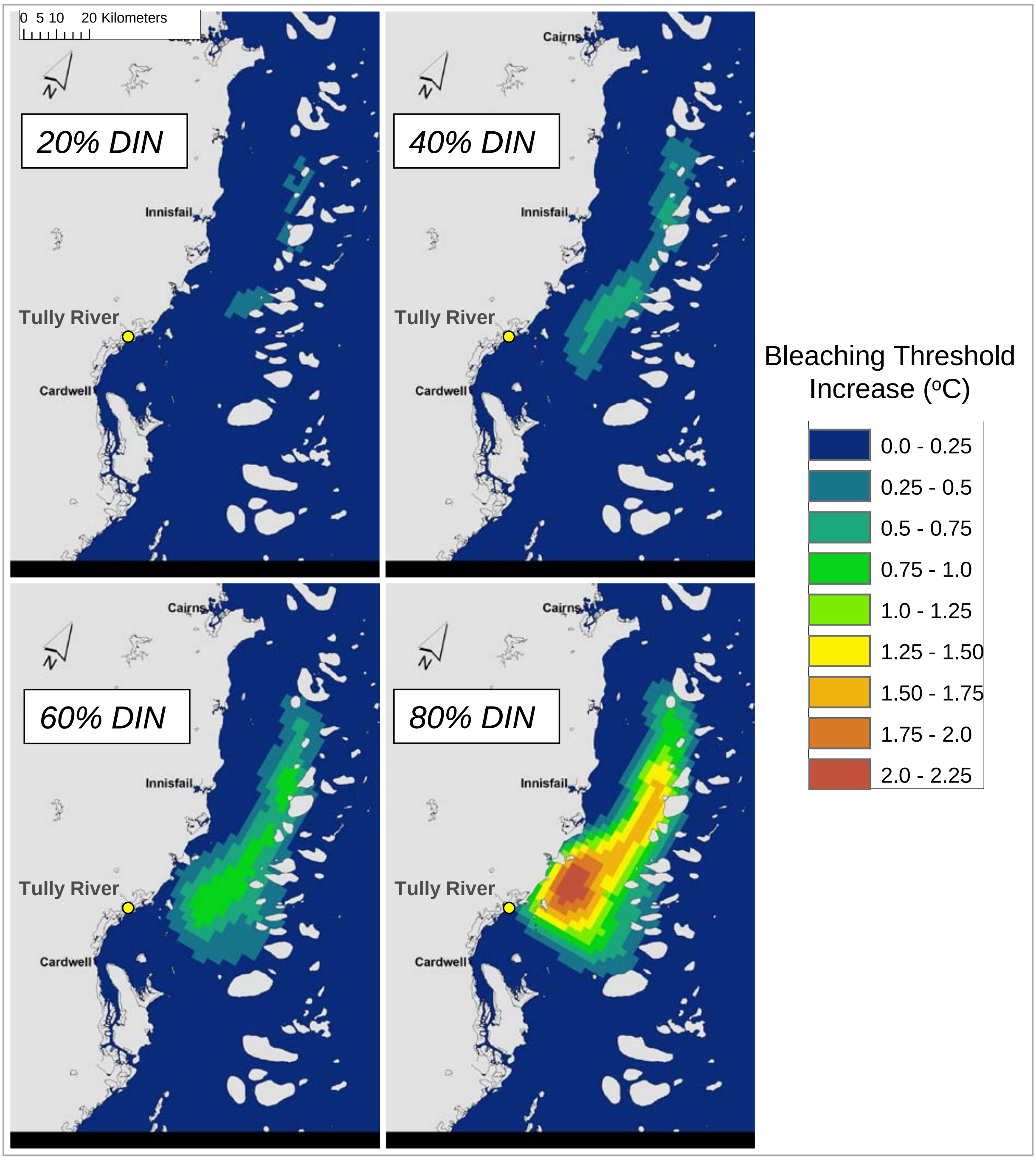

Figure 6: Modelled improvement in upper thermal bleaching threshold (°C) due to a 20%, 40%, 60% and 80% reduction in end-of-river DIN load for the Tully-Murray catchment.

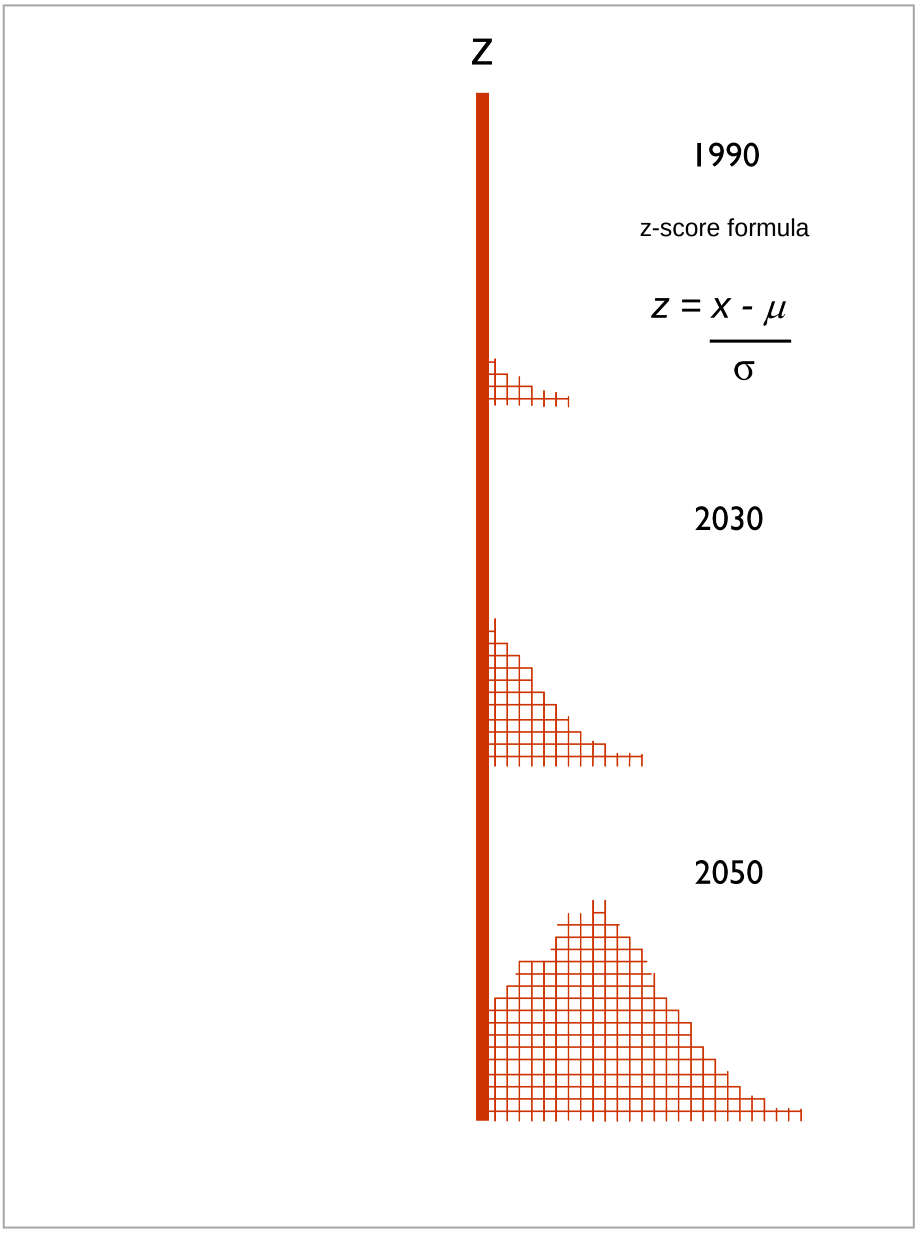

Figure 7: Conceptual representation of the *z*-score approach to modelling the AEP of LD50 mortality events on the Great Barrier Reef.

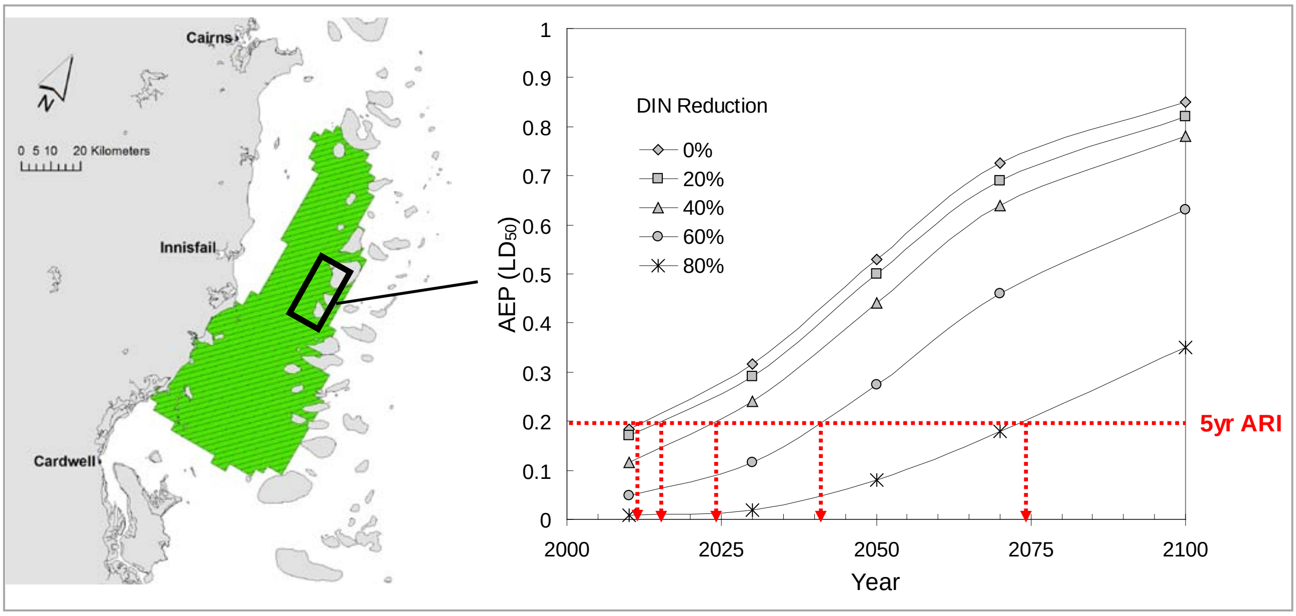

Figure 8: Projected AEP of LD50 mortality events given a 20%, 40%, 60% and 80% reduction in end-of-river DIN load. The five-year ARI (red line) is indicative of the maximum bleaching disturbance frequency for the maintenance of a hard coral-dominated reefscape.

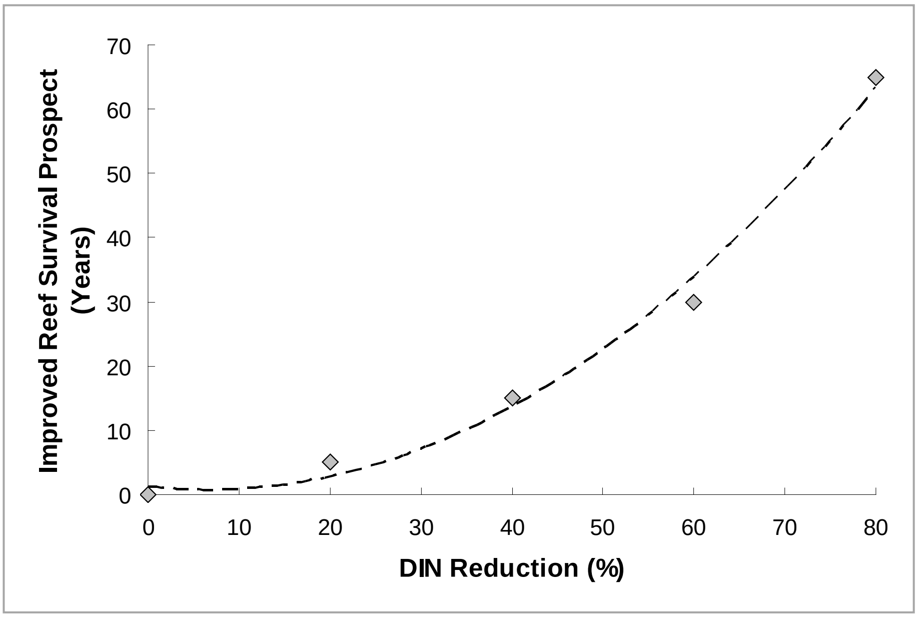

Figure 9: Improved future reef survival prospect (years) for each progressive level of DIN pollution abatement. Results are plotted relative to the 'do nothing' DIN reduction scenario.

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