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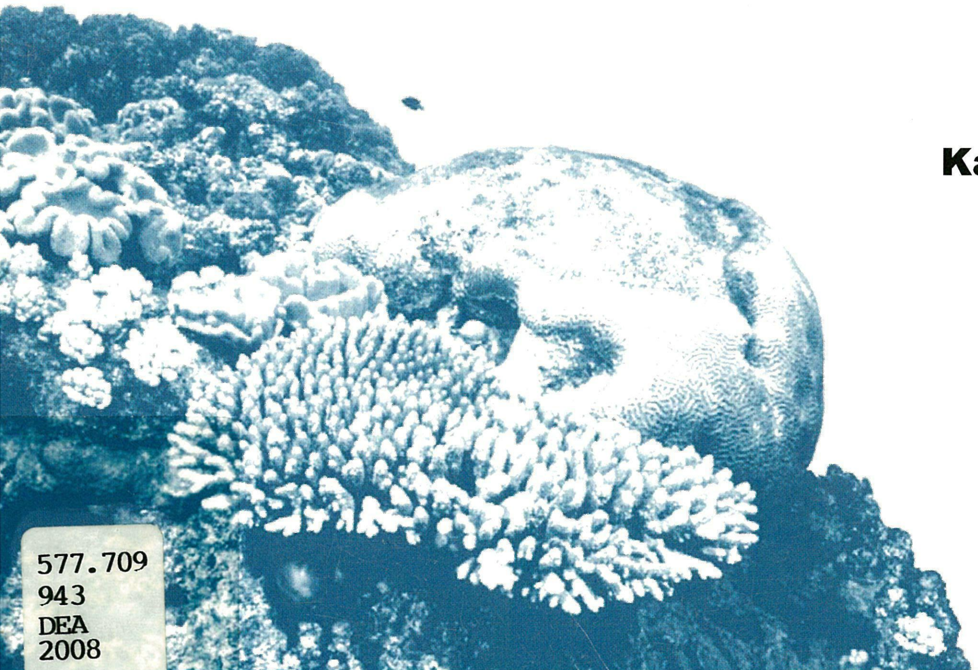

Glenn De'ath and
Katharina Fabricius



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# Water Quality of the Great Barrier Reef: Distributions, Effects on Reef Biota and Trigger Values for the Protection of Ecosystem Health

Report to the Great Barrier Reef Marine Park Authority
February 2008

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# Executive Summary

This Report to the GBRMPA provides technical background information and statistical data analysis for defining improved water quality guideline trigger values for the GBR Water Quality Guidelines.

The report consists of the following sections:

- Rationale for the chosen methods (Chapter 2).
- The spatial and seasonal characterization of water quality conditions in the six NRM regions within the GBR (Chapter 3).
- The spatial characterization of four measures of reef biota used as proxies for reef ecosystem health (Chapter 4).
- An assessment of the relationships between water quality and reef ecosystem health (Chapter 5).
- Suggested trigger values for water quality that will protect ecosystem health (Chapter 6).
- Predicted improvement in ecosystem health should the trigger values be implemented (Chapter 7).

The following spatial and temporal categorisations were made in this study:

- To account for long-shore and cross-shelf gradients in the GBR, the conditions and proposed changes are presented for three zones across the shelf [coastal (<0.1 across the shelf), inner shelf (0.1 – 0.4 across), and offshore (>0.4 across, considered nearly free of terrestrial signals)] within each of the six NRM Regions along the shelf.
- Trigger values are presented as annual mean concentrations that should not be exceeded. Mean values were chosen since exposure to high concentrations was considered ecologically important and acute high values would not have been adequately reflected by percentiles (e.g. medians).
- To account for seasonal variability, regional means were also calculated for the summer and winter quarters (wet and dry season, respectively) for each cross-shelf position within each of the NRM regions.

We define a water quality guideline trigger value as 'a recommended numerical value of a water quality indicator (e.g. water clarity) that will support and maintain the designated environmental conditions of a water body and its pelagic and benthic ecological communities'.

Nine water quality parameters were analysed: Secchi depth, chlorophyll, suspended solids, particulate, dissolved and total nitrogen, and particulate, dissolved and total phosphorus. The concentrations of most water quality variables decrease by 60 – 85% from the coast to a distance 40% across the Reef. For most water quality parameters, changes across the shelf vary along the coast, with declines being steepest across the central third of the GBR while only minor cross-shelf changes occur in the Cape York Region. Differences between the NRM regions are large, with Cape York having the lowest concentrations in the coastal zone but water quality conditions similar to the other regions in the offshore zone. The central regions contain some flood plume data, while the far northern and southern regions do not, which may to some extent contribute to the differences in mean coastal and inshore values between the regions. There are strong seasonal differences in most of the water quality parameters, with summer values 10 – 100% higher than winter values. Concentrations of PN, PP and SS are strongly correlated with Secchi depth, and to a lesser extent with chlorophyll.

Four groups of biota were used as proxies for reef ecosystem status and biodiversity: these were macroalgal cover, species richness of hard corals, and species richness of phototrophic and heterotrophic octocorals. The analyses related algal cover and the three measures of biodiversity to chlorophyll and water clarity, while also accounting for spatial gradients along and across the GBR, and showed that algal cover and the richness of hard corals and octocorals were strongly related to chlorophyll and water clarity. Macroalgal cover increased monotonically 3.5-fold with increasing turbidity (low water clarity), and by 33% with chlorophyll increasing from 0.4 to 1.0 $\mu g\ L^{-1}$. Additionally, macroalgal cover declined four-fold across the shelf and was naturally higher in the south than in the north, having controlled for differences in water clarity and chlorophyll. The richness of both hard corals and phototrophic octocorals decreased with increasing turbidity and chlorophyll. Heterotrophic octocorals increased with greater turbidity and slightly decreased with higher chlorophyll. The two water quality variables explained 38% of the variation in phototrophic octocoral richness, 29% for macroalgal cover, and 25 and 21% in the richness of hard corals and heterotrophic octocorals, respectively.

Two separate approaches were used to define water quality guideline trigger values:

(i) The modeled relationships between the condition of reef biota, Secchi depth and water column chlorophyll concentration were used to identify the highest mean annual chlorophyll and lowest Secchi values that were related to high macroalgal cover and low coral and octocoral richness. For all four groups, these values were 0.4 – 0.5 µg $L^{-1}$ chlorophyll, and 10 – 15 m Secchi depth.

(ii) The analyses of the spatial distribution of water quality showed that Cape York waters had mean annual chlorophyll concentrations of 0.45 µg $L^{-1}$ in the coastal strip (<0.1 across the shelf) and 0.40 µg $L^{-1}$ on the inner shelf (0.1 – 0.4 across), and 10 m and 11 m Secchi depth in coastal and inner shelf waters, respectively. Cape York is subject to only low levels of land use and may therefore be defined as a Reference Condition Site (European_Community 2005; Environmental_Protection_Agency 2006).

**Based on these two approaches, we propose guideline trigger values of mean annual concentrations of chlorophyll of 0.45 g $L^{-1}$ and mean annual Secchi depth of 10 m for both coastal and inner shelf zones in all regions (at shallower depths the seafloor will be visible). Significant benefits for the ecological status of reefs in the GBR are likely obtained if mean annual chlorophyll and turbidity will remain below these values. Further reductions in nutrient loads and improvements in water clarity would likely provide further benefits for ecosystem status. Chlorophyll guideline triggers need to be seasonally adjusted to values 40% higher in summer, i.e. 0.63 µg $L^{-1}$, and winter guideline triggers should be 30% lower, i.e., 0.32 µg $L^{-1}$.** Seasonal adjustments for Secchi depths are presently not suggested since insufficient data on temporal variation are available.

**We also identified approximate maximum annual means as trigger values for SS, PN and PP, based on both the biotic responses and the values found in Cape York. These trigger values are 2.0 mg $L^{-1}$ SS, 1.5 µmol $L^{-1}$ PN (equivalent to 20 µg $L^{-1}$ PN), and 0.09 µmol $L^{-1}$ PP (2.8 µg $L^{-1}$).** Higher levels are related to substantial increases in macroalgal cover and declines of coral biodiversity to low values. Seasonal adjustments for SS, PN and PP are approximately ±20% of mean annual values. **Seasonally adjusted guideline triggers are therefore 2.4 mg $L^{-1}$ SS in summer and 1.6 mg $L^{-1}$ SS in winter. For PN, they are 1.8 µmol $L^{-1}$ (25 µg**

**$L^{-1}$) in summer and 1.25 µmol $L^{-1}$ (17.5 µg $L^{-1}$) in winter. Seasonally adjusted trigger values for PP are 0.11 µmol $L^{-1}$ (3.3 µg $L^{-1}$) in summer and 0.075 µmol $L^{-1}$ (2.3 µg $L^{-1}$) in winter.**

For chlorophyll, Secchi depth, PN and PP, the suggested similar trigger values are supported by both the condition found in the reference region and the relationships expressed through the response curves. For SS, the response curves strongly suggested that trigger values should be lower than the concentrations presently found in the coastal zone of Cape York in order to prevent extensive macroalgal cover and loss of biodiversity.

It is important to emphasise that although water quality improvements to levels lower than the suggested trigger levels would likely lead to further substantial ecosystem benefits, the trigger levels represent an achievable compromise between the current water quality status and that of a pristine system. A choice of substantially lower concentrations as triggers would likely lead to further reductions in macroalgal cover and increased coral biodiversity, but may well not be achievable. It also should be emphasized that the use of annual mean exposure concentrations may under-estimate the role of exposure to episodic events such as acute floods. Last, more research is needed to investigate the response of other organism groups such as microbial communities and responses such as altered ecosystem processes (e.g., coral recruitment) which are known to be sensitive to changes in water quality and play a fundamental role in ecosystem functions.

The required changes in coastal and inner shelf chlorophyll and water clarity were calculated for each of the NRM regions. In coastal waters, reductions in mean annual chlorophyll by 22 to 63%, and increases in water clarity by 56 to 170% will be necessary to re-establish highly diverse coral communities and reduce abundances of macroalgae. The required changes would be greatest north of the mouths of the rivers Burnett, Fitzroy, Burdekin, Herbert, Tully and Johnstone River. In inner shelf waters, water clarity is close to the proposed guideline trigger value in all regions, while chlorophyll would need to be reduced by 46% and 8% on inner shelf reefs of the Burnett Mary and the Burdekin regions, respectively, to allow reef biodiversity to recover. Given the strong correlations between chlorophyll, SS, PN and PP, a reduction in chlorophyll and Secchi depth may be achieved by efforts in reducing loads of SS, PN and PP in rivers.

We estimated the predicted changes in coastal and inner shelf reefs in each region if mean annual Secchi depth is >10 m depth, and mean annual chlorophyll is <0.45 µg $L^{-1}$. The analysis shows that in coastal reefs of all regions other than Cape York, macroalgal cover would likely be reduced to about half of current values if water clarity and chlorophyll were improved simultaneously. Water clarity was related to greater changes in macroalgal cover than changes in chlorophyll. Due to the natural north-south gradient in macroalgal cover, macroalgal cover would still be naturally higher in the three southern regions compared to the northern regions after water quality improvements were implemented. Hard coral richness on coastal reefs in the Burnett Mary, Fitzroy and Wet Tropics would likely increase by 44 – 47% compared to present-day values, and in the Mackay Whitsundays and Burdekin by ~30%. On inner shelf reefs, hard coral richness would still increase by 20 – 25% in the Fitzroy and Mackay Regions. The richness of phototrophic octocorals would likely increase on coastal reefs by 63 – 84% compared to present-day values, and on inner shelf reefs, the increase would be 44 – 51% in the Fitzroy and Mackay Whitsundays regions. For this group, changes in chlorophyll were related to greater changes in coral richness than changes in water clarity. Finally, a reduction in chlorophyll would likely lead to increased richness of heterotrophic octocorals, while increased water clarity would lead to loss of heterotrophic taxa. The simultaneous improvement of chlorophyll and water clarity would lead to only minor changes in the richness of heterotrophic octocorals on coastal and inner shelf reefs. Further research will be needed to assess the responses of other important biotic groups to changes in water quality.

Given the hydrodynamics of the GBR, we suggest that these trigger values should apply throughout the GBR, perhaps with one exception. Water clarity in the Broad Sound is strongly driven by the high tidal ranges leading to intense resuspension regimes while chlorophyll and many of the nutrient concentrations in this zone are low. It is therefore advisable to increase the guideline values for water clarity for areas with >5 m tidal ranges, and an (arbitrary) value of 20% may serve this purpose. In the longer term, local tides and wave height might be included as additional factors in the models to assess ecosystem responses.

The analyses presented here show that levels of chlorophyll and water clarity are useful indicators of ecosystem status of the GBR, and thus they should be considered for use in any monitoring program of reef status. Additionally they are cost-effective since they can be recorded through automated turbidity and chlorophyll loggers at fixed stations. The design of such a monitoring program requires additional consideration of sampling intensity, seasonal variation and site locations prior to implementation.

While chlorophyll and turbidity are proxy measure for water quality, other parameters such as the distribution of benthic irradiance, rates of sedimentation and sediment properties such as grain size and organic content, are primary drivers of ecosystem status. Insufficient field data are available to set trigger guidelines for these parameters in the GBR. **For sedimentation, experimental data suggest that a mean annual value of 3 mg $cm^{-2}$ $d^{-1}$, and a daily maximum of ~15 mg $cm^{-2}$ $d^{-1}$ might guard against excessive coral recruit mortality even in areas where sediments have high organic content.** However more field data on sedimentation quality and quantity are needed to fully assess this value before adoption as trigger value. Such data may eventually lead to the development of sediment quality guidelines for the GBR, and should include properties such as nutrient contents and grain size distribution. Before targets for benthic irradiance can be set, further work is needed to analyse the spatial distribution of benthic irradiance, and its relationship to Secchi depth, turbidity, suspended solids and sedimentation on the GBR, and to better characterise hydrodynamic settings that determine whether ecosystem changes are predominantly due to sedimentation or due to turbidity. These questions should be addressed as a matter of priority. Finally, the Cape York region plays an important role for the ecosystem status assessment in the GBR, being the last remaining Reference region on the coastal and inner shelf GBR. The biodiversity, ecological functions and water quality conditions of the Cape York region should therefore be better documented and researched as a matter of urgency, and should be completed before climate change and other intensifying pressures degrade this ecosystem.

# 1. Background

The identification of trigger values for benthic irradiance, nutrients and sediments for the inner shelf Great Barrier Reef (GBR) is an essential component of the Great Barrier Reef Marine Park Authority's Water Quality Guidelines (Moss et al. 2005, Honchin et al. 2007). Models of river nutrient discharges and proxies of sedimentation recorded in coral skeletons suggest about 5-fold higher mean annual sediment discharges within the last 140 years compared to values before first European settlement and the onset of farming in 1860 (Furnas 2003; McCulloch et al. 2003; McKergow et al. 2005). As rivers are considered the largest source of new nutrients and sediments injected into the inner shelf waters of the GBR (Furnas 2003), future changes in water quality conditions in the inner shelf GBR are assumed to be partly dependent on the nature and intensity of land use. This recognition has lead to the creation of the Reef Water Quality Protection Plan (the Reef Plan), a government initiative with the aim to halt and reverse the amount of nutrients and sediments entering into the GBR lagoon through the adoption of best land management practices.

Water quality targets for turbidity, nutrients and sediments have been set for estuarine, inner shelf and offshore waters of Australia (ANZECC 2000). These were progressively refined for Queensland (Environment Australia 2002; "Water quality targets online", Moss et al. 2005, and Environmental Protection Agency 2006). Moss et al. 2005 distinguished three regions along the coast, and four across the coast, and set guidelines for dissolved and particulate nutrients and chlorophyll. These targets were set with relatively limited knowledge of the ecosystem effects that would be derived from compliance. To guide management in the implementation of the Reef Plan, catchment-specific trigger values, objectives and eventually targets of acceptable levels of pollutants need to be defined that specifically apply to rivers, coastal and inner shelf waters along the whole length of the GBR (Honchin et al. 2007). The following definitions have been set by the Australian and New Zealand Environment and Conservation Council (ANZECC 2000):

- **A water quality guideline (here also called trigger value)** is "a recommended numerical value of an indicator (e.g. of a contaminant) or a descriptive statement (e.g. visual appearance of a water body) that will support and maintain the designated environmental values of a particular water type and its pelagic and benthic ecological communities. Water quality guidelines nowadays encompass not only the physical and chemical characteristics of waters but also biological and habitat characteristics" (ANZECC 2000).

- **A water quality objective** is "a measurable yardstick that need to be achieved to maintain or restore the community's initial choice for environmental values of waterways in the study area and the water quality guidelines to protect them".

- **A water quality target** is a "numerical value or descriptive statement that must be met within a specified period of time to protect a set of environmental values. Customising targets to local conditions following procedures outlined in the guidelines is highly encouraged" (ANZECC 2000).

This report presents work to define improved guideline trigger values based on an improved understanding of ecological effects of water quality, following the ANZECC (2000) definition of trigger values. To aid the setting of trigger values, this report contains:

a) A synthesis of the main spatial, temporal and conceptual considerations when determining trigger values.
b) An assessment of water column nutrients, chlorophyll and turbidity (or their proxies), and of ecosystem status, for the coastal and inner shelf of each Natural Resource Management Region with catchments that drain into the Great Barrier Reef Marine Park.
c) An assessment of the relationship between water quality and ecosystem status in the GBR.
d) Suggested water quality trigger values using the definition by ANZECC (2000).
e) Model-based predictions of ecosystem benefits should the proposed trigger values be implemented.
f) An Appendix containing a review of existing studies and supporting information on the effects of total suspended sediment, turbidity, sedimentation and nutrients (or their proxies) on measures of ecosystem status.

# 2. Methods

## *2.1. Choice of methods to determine water quality trigger values*

### a) Trigger values derived from field data

Methods for setting water quality targets have been developed by the European_Community (2005) through their Water Framework Directive, and some of these methods appear also applicable to the GBR (Ferrier 2007). The EU Water Framework Directive, which is now EU law, requires member states to ensure no further deterioration in the ecological quality of all aquatic environments (i.e., rivers, lakes and wetlands, groundwater, estuarine and coastal waters). It also aims to achieve 'good status' for all waters by 2015. It requires member states to (1) **assess the ecological status of water bodies**, and to then (2) ensure through the development of appropriate environmental quality standards and management strategies that environmental objectives are set for these water bodies. Goal One, the determination of the ecological status, is achieved through a composite measure of biological, hydro-morphological, chemical and physico-chemical 'quality elements' (reviewed in Ferrier 2007). Each member state reports the ecological status of their water bodies using a standardised five-level rating scheme, while chemical pollution is reported using a two-level rating ('good', or 'failing to achieve good'). Ratings are derived by comparison with accepted **'reference condition standards'** that have to be established for each type of water body. Reference conditions describe the 'biology quality elements' that would exist where little or no anthropogenic disturbances occurred, and are derived either from sites with high ecological quality, or through modeling or expert assessment (or a combination of these approaches). The objective of setting reference condition standards is to enable the comparison of current ecological quality against these standards (i.e. the degree of degradation as a measure of deviation from expected values due to anthropogenic pressures). Environmental quality standards are then defined as **maximum annual mean concentrations** (e.g., pollutant concentration) for each of the EU member states.

In this study we use two similar approaches for the GBR: we first assess both the water quality status (using nine water quality variables) and the ecological status (using four measures of ecosystem status) in the coastal and inner shelf waters of the six main NRM regions adjacent to the GBR. We then relate the measures of ecosystem status to water clarity and chlorophyll concentrations. We also identify reference condition standards by characterising water quality and ecosystem conditions found in the relatively undisturbed inner shelf regions of Cape York. Guideline trigger values are then recommended based on two independent assessments: (i) the present-day distribution of GBR water quality and ecosystem status in reference regions, and (ii) an improved understanding of the relationships between exposure and effects. The proposed trigger values should help setting water quality targets, and refine the methods for a comprehensive coastal waters quality and ecosystem status monitoring program.

## b) Targets derived from exposure experiments

Water quality standards are often derived from standardized ecotoxicological experiments. The standards aim at identifying the exposure concentration below which 'unacceptable' effects in the aquatic ecosystem will most likely not occur. They are set to protect *all* water organisms against adverse effects that may be caused by *both chronic and acute* exposure to a chemical substance, sedimentation, etc, and should *not be site specific* (European Community 2005).

For coral reefs, relevant experiments investigating the effects of nutrients, turbidity and sedimentation on corals and other reef organisms are reviewed in Appendix 1 and 2. The review shows that most experiments were not designed to determine trigger or target values, because

- most of the studies do not follow internationally accepted ecotoxicity protocols;
- most studies that investigate acute short-term exposure to high concentrations do not usually determine lethal or half-way effects concentrations (LC50 or EC50);
- few studies investigate the effects of chronic exposure, and in most of these, the 'no observed effects concentrations' (NOEC) are not systematically determined.
- response data are generally available for one or few species of corals, but rarely for any other trophic level (e.g., algae, crustacean or fish species).

Furthermore, the following considerations are relevant when deciding on guideline trigger values of stressors based on laboratory experiments:

- **Susceptibility varies greatly between species**, and depends on size and life history stage within species. For example, whole-colony mortality from sedimentation is more likely in small than in large colonies, while temperature stress may be size independent. Tolerance of low benthic irradiance may be also be independent of colony size, while the settlement behaviour of coral larvae is very responsive to changes in benthic irradiance/turbidity. As ecosystem sensitivity depends on the most sensitive species or processes/functions, guideline trigger values should be set to protect the most sensitive species, life history forms or ecosystem functions.
- **Synergistic, additive or antagonistic effects** complicate the setting of guideline trigger values, but are still poorly understood. For example, crustose coralline algae are far more sensitive to damage by sedimentation when traces of the herbicide diuron are present (Harrington et al. 2005). Other examples are that the uptake of dissolved inorganic nutrients in benthic macroalgae is diffusion limited, i.e., depends on both concentration and water turbulence (Hurd 2000), and that benthic macroalgae may use additional nutrients predominantly where benthic irradiance is not limiting. Similarly, climate change is expected to increase the frequency of disturbances to reefs (through bleaching, ocean acidification, and the intensity of drought – flood cycles and cyclones; Fabricius et al. 2007a), hence the importance of good water quality increases further to maximise resilience and facilitate reef recovery.
- **Both concentration and duration of exposure often co-determine the severity of a response**. Therefore, prolonged or chronic exposure to low levels of pollutants can be as detrimental as short acute exposure to high levels of pollutants. For example, the effects of sedimentation and high temperatures increase linearly with amount and duration of exposure. I.e., a coral exposed to high levels of sedimentation for a short period of time shows a similar level of photophysiological stress compared to one that is exposed to low levels of sedimentation for a prolonged period of time. Guideline trigger values should provide protection against both chronic and acute effects.
- **Exposure-response curves of biota tend to be non-linear**, and in some cases both upper and lower guideline trigger values may be required. Fig. 1 summarises schematically the response curves of a 'typical' coral to the six main physico-chemical environmental conditions, which all become stressors

towards more extreme levels. These response curves vary depending on the type of physico-chemical measure. For example, corals are highly tolerant of exposure to a wide range of levels of nutrients and benthic irradiance, and only very low and very high levels can lead to stress and eventually to mortality. In contrast, sedimentation invokes a monotonic response, with coral status declining with increasing exposure to sedimentation. Corals can also grow in a wide range of turbidity, with very low particle densities providing insufficient heterotrophic nutrition, and high densities leading to reduced photosynthetic carbon gain. However, corals undergo photoadaptation in response to fluctuating light availability by adjusting zooxanthellae densities, which results in stress from photoinhibition for several days after particles have settled out, and stress from low photosynthetic carbon gains for several days after the water has become more turbid (Anthony and Hoegh-Guldberg 2003). Photoadaptation takes around 7 – 10 days, during which the coral photophysiology does not perform at optimum rates. Therefore it is the variability in turbidity rather than the absolute value that determines the level of stress at all but extreme levels of turbidity.

- **Exposure to nutrients, turbidity and sediments varies naturally along spatial gradients**. For example:
    - Light loss from turbidity will have far greater effects on coral communities in deep water than in shallow water.
    - Rates of sedimentation are generally greater in sheltered reef embayments and on lower back reef slopes than on wave-exposed reef slopes. Poorly flushed sheltered, deeper reef slopes in which sediments are deposited and remain for extended periods are therefore more susceptible to impacts than well-flushed shallow areas.
- **Toxicity and mortality thresholds based on short-term exposure experiments are not adequate endpoints to define trigger values**, as long-term exposure at sublethal stress levels can still result in ecosystem degradation, due to reduced growth, reproduction and recruitment, and higher rates of mortality. We therefore chose measures of ecosystem status that integrate over long periods of time (macroalgal cover, reduced species richness in corals and octocorals). High macroalgal cover is widely accepted as an indicator of reef degradation, and is also a causative agent for reduced reproduction in corals and other reef organisms. Reduced species richness is

generally the outcome of selective mortality, slower growth or failed reproduction of the more sensitive species exposed to severe environmental conditions. These measures, together with physiological, population and community-based indicators should therefore be standard components of ecosystem monitoring programs.

These complicating factors are not specific to coral reefs but typical for many ecosystems. For this reason, the European Community (2005) applies uncertainty factors of 10, 50, 100 or 1000 to experimentally measured lowest 'no observable effects concentrations' (NOEC) or effects concentrations (LE50 or EC50), with the factor depending on the data availability and data quality. The following factors are used (European Community 2005):

- At least one acute L(E)C50 from each of three trophic levels of the base set: divide by 1000;
- One chronic NOEC: divide by 100;
- Two chronic NOECs from species representing two trophic levels: divide by 50;
- Chronic NOECs from at least three species representing three trophic levels: divide by 10

In conclusion, due to the large number of complicating factors, trigger values are best derived from assessments of field conditions at recognised reference regions, and by assessing the relationships of selected measures of ecosystem status to water quality parameters. Trigger values based on effects concentration of a pollutant derived from laboratory experiments are unlikely to provide adequate protection to coral reef ecosystems without the application of conservative safety factors. Nevertheless, exposure experiments are needed to ascertain causality and quantify dose-response relationships, and some of the findings from such experiments are summarised in Appendix 1.

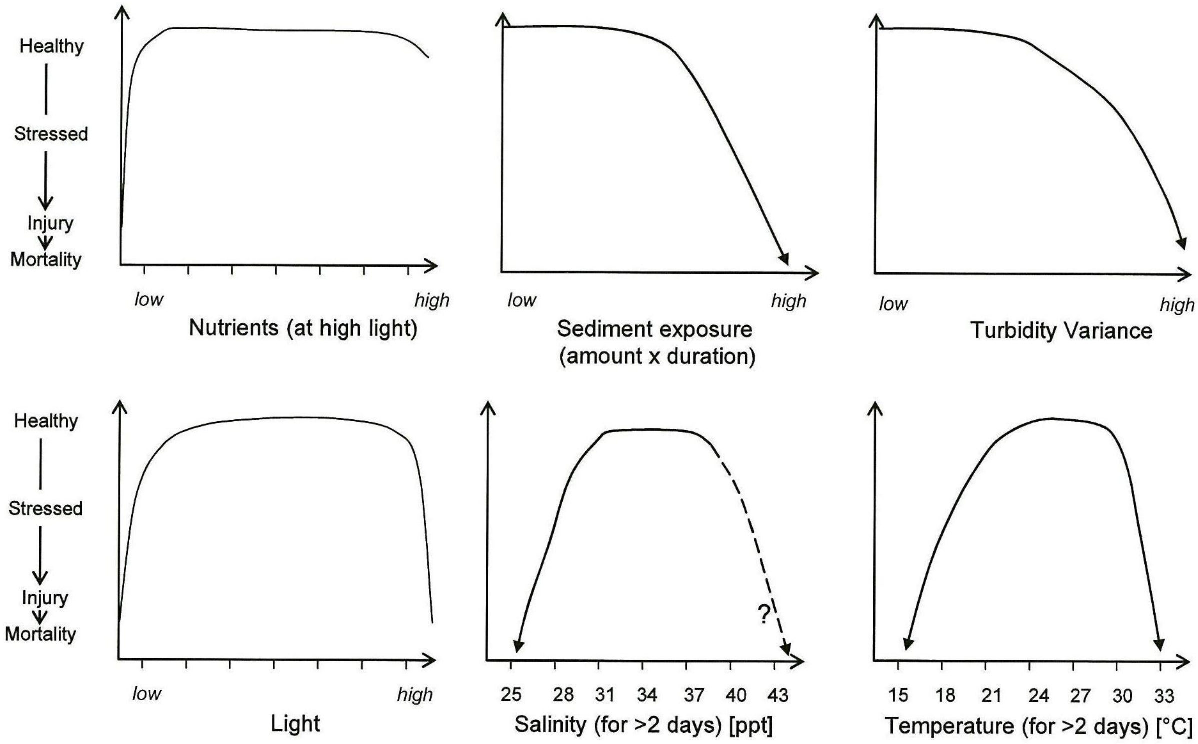


Fig. 1: Schematic diagram of the typically non-linear responses of corals to changes in exposure to nutrients, sedimentation (with exposure being defined as the product of amount times duration), the variability in turbidity, and changes in light attenuation, salinity and nutrients.

## 2.2. Choice of data

### a) Water quality

The following water quality data sets were used (more details of the data and methods are described in De'ath, 2007):

- **Water clarity based on Secchi depth** (m): a composite of DPI seagrass monitoring data (Rob Coles) and AIMS data (Miles Furnas and co-workers, K. Fabricius and co-workers).
- Total **chlorophyll** ($\mu g\ L^{-1}$): A data set composed of the data from the GBRMPA and AIMS Long-term chlorophyll monitoring program over the period 1992-2006, and the AIMS Lagoon water quality chl data.
- Lagoon **water quality** data: Collected by Miles Furnas and co-workers (AIMS) between 1988 and 2006. These include a suite of physical and chemical water quality data, including chlorophyll (chl ($\mu g\ L^{-1}$), suspended solids (SS; mg $L^{-1}$), particulate phosphorus (PP) and particulate nitrogen (PN) ), total dissolved phosphorus and nitrogen (TDP and TDN) and total phosphorus (TP = PP + TDP) and total nitrogen (TN = PN + TDN).

Water clarity is a key indicator for water quality and is an essential environmental factor for phototrophic organisms that dominate coral reefs, seagrass meadows and the seafloor microphytobenthos. Chlorophyll is commonly used as a proxy for phytoplankton biomass and nutrient status in the lagoon. Due to the important roles of these two water quality measures, the availability of extensive data, and their inclusion in ongoing monitoring programs through semi- automated monitoring stations, most analytical effort was given to Secchi depth and total chlorophyll. Secchi data have the highest spatial resolution of the data sets (Fig 2), however some regions have been samples only once, whereas for the other data sets sites have been sampled repeatedly. Seasonal analyses of Secchi data are not possible from these data due to a confounding of space and time. Further sampling of Secchi data is required to determine temporal variation.

Spatial and seasonal patterns were also determined for suspended solids (SS; mg $L^{-1}$), particulate phosphorus (PP), particulate nitrogen (PN), total dissolved phosphorus and nitrogen (TDP and TDN) and total phosphorus (TP = PP + TDP) and total nitrogen (TN = PN + TDN). All nutrients are presented in $\mu mol\ L^{-1}$ following scientific convention. However for comparison with Reef Plan data and other management documents the tables are additionally presented in µg $L^{-1}$ in both the Appendix and text.

Guideline trigger values for dissolved inorganic nutrients have been identified for rivers, estuaries and flood plume waters. By contrast, in the marine waters of the GBR, dissolved inorganic nutrients are rapidly cycled through uptake and release by biota, and their concentrations do not show clear spatial patterns due to this high variability (De'ath 2007b). We were therefore unable to define nutrient trigger values for dissolved inorganic nutrients, and further we suggest that they are less suitable as indicators of water quality in the GBR.

## b) Biotic data

The relationships between water quality and coral reef status have been reviewed in Fabricius (2005) and in Appendix 1. The conclusions from these reviews, together with practical considerations of availability of large-scale data, provided the basis for choosing the following four measures as indicators of ecosystem condition:

- **Taxonomic richness of hard corals.** Data are based on surveys conducted on 110 reefs (599 transects) of the GBR between 1994 and 2001 (DeVantier et al. 2006; Fig 3). Hard coral surveys were conducted at two depth zones (deep and shallow) and at two sites per reef. Survey methods are explained in DeVantier et al. (2006). The analyses presented here are based on reef-averaged data.
- **Macroalgal cover and the taxonomic richness of phototrophic and heterotrophic octocorals:** Data are based on one-off surveys conducted on 150 reefs (1106 transects) of the GBR (Fabricius and De'ath 2001b) between 1997 and 2001 (Fig. 3). Estimates of macroalgal cover do not include crustose coralline and turf algae, and no information on seasonal changes was available for macroalgae. Surveys were usually conducted at 5 depth zones (<1 m, 1 – 3, 3 – 8, 8 – 13, 13 – 18 m) at typically two sites per reef. All analyses presented here are based on reef-averaged data.

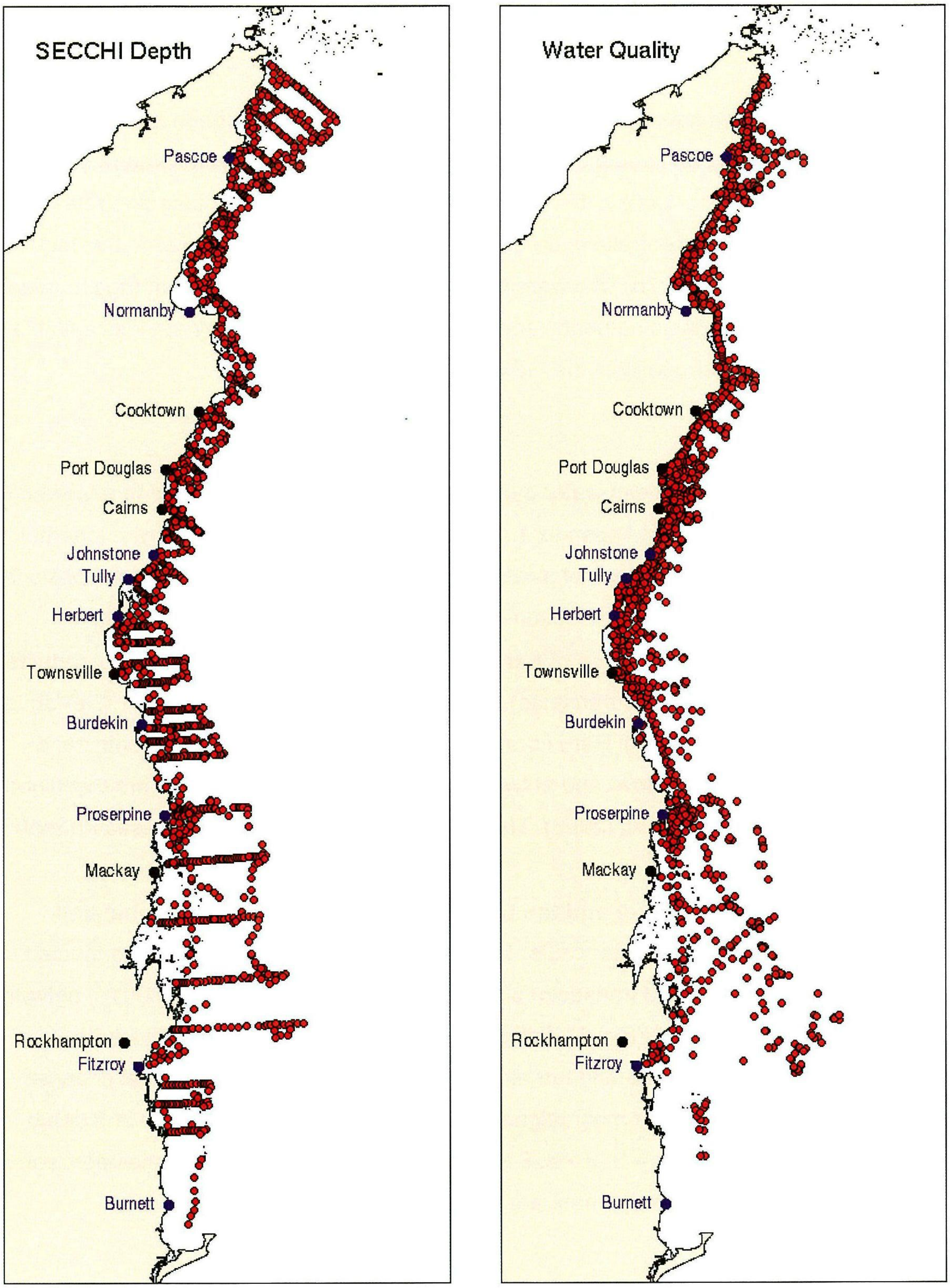


Figure 2: Locations for the 2058 Secchi sites (left panel) and the 4067 lagoon water quality stations (right panel).

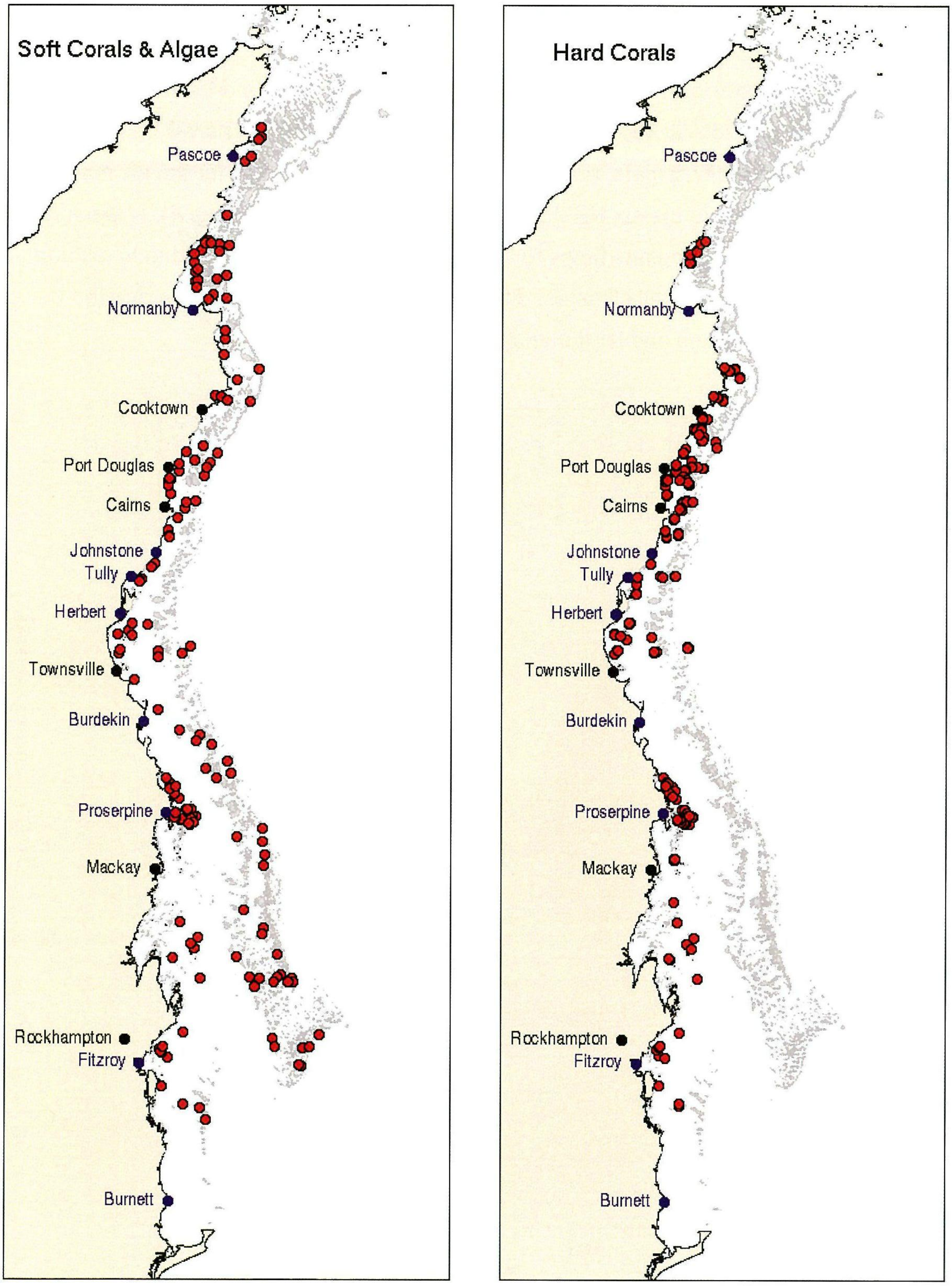


Figure 3: Locations for the 150 reefs surveyed for macroalgal cover and octocoral communities (left panel), and the 110 reefs surveyed for hard coral communities (right panel).

## 2.3. Spatial considerations

**Boundaries along the GBR:** Since the Burnett Mary, Fitzroy, Mackay Whitsundays, Burdekin Dry Tropics, Wet Tropics, and Cape York NRM regions will be responsible to set water quality targets, analyses are presented separately for the six marine regions adjacent to the six NRM regions that border the GBR (Fig. 4). A separate treatment of these regions helps to account for natural differences due to latitude, temperature and rainfall climates, different soil types, and differences due to contrasting land use and land management actions.

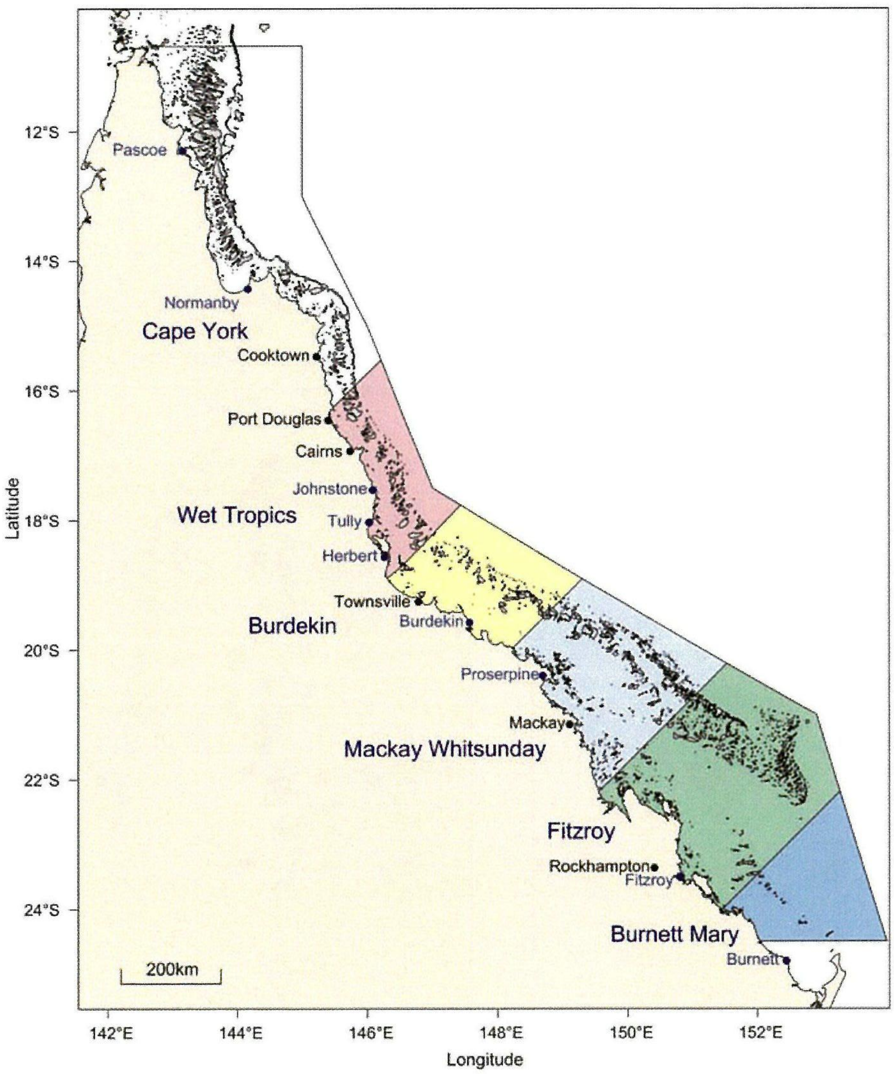


Figure 4: Delineation of the six marine regions adjacent to the NRM Regions with GBR boundaries. These regions cover the whole World Heritage Area. Cross-shelf sub-regions are of the NRM Regions are based on relative distances from the coast to the edge of the continental shelf (see Fig. 6).

**Boundaries across the shelf:** Many options have been proposed to delineate boundaries across the GBR shelf. A fixed distance from the shore (e.g., 3 nautical miles off the shore) has been used as outer boundary by the Environmental_Protection_Agency (2006) following the State boundary. A problem with this definition is that bathymetry and the cross-shelf influences of rivers varies greatly between regions, with plumes of the larger rivers such as the Burdekin often extending >50 km offshore, whereas plumes from smaller rivers such as the Haughton will rarely travel more than 10 km offshore. A slightly larger distance from the shore (e.g., 15 km) will encompass inner shelf conditions in the Wet Tropics and Cape York region where the continental shelf is narrow, but will only represent coastal conditions in the Fitzroy region. Honchin et al. (2007) propose to use the 10-m bathymetry line as boundary for the coastal zone. This delineation has the advantage that it is ecologically meaningful, and a homogeneous measure across the 6 NRM regions as resuspension rates are a function of the depth of the seafloor. However shallow offshore patches would need to be ignored to avoid convoluted boundaries, making this a less than desirable measure to define offshore boundaries. We have consistently found relative distance across the shelf to be the most meaningful measure to define offshore structure (De'ath 2007b; Fig. 5). It is a homogeneous measure across the 6 NRM regions and more practical than an absolute distance from the shore as it also considers the distance from the open ocean at the edge of the continental shelf. We set the boundaries at a relative distance of 0.1 and 0.4 across the shelf. These boundaries together with the coast (across = 0) and the outer edge of the continental shelf (across = 1) define three regions: (i) coastal = 0 – 0.1, (ii) inner shelf = 0.1 – 0.4, and (iii) offshore = 0.4 – 1.0 (Fig. 6). The coastal zone boundary is located 5 - 7 km off the shore (and hence similar to EPA's 3 nautical miles) in the Cape York, Wet Tropics and Burnett Mary Regions where the shelf width is 50 - 70 km, and ~20 km off the shore in the Fitzroy Region (Table 1).

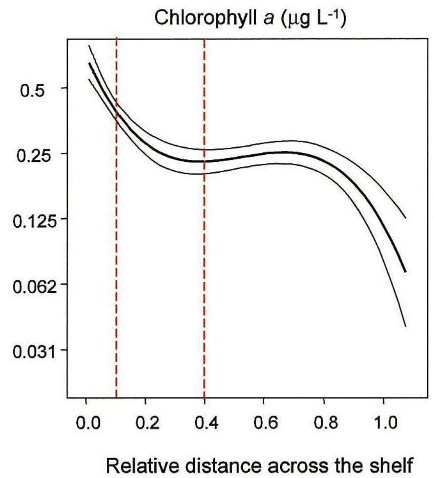


Figure 5. Distribution of chlorophyll a across the GBR continental shelf (from Brodie et al. 2007). The red lines added here show the zonation based on boundaries located at 0.1 and 0.4 across the shelf.

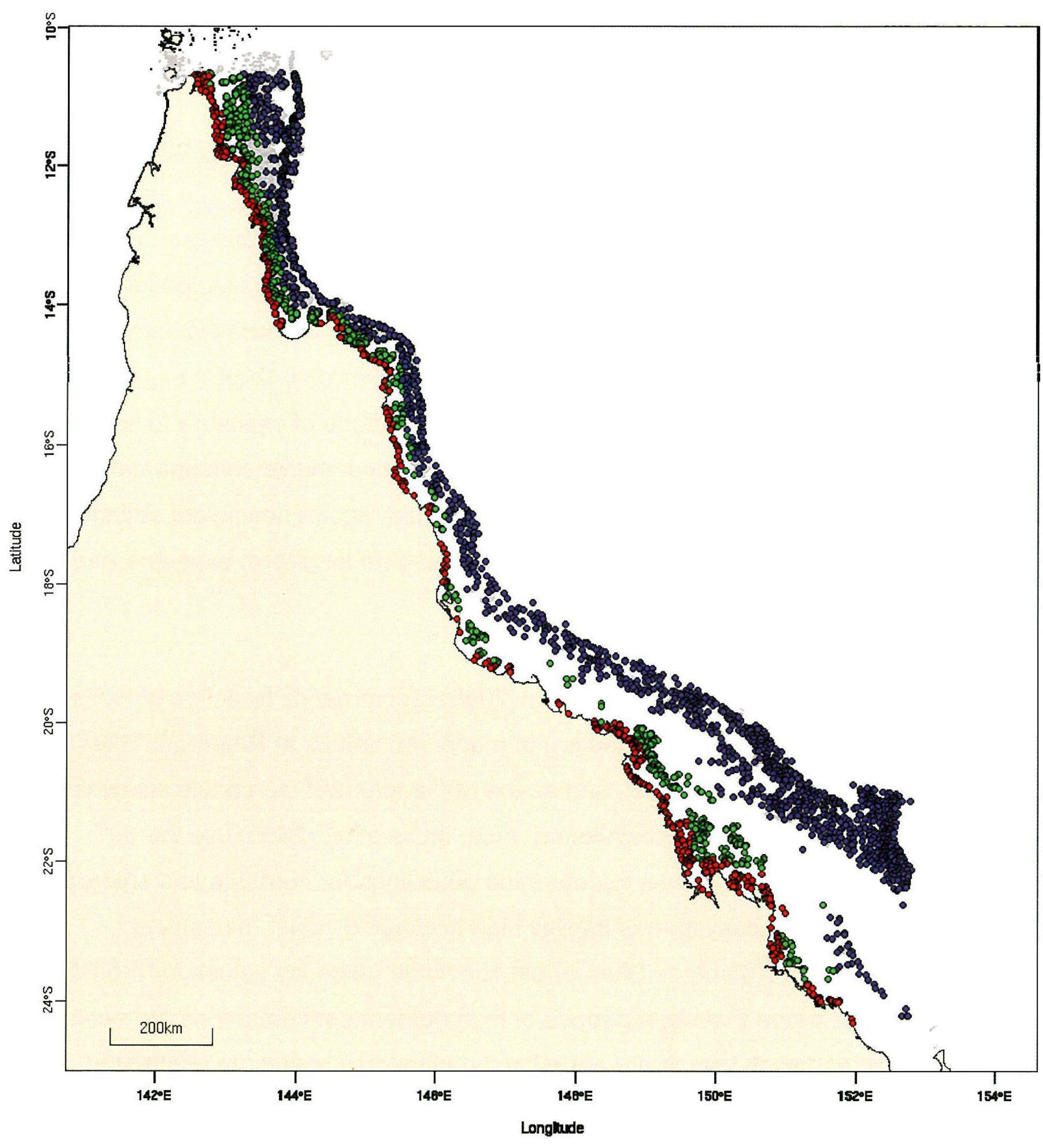


Figure 6: Location of reefs within the three cross-shelf zones in the GBR. Red = coastal, green = inner shelf, blue = offshore.

Table 1: Approximate mean distances of the coastal boundary (0.1 across) and inner shelf-offshore boundary (0.4 across) from the coast in the 6 NRM regions.

| | Mean shelf width (approximate, km) | 0.1 across (km) | 0.4 across (km) |
|---|---|---|---|
| Burnett Mary | 70 | 7 | 28 |
| Fitzroy | 200 | 20 | 80 |
| Mackay Whitsundays | 150 | 15 | 60 |
| Burdekin Dry Tropics | 120 | 12 | 48 |
| Wet Tropics | 60 | 6 | 24 |
| Cape York | 60 | 6 | 24 |

## 2.4. Temporal considerations

### a) Acute versus long-term exposure

The concentrations of chlorophyll and some of the nutrients vary by more than an order of magnitude over time, depending on wind, tides, weather and season. Few experimental data are available to assess causal relationships between long-term exposure (months to years) and pollutants and biotic responses (Appendix 1). In some cases, short-term exposure to high levels of pollutants has the same outcome as prolonged exposure to lower concentrations (Weber et al. 2006). Figure 7 shows the conceptual relationship between loads and durations of exposure to sediments, turbidity, salinity and benthic irradiance, with indicative effects concentrations set for relatively robust coral species. These values would require downward adjustment for more sensitive species. The diagrams show that both long-term exposure and acute concentrations are ecologically relevant.

The Environmental_Protection_Agency (2006) recommends to define guideline values as the 50$^{th}$ percentile (median) of measured values at Reference Sites in areas of 'high ecological value', and as the 80$^{th}$ and/or 20$^{th}$ percentile elsewhere (in slightly to highly modified ecosystems). Also, Moss et al. (2005) use the 80$^{th}$ percentile of observed values to determine guidelines for nutrients and chlorophyll. As the GBR is an ecosystem of implicit high ecological value, medians of concentrations at Reference Sites would constitute guideline values for the GBR. However, we argue that short periods of high nutrient concentrations are ecologically significant, and such values are not reflected in median values. In contrast to medians, mean annual values at least partially capture and reflect both the frequency and magnitude of 'water quality events' (e.g., floods and other events that result in high values), and annual average values are therefore proposed to be used as the preferred measure for guideline values, as also recommended by the European Water Framework Directive (European_Community 2005).

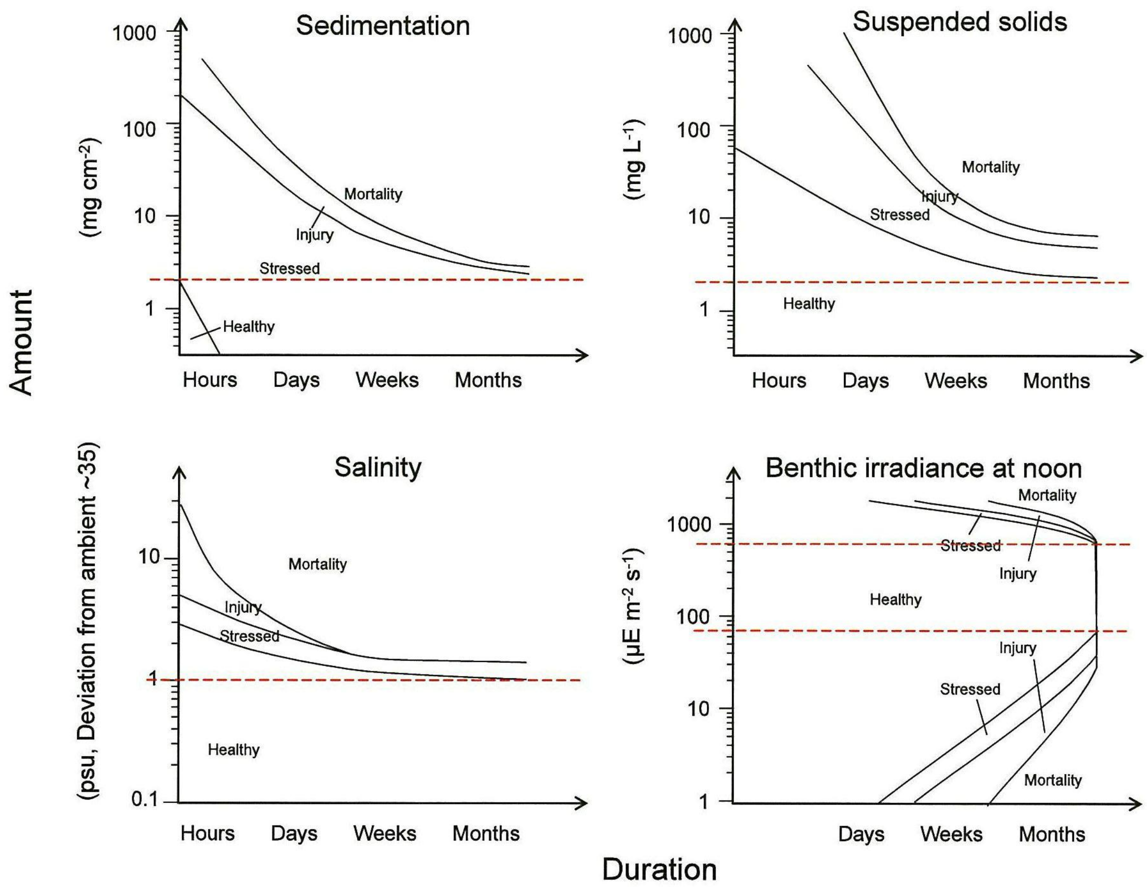


Figure 7. Conceptual relationships between the condition of robust inshore corals and the level of exposure (amounts and duration) to sedimentation, suspended solids, salinity and benthic irradiance. More sensitive species will respond at lower loads and/or shorter durations. Salinity is scaled as the deviation from mean marine salinity (35 psu). The effects of variation in salinity are not well known, but as low-salinity events are usually limited to days to weeks, it is assumed that salinity concentrations are more important than the duration of exposure, resulting in an intersection of the injury and mortality curves. Like salinity, benthic irradiance is a stressor both at low and high levels. In general, corals have wide tolerance ranges of variation in benthic irradiance, and only very low levels for prolonged periods of time, and very high levels result in stress. The tolerance of low benthic irradiance varies with the ability of corals to compensate through heterotrophic nutrition.

## b) Seasonal changes in water quality

Concentrations of chlorophyll and some of the nutrients vary seasonally, related to higher nutrient inputs, temperatures and benthic irradiance in summer than in winter

(Furnas 2003). Long-term averages of chlorophyll are about 70% higher in March than in September in the GBR (Fig. 8; De'ath 2007b). River floods carrying new nutrients and sediments into the GBR are also most commonly observed in the late wet season when monsoonal rainfall is greatest (Devlin et al. 2001; Furnas 2003; Brodie et al. 2003). The relative contribution of river floods vs. other intrinsic and extrinsic factors to this long-term seasonal pattern is however not yet understood. At intra-annual time scales, other processes add variability to concentrations of chlorophyll, nutrients and suspended solids. Probably most importantly, concentrations in the inner shelf area are strongly dependent on wind- and wave-driven resuspension of material from the seafloor, and blooms of the nitrogen-fixing *Trichodesmium* can also significantly increase nitrogen and chlorophyll concentrations.

Although trigger values should ideally include additional separate trigger values for flood conditions, this appears impractical due to the unpredictable timing and varying intensity of monsoonal floods. **Seasonally adjusted long-term averages** rather than flood values are therefore the most practical solution to define guideline trigger values for the time being. We define summer values as January – March, and winter values as July – September.

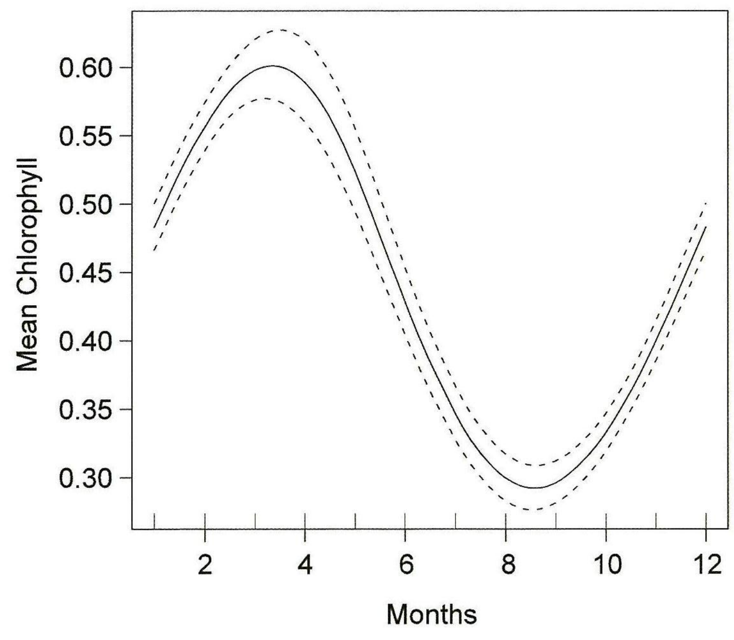


Figure 8. Estimated seasonal variation of chlorophyll concentrations in the GBR, averaged over all locations of the GBR (from De'ath 2007).

## 2.5. Statistical methods

The water quality and benthic variables were each modelled spatially (Chapters 3 & 4) using generalised additive models (GAMs) and smoothing splines (Wood 2003). In all analyses the spatial predictors were relative distance across and along the Reef rather than the usual latitude and longitude. Relative distance across and along the Reef takes advantage of the natural boundaries of the GBR that affect many of the bio-physical processes of the Reef, and thus one might expect that spatial distributions of observed data would be best explained (and best predicted) in this coordinate system. This has been shown to be the case in several published analyses of the data sets used here (e.g. Fabricius and De'ath 2001a; Fabricius and De'ath 2001b; DeVantier et al. 2006; Brodie et al. 2007). Using GAMs, predictions of means and SE were made for each of the 3 cross-shelf zones within each of the 6 NRM regions.

Boosted regression tree analyses (De'ath 2007a) were used to assess the predictability of reef benthos by the spatial and water quality variables (Chapter 4). Partial effects plots were used to display these relationships and the relative contributions of each of the predictors were also estimated. The sampling locations of the water quality, Secchi and biotic data sets differed, and hence in order to assess the relationships between water quality and biota, the first requirement was to predict the values of the chosen water quality parameters for the sites at which the biotic data were sampled. These predictions were made using spatial GBMs where the predictors were across and along. In this way we thus generated the predictors for each of the reef benthos variables at each site on which they were observed The predicted values of the water quality variables (chlorophyll, suspended solids and six nutrient species) were highly correlated and hence when they were used to predict the biotic variables it was difficult to assess the best models. However, extensive analyses showed that Secchi depth and chlorophyll concentrations together with the spatial predictors (across and along the GBR) were better predictors of the biota compared to the remaining water quality measures (De'ath 2007b).

The boosted regression tree analyses used for prediction of the biota from Secchi depth, chlorophyll concentrations and spatial data (across and along the GBR) were then used to predict changes in biota if the proposed trigger values of chlorophyll and Secchi depth were attained. These were estimated separately for each NRM region and the coastal and inner reef zones (Chapter 6), with estimates based on the assumptions that there is little or no change due to other forms of disturbance.

All analyses were done using the R statistical software system (R_Development_Core_Team 2007).

# 3. Spatial and seasonal patterns in nutrients, sediments and turbidity in the GBR

## *3.1. Spatial patterns in water quality in the GBR*

The spatial distribution of water quality variables across the 6 NRM regions, split by the 3 cross-shelf positions into coastal (≤0.1 across), inner shelf (0.1 – 0.4 across) and offshore (≥0.4 across) values is presented in Table 2. Among the coastal strips, Cape York had the lowest concentration of most of the water quality parameters of all coastal regions. The coastal zone of the Burnett Mary NRM had the highest values of chlorophyll but relatively low levels of SS and PN. The coastal zone of the Burdekin had the highest values of SS, PN and PP, the second-highest chlorophyll value and the lowest Secchi depth value. The Wet Tropics had the second-highest values of SS, PN and PP.

### a) Secchi depth

Modeled mean Secchi depth averaged 12 m across the whole GBR (Table 2a) with values ranging from <1 m to 26 m. Low values were encountered in the coastal strip between Port Douglas and Rockhampton (Fig. 9), with a mean Secchi depth of 3.7 m in the Burdekin region, and 4.4 m in the Mackay Whitsundays region, compared to 10.2 m in the coastal zone of the Cape York region. In the inner shelf region, Secchi depth was lowest in the Mackay Whitsundays (8.7 m), and highest in the Fitzroy (14.3 m). Changes across the continental shelf were steepest between Cairns and Mackay, and were weak north of Cape Flattery. Water clarity was greatest along the outer edge of the continental shelf, and in the Swains where values averaged 13 – 16 m.

### b) Chlorophyll

Modeled mean chlorophyll averaged 0.46 μg $L^{-1}$ across the whole GBR, ranging from 0.16 to 1.6 μg $L^{-1}$ (Fig. 10, Table 2b). In the coastal zone, lowest values were measured in the Cape York region, followed by the Mackay Whitsundays, Fitzroy, Wet Tropics and Burdekin, with highest values in the southern Burnett Mary. Inner shelf values varied little between regions except for high values in the Burnett Mary. Offshore values varied almost two-fold, with lowest values in the Wet Tropics and Burdekin, and highest values in the Mackay Whitsundays. Changes across the continental shelf were large in the southern and central parts of the GBR, but were small in Cape York.

## c) Suspended solids

Modeled mean SS averaged 2.1 mg $L^{-1}$ across the whole GBR, ranging from 0.28 to >8 mg $L^{-1}$ (Fig. 11, Table 2c). Values were highest and cross-shelf changes were most pronounced from the Burdekin to Port Douglas, with highest coastal values between the Burdekin and Hinchinbrook Island. Inner shelf values were highest in the Burdekin. Offshore values were all below 1.0 mg $L^{-1}$.

## d) Particulate nitrogen

PN averaged 1.4 µmol $L^{-1}$ (19.6 µg $L^{-1}$) across the whole GBR, ranging from 0.57 to 3.2 µmol $L^{-1}$ (Fig. 12, Table 2d). Values were highest and cross-shelf changes were most pronounced between the Burdekin and Port Douglas. Coastal values were highest in the Burdekin region (2.6 µmol $L^{-1}$ = 36.4 µg $L^{-1}$). Offshore values were lowest in the Burnett Mary and highest in Cape York. Changes across the continental shelf were small in Cape York.

## e) Particulate phosphorus

PP averaged 0.1 µmol $L^{-1}$ (3.1 µg $L^{-1}$) across the whole GBR, with values ranging from 0.04 to 0.24 µmol $L^{-1}$ (Fig. 13, Table 2e). Values were highest and cross-shelf changes most pronounced between the Whitsundays and Cairns, i.e. in the Burdekin and Wet Tropics region from south of the mouth of the Burdekin to Port Douglas. Offshore values were similar across all regions, averaging 0.06 µmol $L^{-1}$ (1.86 µg $L^{-1}$). Changes across the continental shelf were large in the southern and central parts of the GBR but small in Cape York.

## f) Total dissolved nitrogen

TDN averaged 5.3 µmol $L^{-1}$ (78.4 µg $L^{-1}$) across the whole GBR, with values ranging from 4.2 to 9.1 µmol $L^{-1}$ (Fig. 14, Table 2f). Values were highest and cross-shelf changes most pronounced in the Wet Tropics and the central part of Cape York. Values were extremely low around Cape Flattery, and were also low near Gladstone and the northern section of Cape York. Offshore values were similar across all regions, averaging 5.0 µmol $L^{-1}$ (70 µg $L^{-1}$). Changes across the continental shelf were strong in the Wet Tropics and Burdekin, and small in the southern regions.

## g) Total dissolved phosphorus

TDP averaged 0.23 µmol $L^{-1}$ (7.1 µg $L^{-1}$) across the whole GBR, with values ranging from 0.05 to 0.65 µmol $L^{-1}$ (Fig. 15, Table 2g). Values were highest and cross-shelf changes most pronounced in the Burdekin, the Mackay Whitsundays, the Fitzroy and Wet Tropics Region. Values were extremely low around Cape Flattery, and were also low in the northern section of Cape York and near Gladstone. Offshore values doubled from the north to the south, and averaged 0.19 µmol $L^{-1}$ (5.9 µg $L^{-1}$). Changes across the continental shelf were greatest in the Burdekin, Wet Tropics and Mackay Whitsundays region.

## h) Total nitrogen

TN averaged 7.2 µmol $L^{-1}$ (101 µg $L^{-1}$) across the whole GBR, with values ranging from 4.8 to 12 µmol $L^{-1}$ (Fig. 16, Table 2g). Values were highest and cross-shelf changes most pronounced in the Wet Tropics and Burdekin Region. Values were extremely low around Cape Flattery, and were also low in the northern section of Cape York and near Gladstone. Offshore values were similar in all regions, averaging 7.0 µmol $L^{-1}$ (98 µg $L^{-1}$). Changes across the continental shelf were great in the Burdekin, Wet Tropics and Mackay Whitsundays region, and small in Cape York, Fitzroy and Burnett Mary Regions.

## i) Total phosphorus

TP averaged 0.34 µmol $L^{-1}$ (10.5 µg $L^{-1}$) across the whole GBR, with values ranging from 0.11 to 0.87 µmol $L^{-1}$ (Fig. 17, Table 2g). Values were highest and cross-shelf changes most pronounced in the Burdekin, followed by the Wet Tropics and the Mackay Whitsundays Regions. Values were extremely low around Cape Flattery, and in the northern section of Cape York. Offshore values were similar in all regions, averaging 0.30 µmol $L^{-1}$ (9.3 µg $L^{-1}$).

Table 2: Mean annual values and standard errors of Secchi depth, chlorophyll, SS, PP, TDP, PN TDN, TP and TN, predicted across the 6 regions and 3 cross-shelf positions in the GBR. Estimates are based on measurements conducted between 1985 and 2006. ***For comparison with other Reef Plan documents, the nutrient concentations are also presented in µg $L^{-1}$ in Appendix 2.***

| | Coastal | | Inner shelf | | Offshore | | Across all zones | |
|---|---|---|---|---|---|---|---|---|
| | **mean** | **SE** | **mean** | **SE** | **mean** | **SE** | **mean** | **SE** |
| **(a) Secchi depth (m)** | | | | | | | | |
| GBR Mean | **5.7** | 0.9 | **11.4** | 0.7 | **17.7** | 0.9 | **11.9** | 0.1 |
| Burnett Mary | **6.4** | 1.3 | **11.4** | 1.1 | **17.4** | 1.5 | **15.8** | 1.5 |
| Fitzroy | **5.5** | 0.9 | **14.3** | 0.8 | **19.2** | 1.0 | **16.7** | 0.9 |
| Mackay W | **4.4** | 0.8 | **8.7** | 0.7 | **17.0** | 0.9 | **13.2** | 0.8 |
| Burdekin | **3.7** | 0.6 | **13.3** | 0.6 | **18.7** | 0.8 | **15.7** | 0.7 |
| Wet Tropics | **4.7** | 0.5 | **11.0** | 0.5 | **17.0** | 1.0 | **14.5** | 0.9 |
| Cape York | **10.2** | 0.9 | **10.9** | 0.7 | **16.0** | 0.9 | **13.7** | 0.9 |
| **(b) Chl a (µg $L^{-1}$)** | | | | | | | | |
| GBR Mean | **0.7** | 0.06 | **0.4** | 0.04 | **0.4** | 0.05 | **0.5** | 0.01 |
| Burnett Mary | **1.2** | 0.10 | **0.8** | 0.06 | **0.5** | 0.03 | **0.5** | 0.04 |
| Fitzroy | **0.7** | 0.05 | **0.5** | 0.04 | **0.4** | 0.04 | **0.4** | 0.04 |
| Mackay W | **0.6** | 0.06 | **0.5** | 0.05 | **0.5** | 0.05 | **0.5** | 0.05 |
| Burdekin | **0.9** | 0.07 | **0.5** | 0.04 | **0.3** | 0.04 | **0.4** | 0.04 |
| Wet Tropics | **0.9** | 0.04 | **0.5** | 0.03 | **0.3** | 0.03 | **0.4** | 0.03 |
| Cape York | **0.5** | 0.05 | **0.4** | 0.04 | **0.5** | 0.08 | **0.4** | 0.06 |
| **(c) SS (mg $L^{-1}$)** | | | | | | | | |
| GBR Mean | **3.4** | 0.4 | **1.7** | 0.2 | **0.7** | 0.1 | **2.1** | 0.1 |
| Burnett Mary | **2.4** | 0.6 | **1.5** | 0.4 | **0.6** | 0.2 | **0.8** | 0.2 |
| Fitzroy | **2.7** | 0.4 | **1.6** | 0.2 | **0.7** | 0.1 | **1.1** | 0.2 |
| Mackay W | **3.1** | 0.3 | **1.8** | 0.2 | **0.8** | 0.1 | **1.4** | 0.2 |
| Burdekin | **5.5** | 0.4 | **2.5** | 0.2 | **0.9** | 0.1 | **1.9** | 0.2 |
| Wet Tropics | **5.0** | 0.3 | **1.6** | 0.1 | **0.7** | 0.1 | **1.3** | 0.1 |
| Cape York | **2.2** | 0.3 | **1.4** | 0.2 | **0.6** | 0.2 | **1.0** | 0.2 |
| **(d) PN (µmol $L^{-1}$)** | | | | | | | | |
| GBR Mean | **1.9** | 0.1 | **1.6** | 0.1 | **1.2** | 0.1 | **1.5** | 0.0 |
| Burnett Mary | **2.0** | 0.3 | **1.6** | 0.3 | **0.8** | 0.2 | **1.0** | 0.2 |
| Fitzroy | **2.0** | 0.2 | **1.8** | 0.2 | **1.1** | 0.1 | **1.4** | 0.1 |
| Mackay W | **1.7** | 0.1 | **1.6** | 0.1 | **1.2** | 0.1 | **1.4** | 0.1 |
| Burdekin | **2.6** | 0.2 | **1.9** | 0.1 | **1.4** | 0.1 | **1.6** | 0.1 |
| Wet Tropics | **2.3** | 0.1 | **1.5** | 0.1 | **1.0** | 0.1 | **1.2** | 0.1 |
| Cape York | **1.5** | 0.1 | **1.5** | 0.1 | **1.5** | 0.2 | **1.5** | 0.1 |

Table 2 (cont):

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **(e) PP (µmol L$^{-1}$)** | | | | | | | | |
| GBR Mean | **0.12** | 0.01 | **0.08** | 0.01 | **0.06** | 0.01 | **0.10** | 0.00 |
| | | | | | | | | |
| Burnett Mary | **0.12** | 0.02 | **0.10** | 0.02 | **0.06** | 0.01 | **0.06** | 0.02 |
| Fitzroy | **0.09** | 0.01 | **0.08** | 0.01 | **0.06** | 0.01 | **0.06** | 0.01 |
| Mackay W | **0.11** | 0.01 | **0.07** | 0.01 | **0.06** | 0.01 | **0.07** | 0.01 |
| Burdekin | **0.18** | 0.01 | **0.10** | 0.01 | **0.07** | 0.01 | **0.09** | 0.01 |
| Wet Tropics | **0.16** | 0.01 | **0.08** | 0.00 | **0.06** | 0.01 | **0.08** | 0.01 |
| Cape York | **0.09** | 0.01 | **0.08** | 0.01 | **0.07** | 0.01 | **0.07** | 0.01 |
| | | | | | | | | |
| **(f) TDN (µmol L$^{-1}$)** | | | | | | | | |
| GBR Mean | **6.1** | 0.3 | **5.6** | 0.3 | **5.0** | 0.3 | **5.3** | 0.3 |
| | | | | | | | | |
| Burnett Mary | **5.0** | 0.6 | **4.8** | 0.5 | **4.7** | 0.4 | **4.8** | 0.4 |
| Fitzroy | **5.4** | 0.5 | **5.1** | 0.4 | **4.8** | 0.3 | **5.0** | 0.3 |
| Mackay W | **5.8** | 0.3 | **5.7** | 0.3 | **5.1** | 0.3 | **5.4** | 0.3 |
| Burdekin | **6.7** | 0.3 | **5.8** | 0.3 | **4.9** | 0.3 | **5.4** | 0.3 |
| Wet Tropics | **7.6** | 0.2 | **6.5** | 0.2 | **5.4** | 0.3 | **5.8** | 0.3 |
| Cape York | **6.1** | 0.3 | **5.5** | 0.3 | **5.1** | 0.4 | **5.3** | 0.3 |
| | | | | | | | | |
| **(g) TDP (µmol L$^{-1}$)** | | | | | | | | |
| GBR Mean | **0.35** | 0.04 | **0.28** | 0.03 | **0.19** | 0.03 | **0.23** | 0.03 |
| | | | | | | | | |
| Burnett Mary | **0.28** | 0.06 | **0.25** | 0.05 | **0.25** | 0.04 | **0.25** | 0.05 |
| Fitzroy | **0.38** | 0.06 | **0.31** | 0.04 | **0.22** | 0.03 | **0.26** | 0.03 |
| Mackay W | **0.36** | 0.04 | **0.33** | 0.04 | **0.20** | 0.03 | **0.26** | 0.03 |
| Burdekin | **0.39** | 0.04 | **0.33** | 0.03 | **0.18** | 0.03 | **0.24** | 0.03 |
| Wet Tropics | **0.35** | 0.02 | **0.27** | 0.02 | **0.20** | 0.02 | **0.23** | 0.02 |
| Cape York | **0.28** | 0.03 | **0.19** | 0.02 | **0.12** | 0.03 | **0.16** | 0.03 |
| | | | | | | | | |
| **(h) TN (µmol L$^{-1}$)** | | | | | | | | |
| GBR Mean | **7.8** | 0.5 | **7.3** | 0.4 | **7.0** | 0.6 | **7.2** | 0.5 |
| | | | | | | | | |
| Burnett Mary | **6.0** | 0.8 | **5.9** | 0.8 | **5.6** | 0.9 | **5.6** | 0.9 |
| Fitzroy | **6.9** | 0.6 | **7.1** | 0.5 | **6.8** | 0.6 | **6.9** | 0.6 |
| Mackay W | **7.3** | 0.4 | **7.4** | 0.4 | **7.4** | 0.5 | **7.4** | 0.5 |
| Burdekin | **8.7** | 0.5 | **7.4** | 0.4 | **7.2** | 0.6 | **7.5** | 0.5 |
| Wet Tropics | **10.0** | 0.3 | **8.2** | 0.3 | **6.8** | 0.4 | **7.4** | 0.4 |
| Cape York | **7.8** | 0.4 | **7.1** | 0.4 | **7.0** | 0.7 | **7.1** | 0.6 |
| | | | | | | | | |
| **(i) TP (µmol L$^{-1}$)** | | | | | | | | |
| GBR Mean | **0.49** | 0.06 | **0.38** | 0.04 | **0.30** | 0.05 | **0.34** | 0.05 |
| | | | | | | | | |
| Burnett Mary | **0.47** | 0.11 | **0.42** | 0.11 | **0.27** | 0.09 | **0.30** | 0.09 |
| Fitzroy | **0.46** | 0.07 | **0.42** | 0.06 | **0.29** | 0.05 | **0.34** | 0.06 |
| Mackay W | **0.48** | 0.06 | **0.42** | 0.05 | **0.37** | 0.06 | **0.40** | 0.06 |
| Burdekin | **0.59** | 0.06 | **0.46** | 0.04 | **0.33** | 0.06 | **0.39** | 0.05 |
| Wet Tropics | **0.52** | 0.03 | **0.37** | 0.03 | **0.26** | 0.04 | **0.31** | 0.03 |
| Cape York | **0.43** | 0.05 | **0.25** | 0.03 | **0.24** | 0.05 | **0.27** | 0.05 |

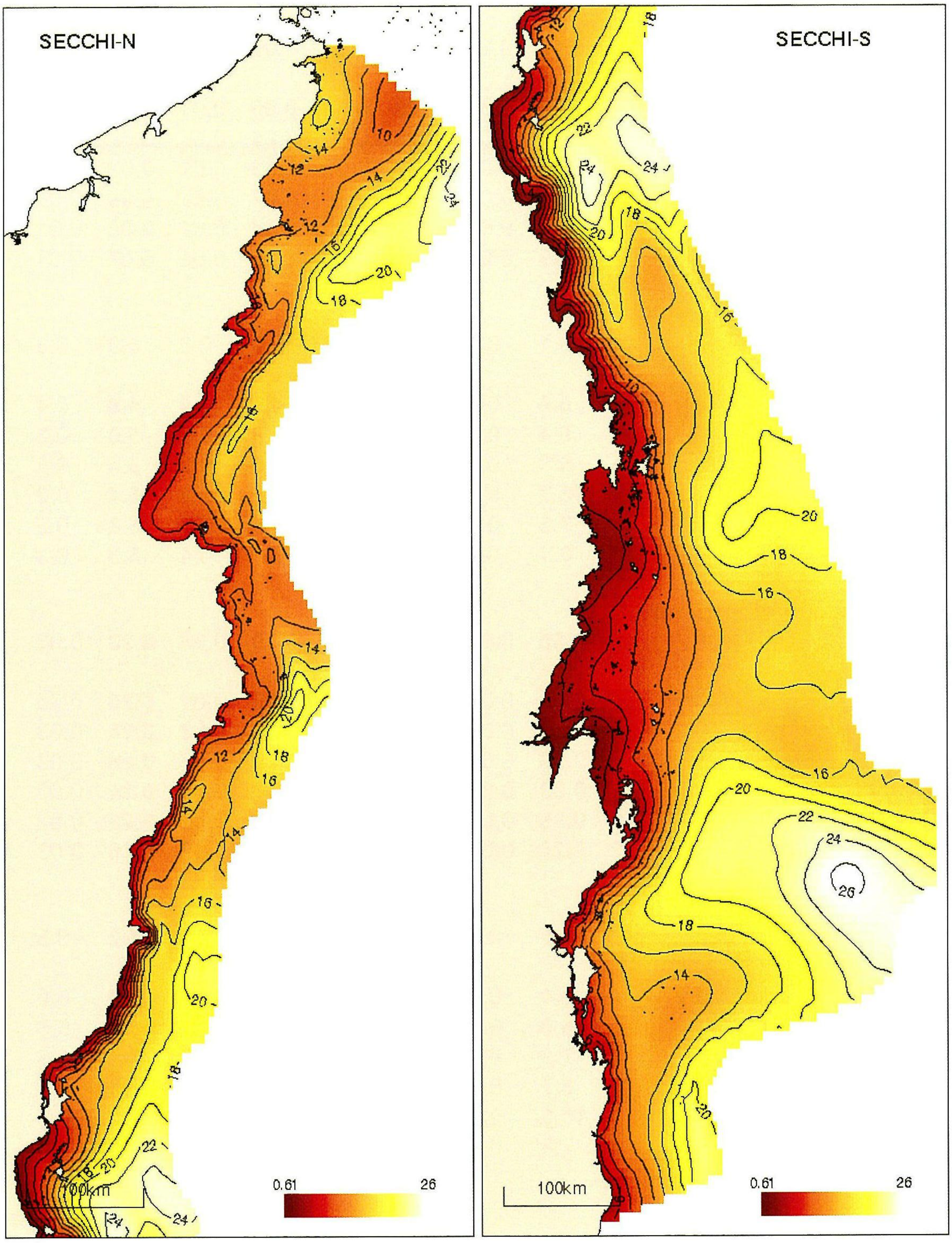


Figure 9: Estimated spatial distribution of Secchi depth (m). Mean annual and seasonal values are presented in Tables 2a and Appendices 2 and 3.

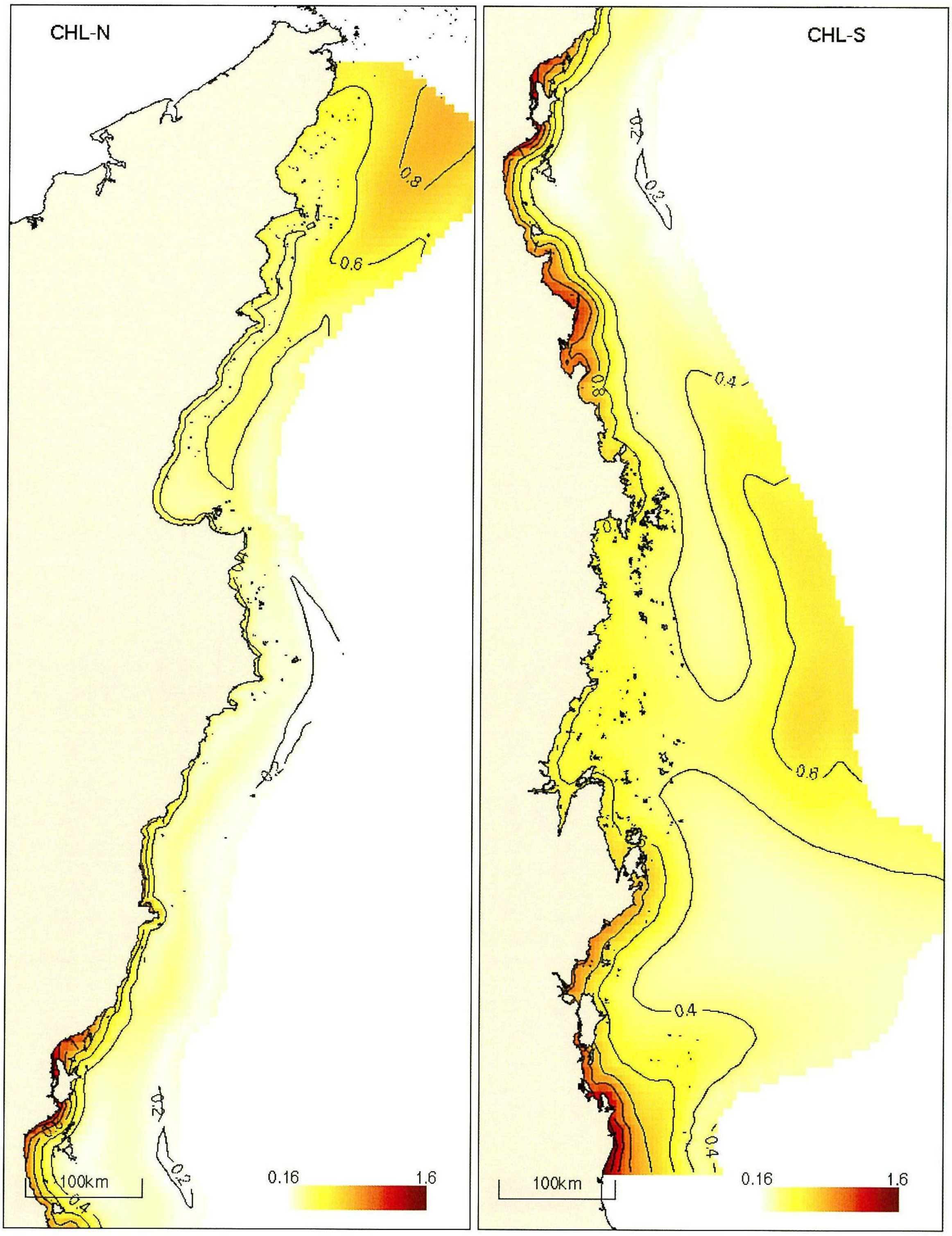


Figure 10: Estimated spatial distribution of chlorophyll (µg $L^{-1}$). Mean annual and seasonal values are presented in Tables 2b and Appendices 2 and 3.

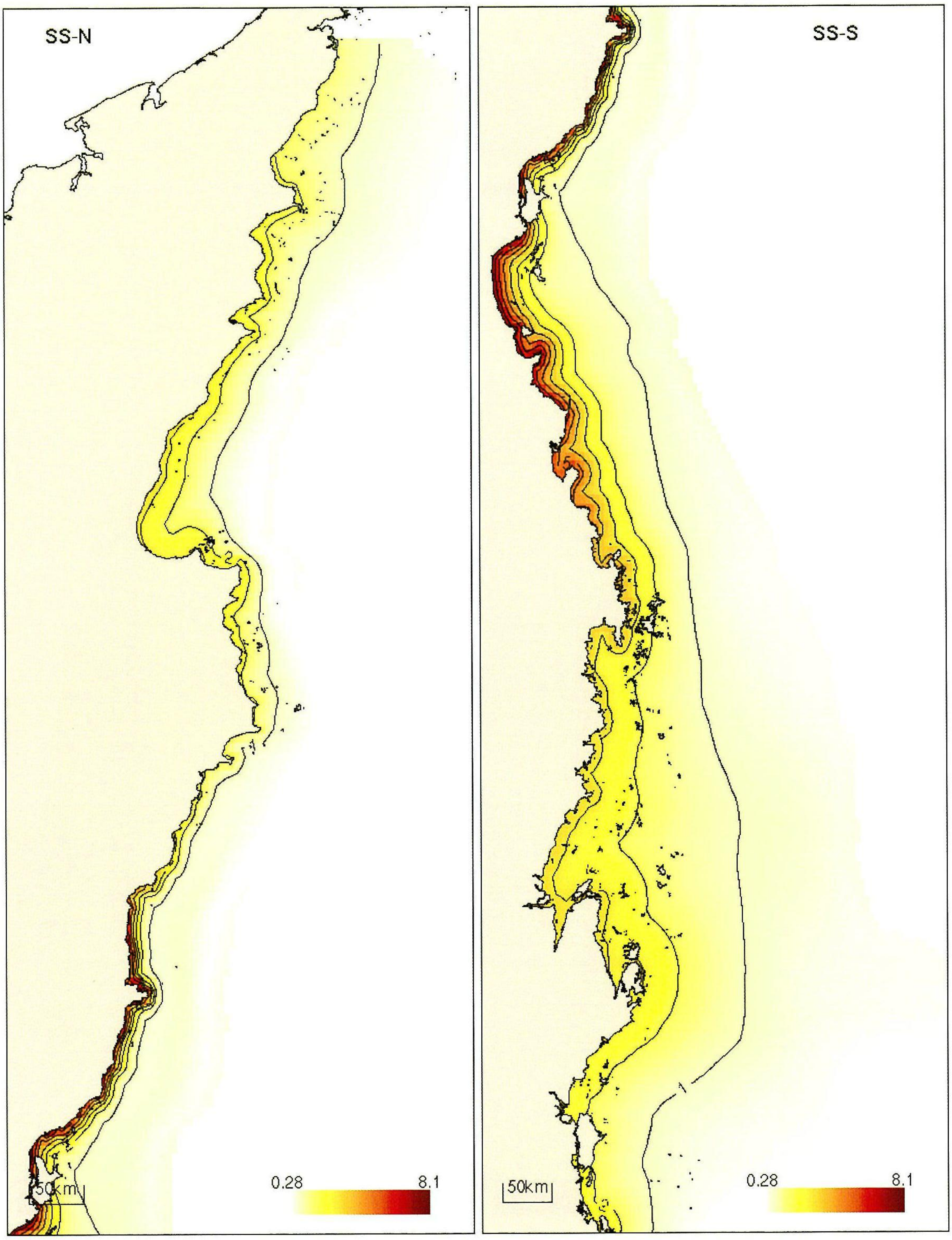


Figure 11: Estimated spatial distribution of suspended solids (mg $L^{-1}$). Mean annual and seasonal values are presented in Tables 2c and Appendices 2 and 3.

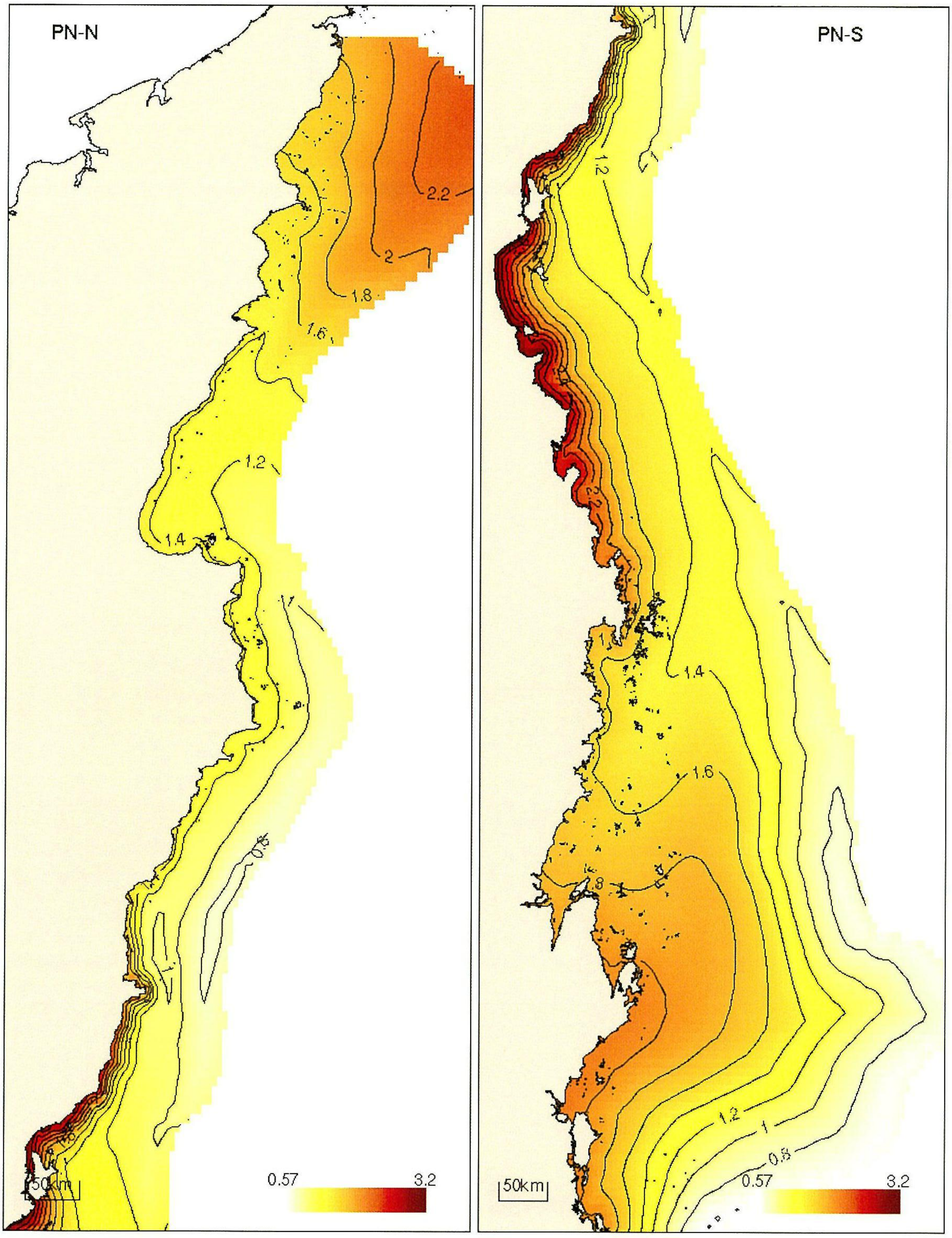


Figure 12: Estimated spatial distribution of particulate nitrogen (µmol $L^{-1}$). Mean annual and seasonal values are presented in Tables 2d and Appendices 2 and 3.

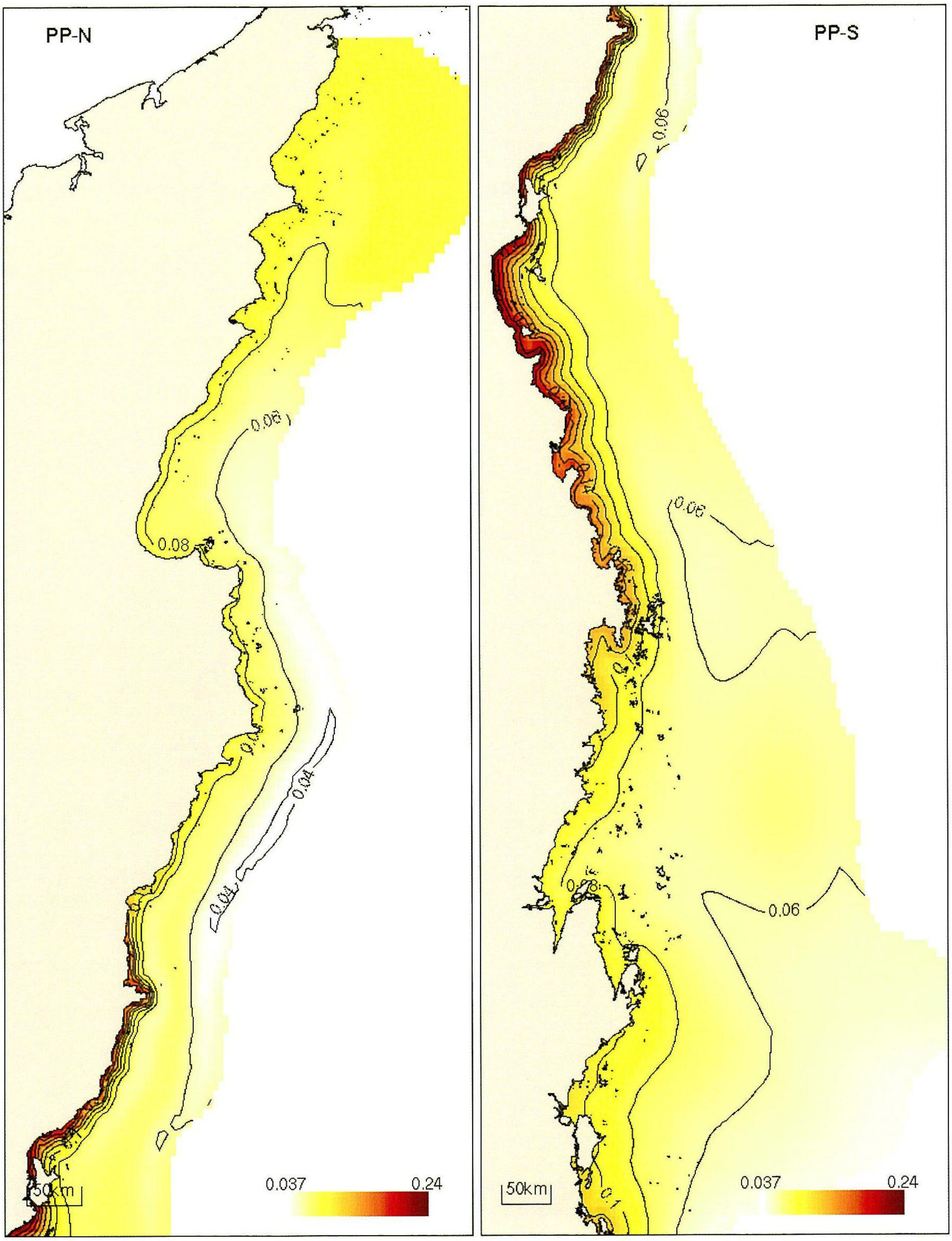


Figure 13: Estimated spatial distribution of particulate phosphorus (µmol $L^{-1}$). Mean annual and seasonal values are presented in Tables 2e and Appendices 2 and 3.

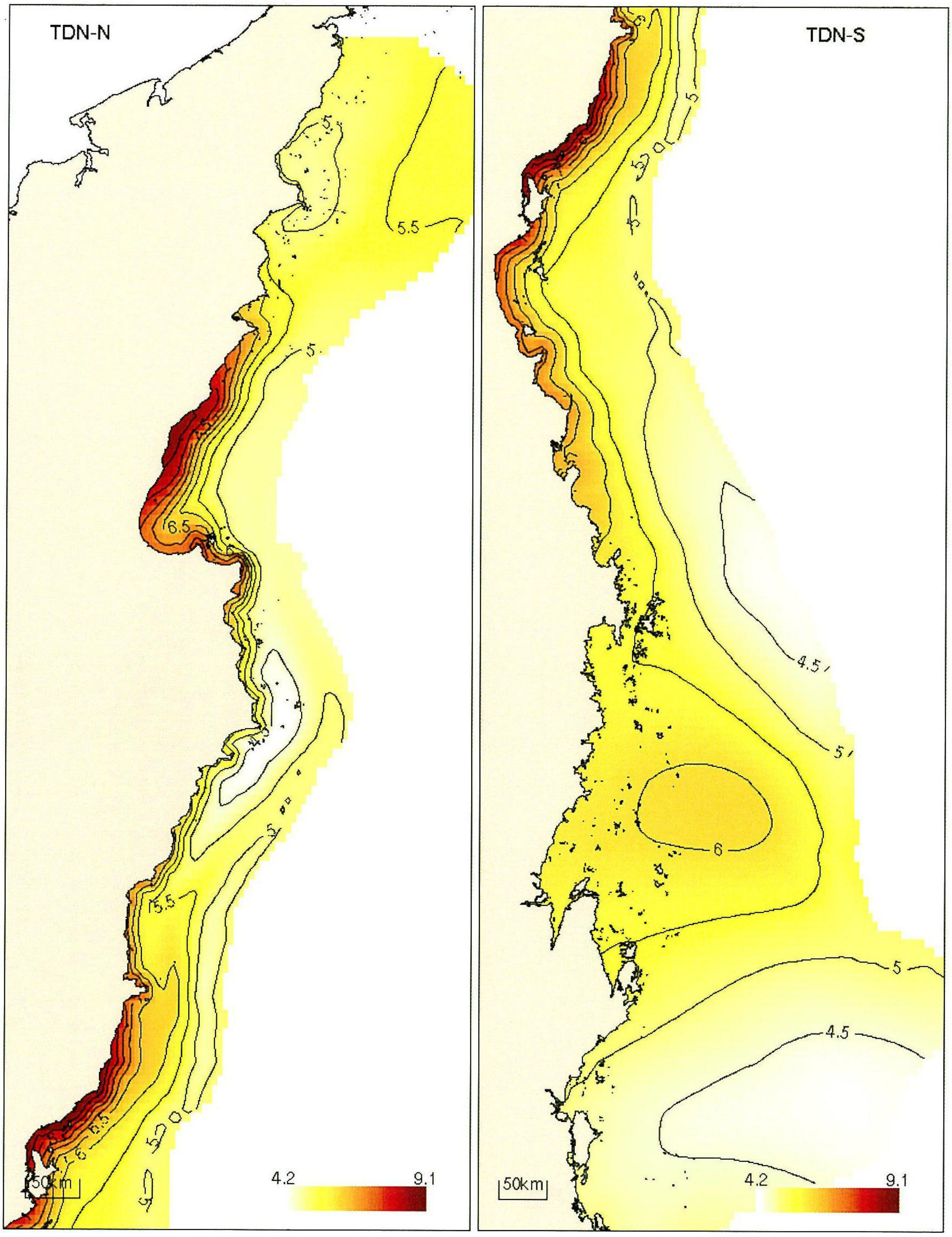


Figure 14: Estimated spatial distribution of total dissolved nitrogen (µmol $L^{-1}$). Mean annual and seasonal values are presented in Tables 2f and Appendices 2 and 3.

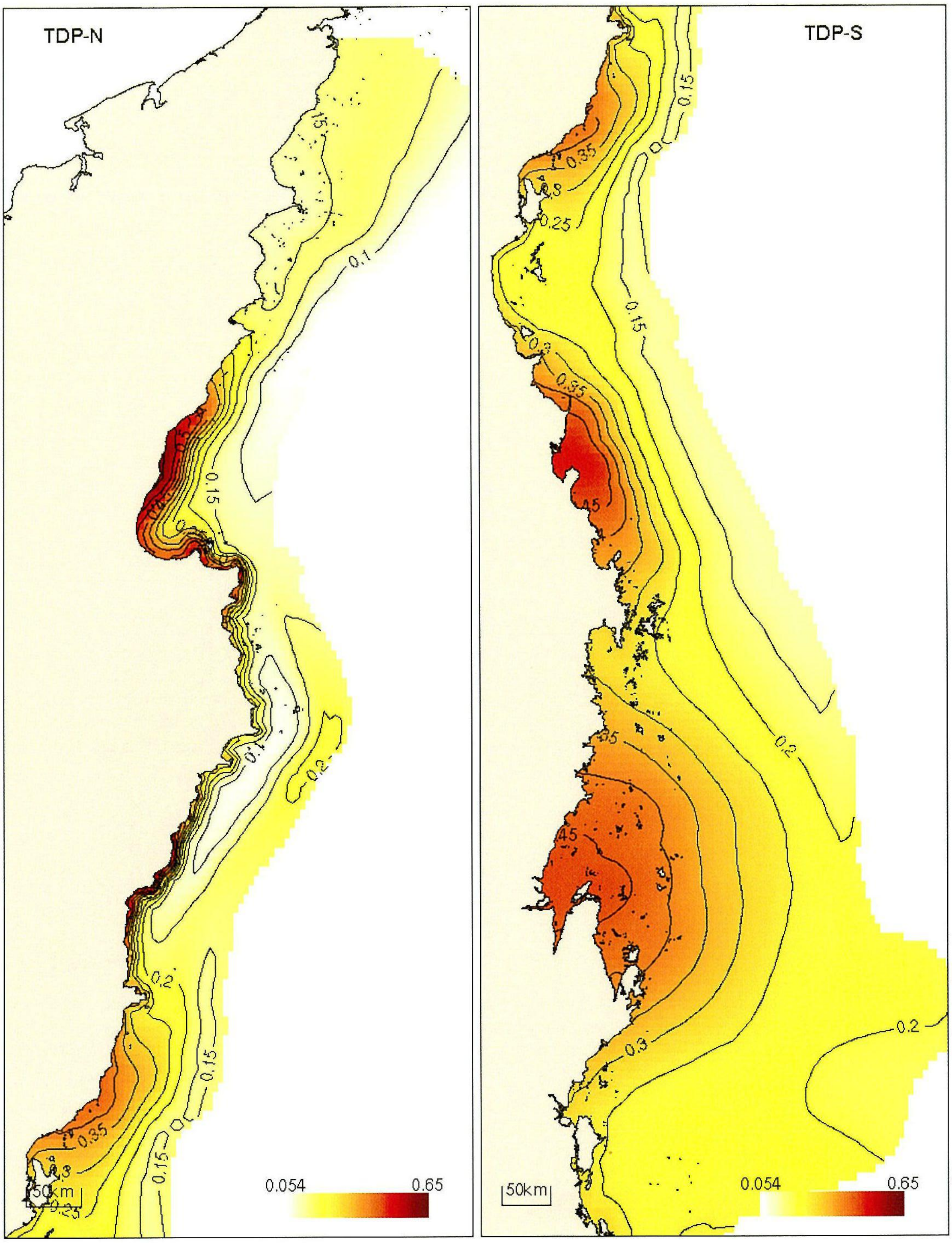


Figure 15: Estimated spatial distribution of total dissolved phosphorus (µmol $L^{-1}$). Mean annual and seasonal values are presented in Tables 2g and Appendices 2 and 3.

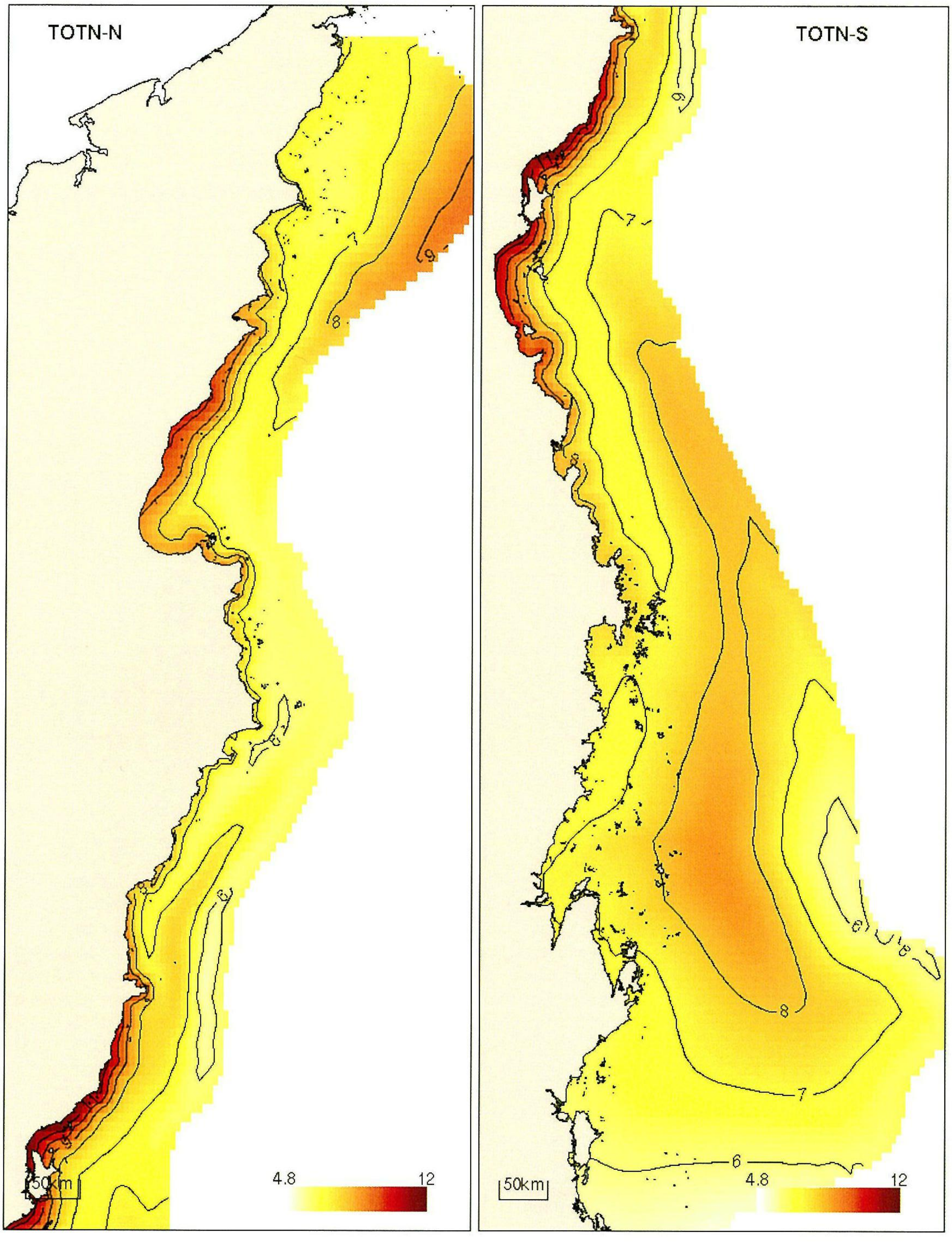


Figure 16: Estimated spatial distribution of total nitrogen (µmol $L^{-1}$). Mean annual and seasonal values are presented in Tables 2h and Appendices 2 and 3.

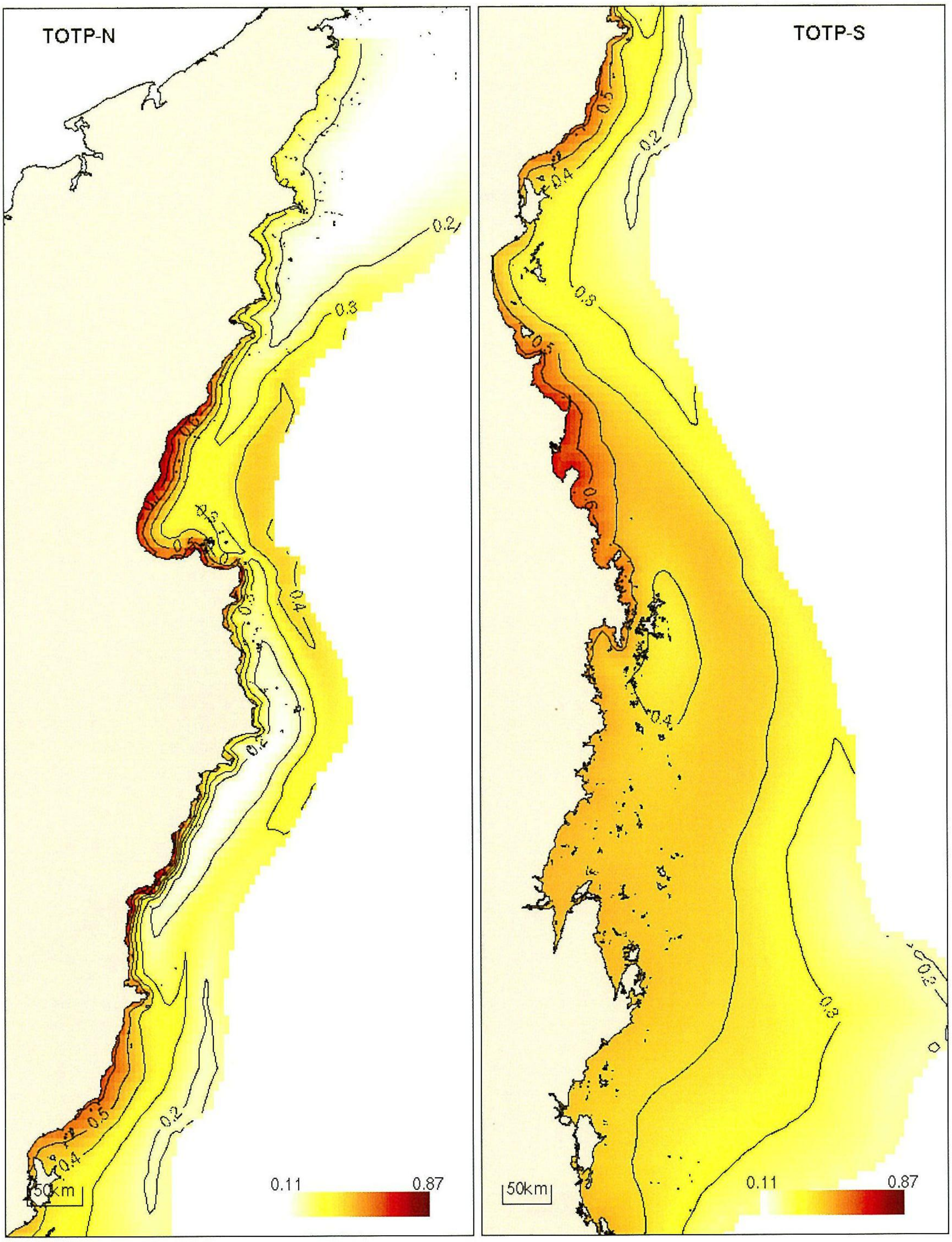


Figure 17: Estimated spatial distribution of total phosphorus (µmol $L^{-1}$). Mean annual and seasonal values are presented in Tables 2i and Appendices 2 and 3.

## 3.2. *Seasonal patterns in water quality in the GBR*

Changes in nutrients and chlorophyll were well predicted by season, regions and cross-shelf locations (Fig. 18, Table 3 and Appendix 3). Most values were consistently higher in the summer quarter compared to the winter quarter, whereas TDN and TN were often higher in winter than in summer. Seasonal differences were greatest in chlorophyll (summer to winter ratio: 2.2 across all regions), less in PP and PN (summer to winter ratio: 1.6 and 1.7, respectively) and weak in SS (summer to winter ratio: 1.2). Seasonal differences in chlorophyll and PP were consistent across the shelf and differed also weakly between the NRM regions. The most extreme seasonal differences were found in the coastal Fitzroy and Burdekin, where chlorophyll and PN were >4 and 2.6 times higher in summer than in winter, respectively, while SS and PP varied little between seasons in this region.

Table 3: ANOVA results assessing the effects of season, region and cross-shelf position on water quality variables across the NRM regions (excluding Burnett Mary, and excluding Secchi depth, for which insufficient data were available).

| | | Chlorophyll | | SS | | PN | | PP | |
|---|---|---|---|---|---|---|---|---|---|
| | DF | F | P | F | P | F | P | F | P |
| Season | 1 | 427.18 | <0.0001 | 11.79 | 0.0006 | 172.03 | <0.0001 | 117.92 | <0.0001 |
| Shelf | 2 | 92.13 | <0.0001 | 154.62 | <0.0001 | 88.36 | <0.0001 | 130.72 | <0.0001 |
| Region | 4 | 35.12 | <0.0001 | 15.63 | <0.0001 | 9.25 | <0.0001 | 17.56 | 0 |
| Season:Shelf | 2 | 1.53 | 0.2161 | 1.06 | 0.3471 | 3.29 | 0.0375 | 0.3 | 0.738 |
| Season:Region | 4 | 2.77 | 0.026 | 5.98 | 0.0001 | 4.75 | 0.0008 | 2.44 | 0.0452 |
| Shelf:Region | 8 | 7.23 | <0.0001 | 4.65 | <0.0001 | 7.02 | <0.0001 | 2.81 | 0.0043 |
| Season:Shelf:Region | 8 | 3.69 | 0.0003 | 0.72 | 0.6757 | 2.87 | 0.0036 | 1.78 | 0.0771 |
| Error | 2287 | | | | | | | | |

| | | TDN | | TDP | | TN | | TP | |
|---|---|---|---|---|---|---|---|---|---|
| | DF | F | P | F | P | F | P | F | P |
| Season | 1 | 41.92 | <0.0001 | 14.05 | 0.0002 | 99.33 | <0.0001 | 0.05 | 0.827 |
| Shelf | 2 | 51.26 | <0.0001 | 21.37 | <0.0001 | 42.38 | <0.0001 | 30.44 | <0.0001 |
| Region | 4 | 22.97 | <0.0001 | 1.07 | 0.3717 | 17.99 | <0.0001 | 3.02 | 0.017 |
| Season:Shelf | 2 | 18.04 | <0.0001 | 0.66 | 0.5167 | 12.53 | <0.0001 | 0.59 | 0.554 |
| Season:Region | 4 | 3.8 | 0.0044 | 4.36 | 0.0016 | 4.08 | 0.0027 | 2.97 | 0.019 |
| Shelf:Region | 8 | 1.73 | 0.0878 | 0.82 | 0.5814 | 1.03 | 0.4127 | 0.67 | 0.722 |
| Season:Shelf:Region | 8 | 2.64 | 0.0069 | 2.1 | 0.033 | 1.05 | 0.3952 | 1.3 | 0.237 |
| Error | 2287 | | | | | | | | |

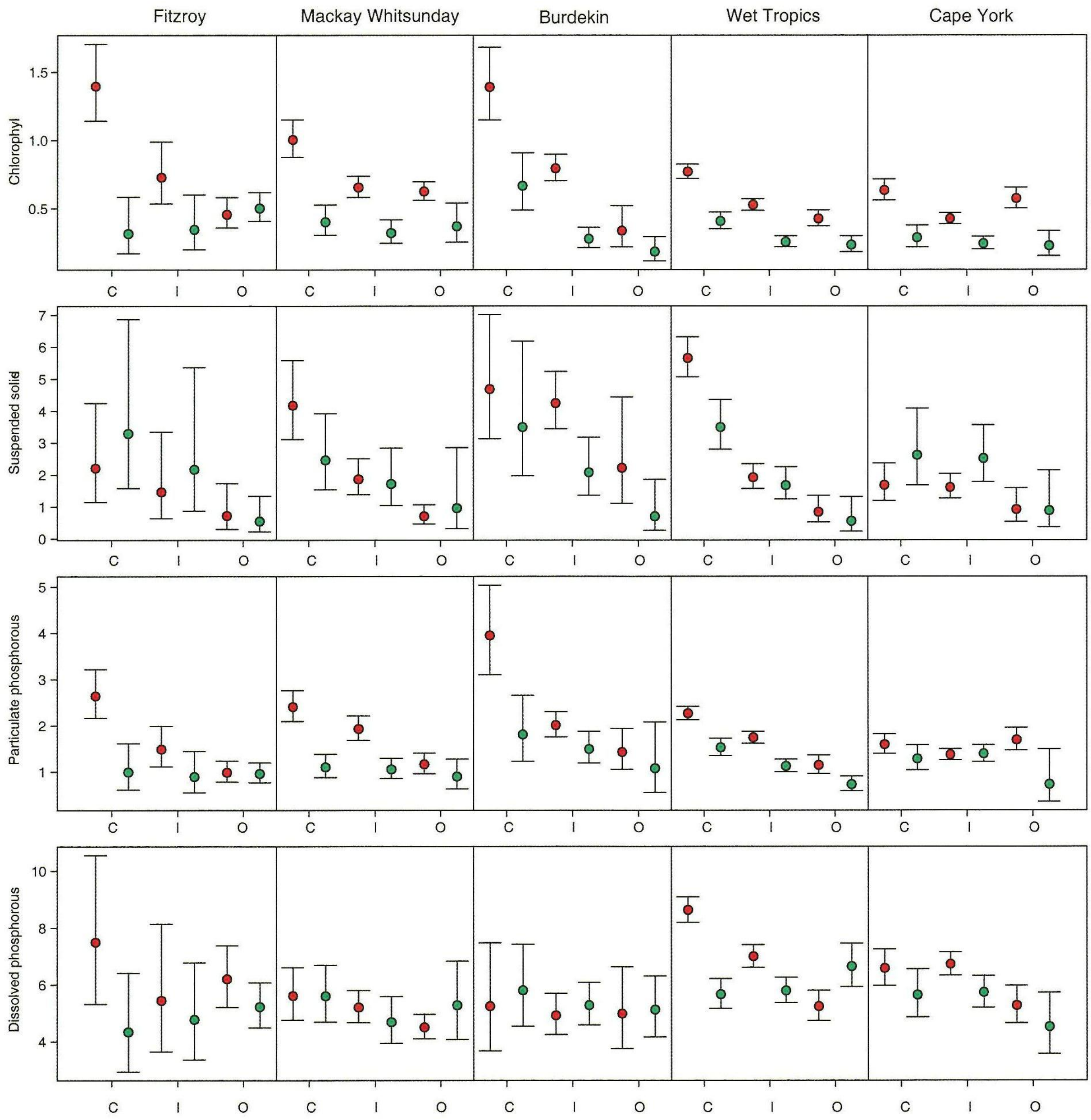


Figure 18 (continued next page) : Mean summer and winter concentrations of chlorophyll, SS, and nutrients in the GBR. Red: summer quarter (January – March), green: winter quarter (July – September). Data are also split into three groups <0.1, 0.1 – 0.4, and >0.4 across the shelf (labeled as C, I, O), and by regions. Secchi data and data for the Burnett Mary Region are insufficient to allow seasonal comparison. Error bars represent 95% confidence intervals. Data units are in µg $L^{-1}$ for chl, mg $L^{-1}$ for SS, and µmol $L^{-1}$ for all nutrients. Values and confidence intervals are also listed in Appendix 3.

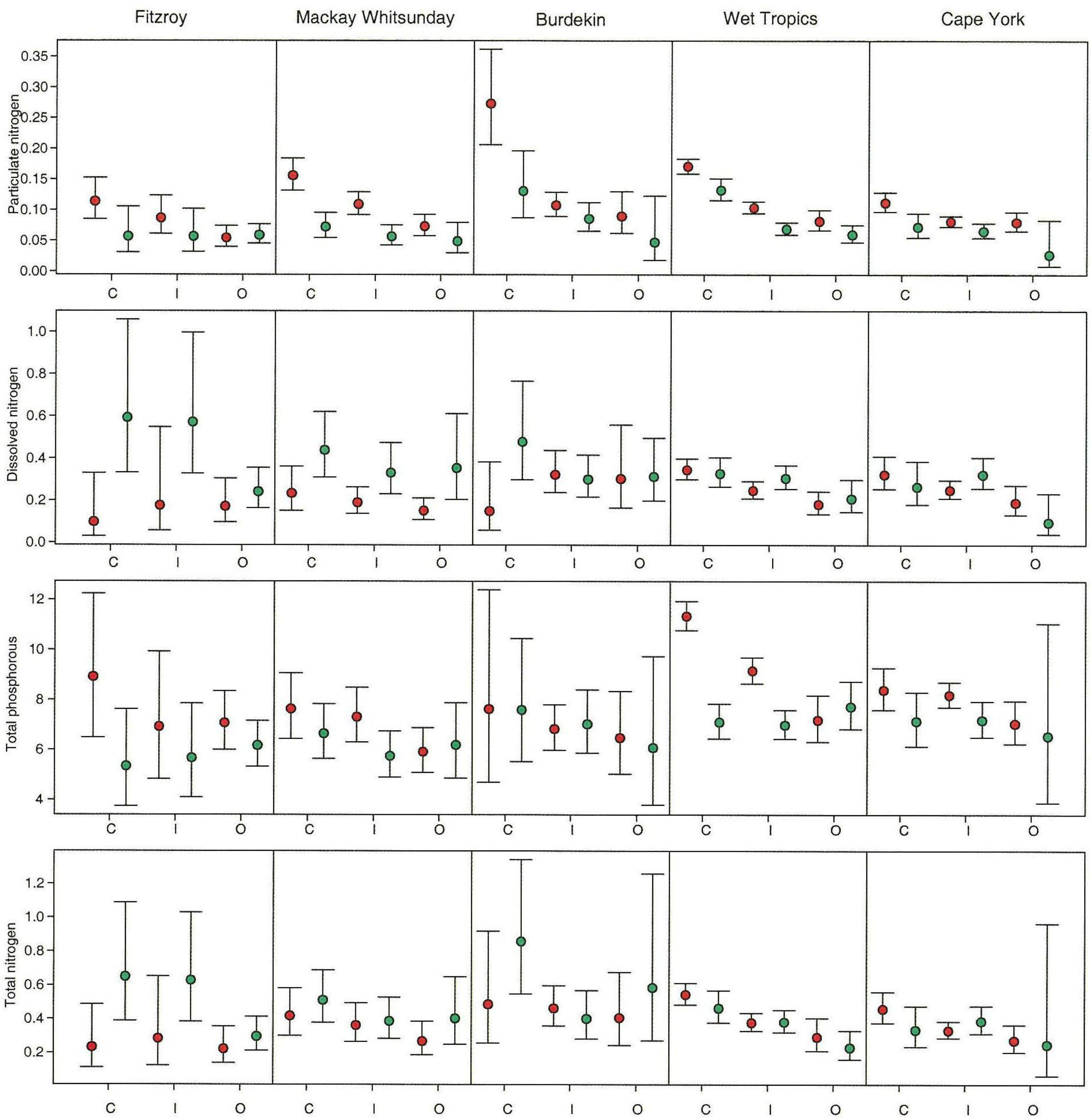


Figure 18, continued.

# 4. Spatial distribution of reef biota

The spatial distributions of reef biota across the NRM regions and the three cross-shelf zones are displayed in Figures 19 – 22 and are summarised in Table 4.

## a) Macroalgal cover

Macroalgal cover increased >10-fold from offshore to the coastal zones, and ~3-fold with latitude from north to the south within each of the cross-shelf zones (Fig. 19). Highest values were found on the southern coastal reefs between the Burnett and the Burdekin, and lowest on northern offshore reefs. On inner shelf reefs (0.1 – 0.4 across), macroalgal cover was high in the southern half of the GBR and low in the north. The high reef-averaged values in the Broadsound region were partly due to the unusually deep depth distribution of macroalgae in this region. Typically, macroalgal cover declined strongly with depth, and, except in the Broadsound region, no macroalgae were found in the survey transects at 8 – 13 m and 13 – 18 m depth. Reef-averaged, a 20% macroalgal cover typically represented 60% cover on the reef flat, 30% on the reef crest, 10% at 3 – 8 m depth, and 0% cover in the two survey transects below this. In the Broadsound, macroalgal cover was less depth-dependent, probably due to the high tidal range, and reef-averaged values were therefore higher.

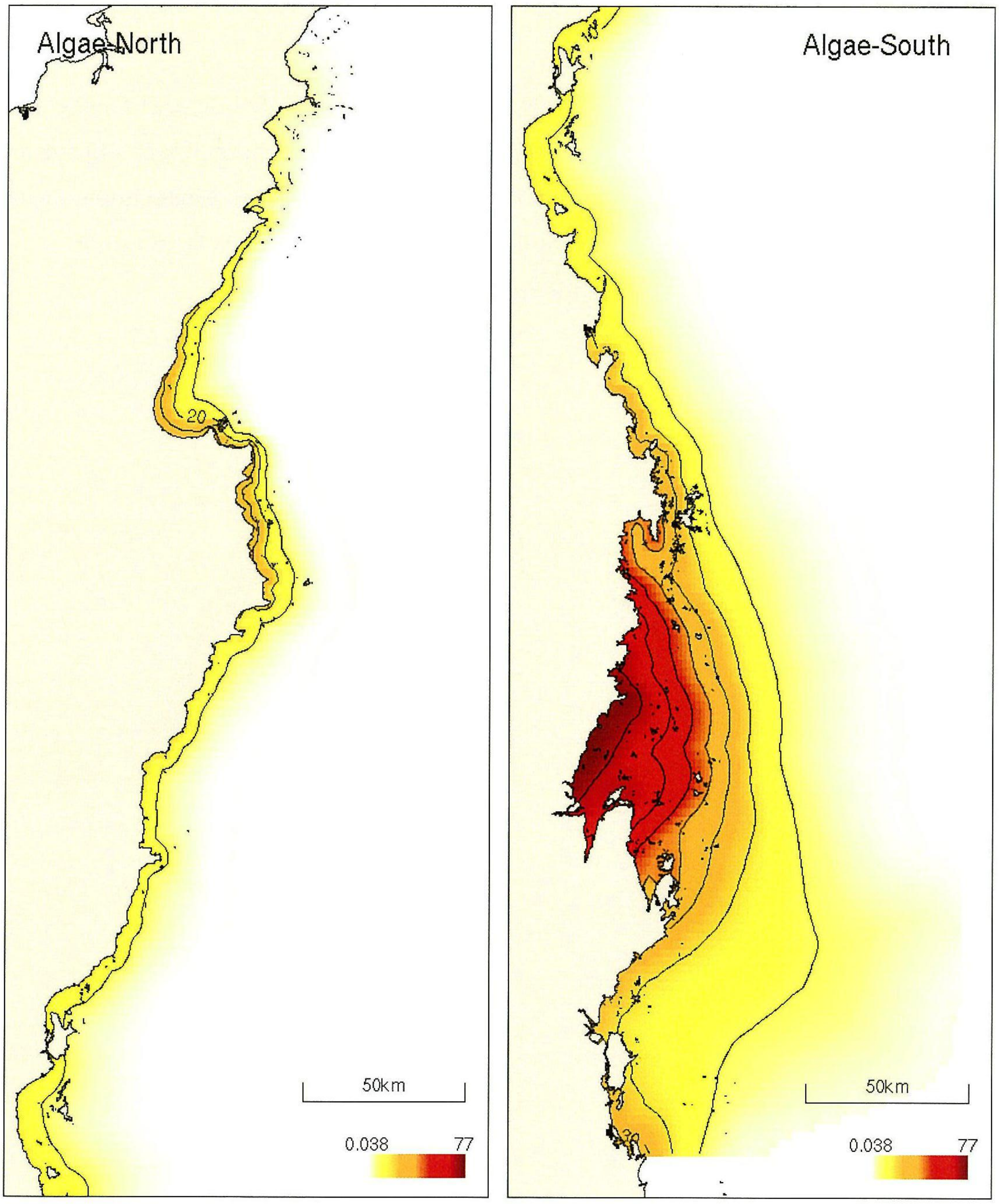


Figure 19: Macroalgal cover (reef-averaged) in the GBR. Values were predicted for each of the 2870 reefs of the GBR. Shading of orange or darker represents >20% macroalgal cover, yellow to white represent reef-averaged over <20%. Note that values are reef-averaged, and the high values in the Broad Sound area are partly due to its high macroalgal cover below 8 m depth. Elsewhere deeper depths have low cover, resulting in lower reef-averaged values even though reef flats and crests often have >70% cover in the Whitsundays, Burdekin and Wet Tropics.

## b) Hard coral species richness

Hard coral species richness declined with latitude by about 50%; however richness was lower in the Wet Tropics and in the Broadsound region compared with adjacent regions (Fig. 20). It was highest in Cape York, and also high in the Whitsundays. Not enough information exists on hard coral richness on offshore reefs of the northern and southern GBR to assess latitudinal and cross-shelf changes.

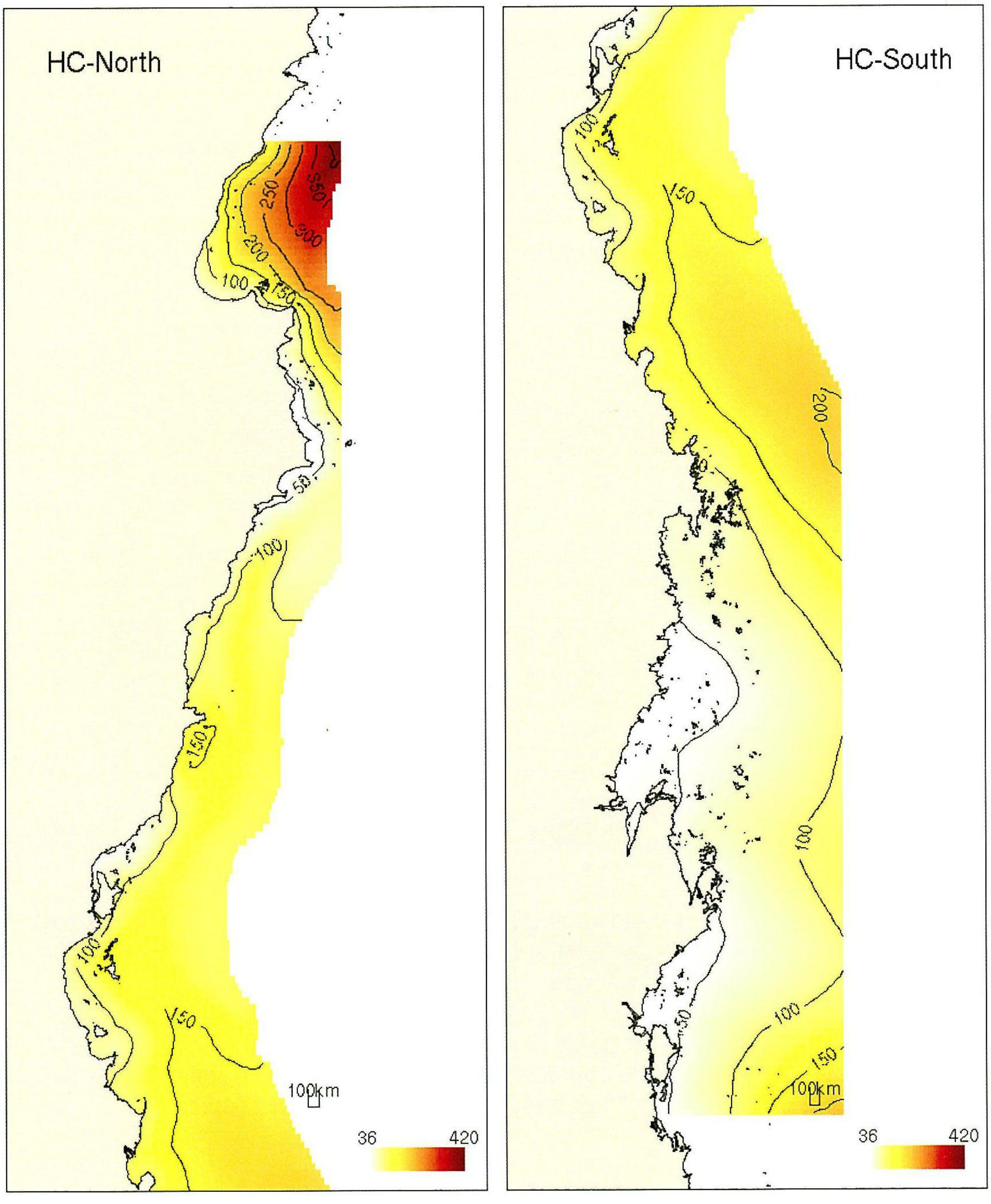


Figure 20: Predicted species richness of hard corals in the GBR.

## c) Richness of phototrophic and heterotrophic octocorals

The richness of phototrophic octocorals declined with latitude on inner shelf reefs but not on coastal or offshore reefs (Fig. 21). It increased by ~50% across the shelf from low values in the coastal zone to higher ones offshore. Conversely, the richness of heterotrophic octocorals decreased almost fourfold with latitude, and also declined from coastal to offshore (Fig. 22).

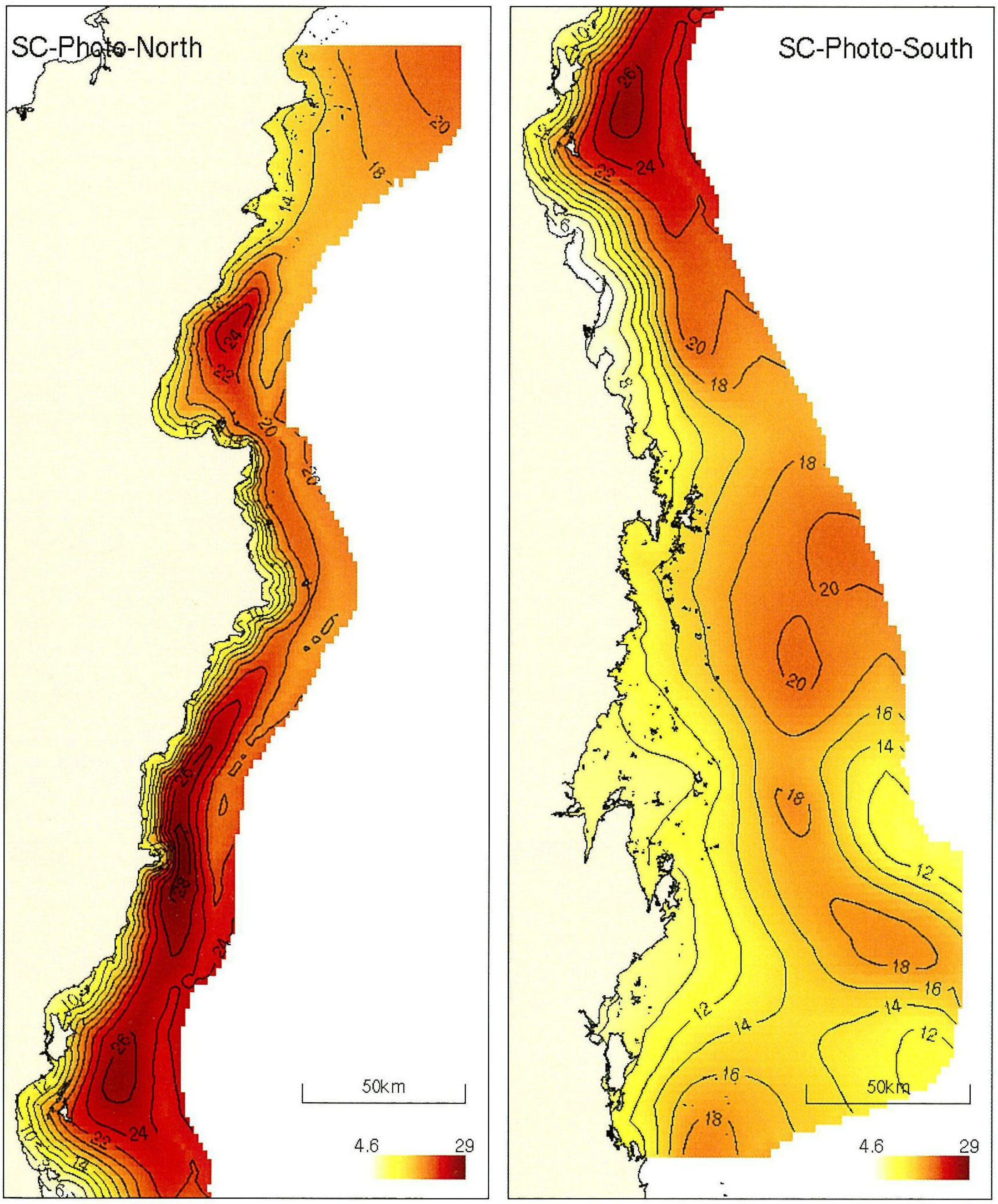


Figure 21: Predicted taxonomic richness of phototrophic octocorals in the GBR.

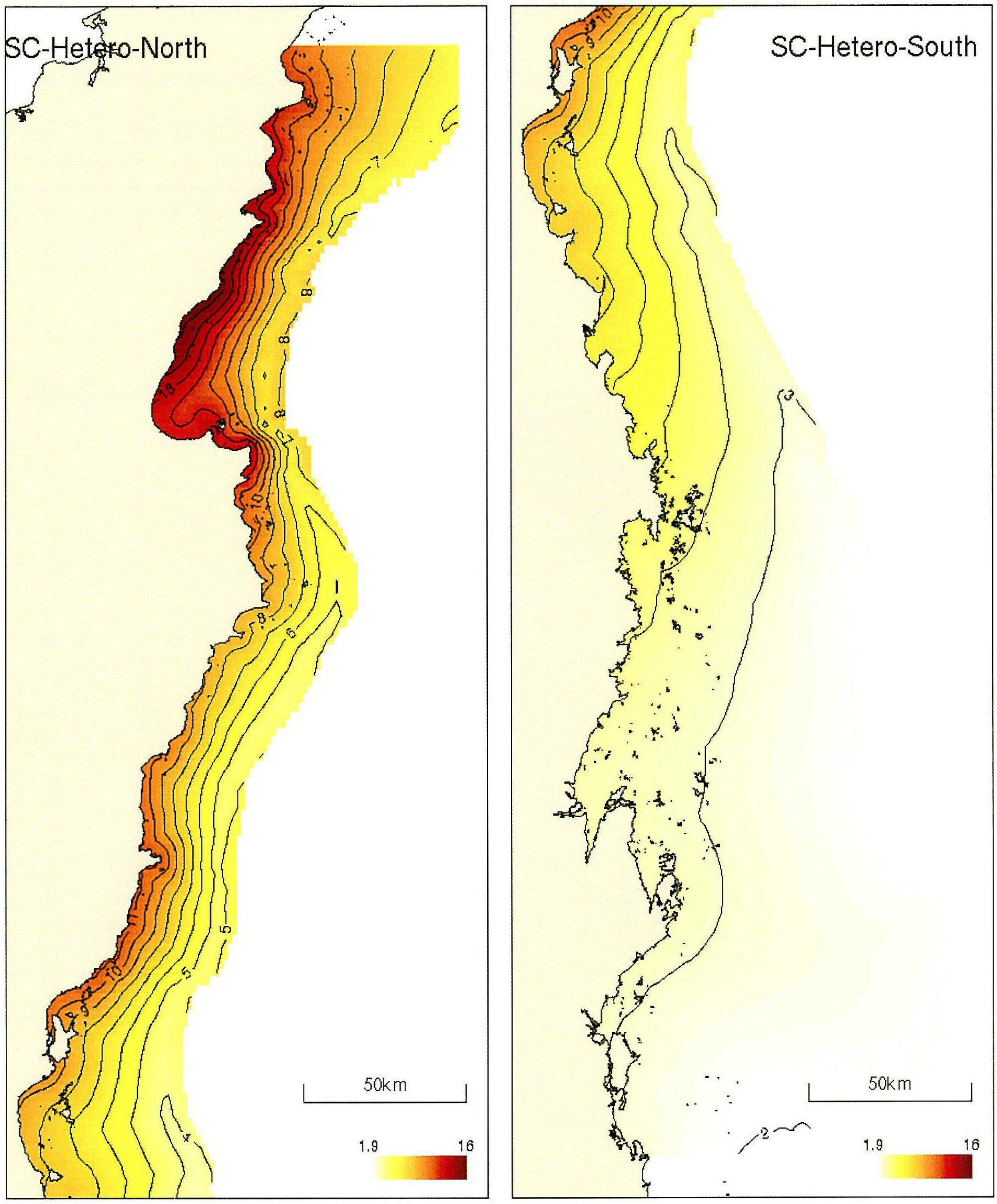


Figure 22: Predicted taxonomic richness of heterotrophic octocorals in the GBR. Reef-averaged data.

Table 4: Mean values of macroalgal cover, and the richness of hard corals, phototrophic and heterotrophic octocorals, predicted for all 2870 reefs of the GBR. N = number of predicted reefs in the region or zone. There are no inner shelf reefs in Burnett Mary (marked with na).

| | Coastal | | | Inner shelf | | | Offshore | | | Across all zones | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **mean** | SE | N | **mean** | SE | N | **mean** | SE | N | **mean** | SE | Overall N |
| **(a) Macroalgal cover** | | | | | | | | | | | | |
| GBR Mean | **26.8** | 7.8 | 575 | **17.1** | 4.9 | 682 | **2.5** | 1.7 | 1613 | | | |
| Burnett Mary | **20.3** | 9.7 | 12 | **na** | na | 0 | **4.4** | 3.6 | 13 | **12.0** | 6.5 | 25 |
| Fitzroy | **33.3** | 8.8 | 116 | **31.3** | 7.9 | 98 | **3.5** | 2.0 | 544 | **11.7** | 3.8 | 758 |
| Mackay W | **41.0** | 7.4 | 162 | **26.6** | 6.1 | 217 | **3.0** | 1.8 | 340 | **18.7** | 4.4 | 719 |
| Burdekin | **23.3** | 7.1 | 19 | **7.4** | 3.1 | 36 | **2.4** | 1.8 | 129 | **5.5** | 2.6 | 184 |
| Wet Tropics | **17.6** | 4.9 | 34 | **7.3** | 3.0 | 35 | **2.5** | 2.0 | 133 | **5.9** | 2.6 | 202 |
| Cape York | **14.0** | 7.9 | 200 | **7.8** | 3.4 | 294 | **1.0** | 1.1 | 451 | **5.9** | 3.3 | 945 |
| **(b) Hard coral richness** | | | | | | | | | | | | |
| GBR Mean | **104.9** | 29.9 | 575 | **126.2** | 28.8 | 682 | **121.5** | 42.3 | 1613 | | | |
| Burnett Mary | **41.0** | 17.2 | 12 | **na** | na | 0 | **111** | 54.6 | 13 | **77.6** | 36.6 | 25 |
| Fitzroy | **50.5** | 13.8 | 116 | **57.8** | 12.6 | 98 | **120** | 46.7 | 544 | **101** | 37.3 | 758 |
| Mackay W | **82.5** | 14.3 | 162 | **72.3** | 11.3 | 217 | **126** | 39.3 | 340 | **100** | 25.2 | 719 |
| Burdekin | **99.1** | 17.5 | 19 | **121** | 20.8 | 36 | **128** | 33.7 | 129 | **124** | 29.5 | 184 |
| Wet Tropics | **83.5** | 12.7 | 34 | **112** | 17.2 | 35 | **122** | 24.0 | 133 | **114** | 20.9 | 202 |
| Cape York | **165** | 57.4 | 200 | **190** | 48.8 | 294 | **118** | 46.7 | 451 | **150** | 49.6 | 945 |

| | Coastal | | | Inner shelf | | | Offshore | | | Across all zones | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **mean** | SE | N | **mean** | SE | N | **mean** | SE | N | **mean** | SE | Overall N |
| **(c) Richness phototrophic octocorals** | | | | | | | | | | | | |
| GBR Mean | **10.4** | 1.2 | 575 | **15.0** | 1.3 | 682 | **18.1** | 1.8 | 1613 | | | |
| Burnett Mary | **8.0** | 1.3 | 12 | **na** | na | 0 | **14.5** | 2.0 | 13 | **11.4** | 1.7 | 25 |
| Fitzroy | **9.1** | 1.1 | 116 | **11.0** | 1.1 | 98 | **14.8** | 1.3 | 544 | **13.4** | 1.2 | 758 |
| Mackay W | **10.0** | 0.9 | 162 | **12.4** | 0.9 | 217 | **17.4** | 1.5 | 340 | **14.2** | 1.2 | 719 |
| Burdekin | **10.2** | 0.9 | 19 | **17.4** | 1.5 | 36 | **20.0** | 1.9 | 129 | **18.5** | 1.7 | 184 |
| Wet Tropics | **10.6** | 0.9 | 34 | **18.1** | 1.4 | 35 | **22.8** | 2.1 | 133 | **19.9** | 1.8 | 202 |
| Cape York | **11.5** | 1.6 | 200 | **17.6** | 1.6 | 294 | **20.7** | 2.7 | 451 | **17.8** | 2.1 | 945 |
| **(d) Richness heterotrophic octocorals** | | | | | | | | | | | | |
| GBR Mean | **6.2** | 1.5 | 575 | **7.3** | 1.3 | 682 | **4.7** | 1.3 | 1613 | | | |
| Burnett Mary | **2.7** | 1.1 | 12 | **na** | na | 0 | **2.3** | 0.9 | 13 | **2.5** | 1.0 | 25 |
| Fitzroy | **3.1** | 0.9 | 116 | **2.8** | 0.7 | 98 | **2.4** | 0.6 | 544 | **2.6** | 0.7 | 758 |
| Mackay W | **4.2** | 0.8 | 162 | **3.8** | 0.7 | 217 | **2.6** | 0.7 | 340 | **3.3** | 0.7 | 719 |
| Burdekin | **6.7** | 1.3 | 19 | **8.0** | 1.5 | 36 | **3.2** | 0.9 | 129 | **4.5** | 1.0 | 184 |
| Wet Tropics | **9.7** | 1.4 | 34 | **9.2** | 1.5 | 35 | **5.9** | 1.4 | 133 | **7.1** | 1.4 | 202 |
| Cape York | **9.1** | 2.4 | 200 | **11.1** | 1.9 | 294 | **9.0** | 2.7 | 451 | **9.7** | 2.4 | 945 |

# 5. Relationships of reef biota to water quality

## *5.1. Relationships between the predicted water quality variables*

The water quality values were predicted for the soft coral and hard coral sampling locations from the Secchi and water quality data sets. The correlations between the predicted water quality variables for both biotic data sets were very high, especially between Secchi, PN, PP and SS (Figs. 23 and 24). These high correlations precluded the joint use of all of the water quality predictors in assessing the dependencies of the four biotic responses on water quality, and hence for other than Secchi and chlorophyll, each dependence was assessed separately.

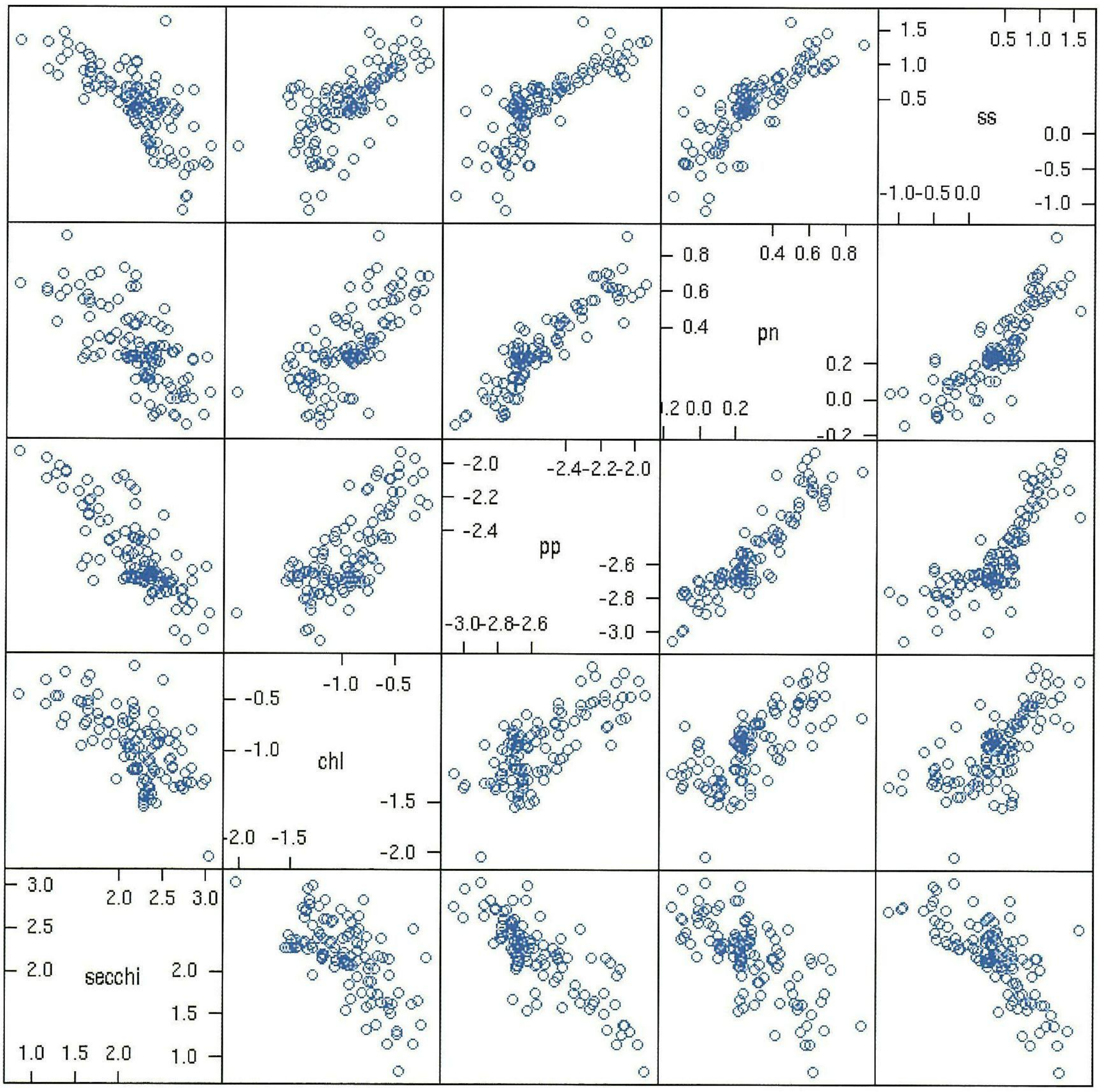


Figure 23: Scatterplot showing strong correlations between the predicted values of the five water variables at the hard coral sites.

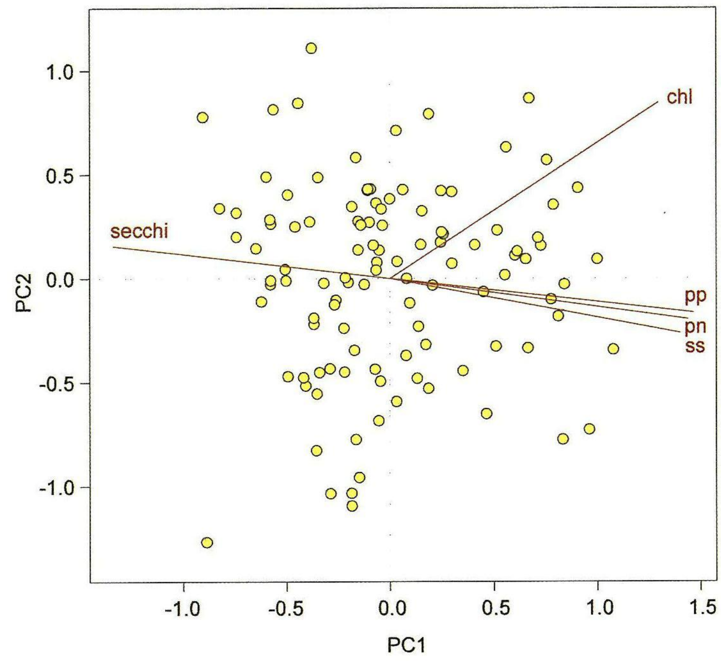


Figure 24: Principal components biplot showing strong correlations between PP, PN, SS and Secchi and somewhat weaker relationships to chlorophyll.

Boosted regression tree analyses were used to investigate the relationships of benthos to water quality and distance across and along the GBR. Initially, only Secchi depth and chlorophyll were included as water quality variables since they were (1) weakly correlated and (2) the best predictors. The relative error of the models is shown in Table 5. Note that the analyses are additive (e.g., the predicted macroalgal cover at anyone site is the sum of the relative effects of Secchi, chlorophyll, across and along) and presented as partial effects plots. The analyses were then repeated to assess trigger values of SS, PN and PP: each of these water quality variable was assessed together with across and along (but not including any of the other, highly correlated water quality variables) in order to identify concentrations related to a change in ecosystem status.

Table 5: Relative error (%) of the boosted regression tree models, and relative importance (%) of each of the two water quality and two spatial variables in explaining biotic responses. Models are based on partial effects, e.g, the Secchi effect is assessed *after* removal of the effects of across, chlorophyll and along, etc.

| | Macroalga l cover | Richness hard corals | Richness phototrophic octocorals | Richness heterotrophic octocorals |
|---|---|---|---|---|
| Relative error | 72.1 | 76.3 | 56.8 | 59.5 |
| Secchi | 27.0 | 10.1 | 16.7 | 10.8 |
| Chlorophyll | 5.7 | 6.4 | 28.1 | 6.7 |
| Across | 41.5 | 8.8 | 37.4 | 16.5 |
| Along | 25.8 | 74.8 | 17.8 | 66.0 |

## 5.2. Responses of biota to changes in Secchi and chlorophyll

### a) Macroalgal cover

Macroalgal cover increased steeply with declining water clarity at Secchi values <13 m, but was only weakly related to chlorophyll (Fig. 25). Macroalgal cover increased 3.5-fold (from 6 to 21%) as water clarity declined from 13 to 4 m, and additionally by 33% (from 9.5 to 12.5%) as chlorophyll increased from 0.3 to 0.8 µg $L^{-1}$. Additionally, macroalgal cover declined four-fold across the shelf and four-fold along the shelf. The predicted error was 72%, i.e., 28% of variation in macroalgal cover was predicted by the four variables (Table 5). The strongest predictors were across (41.5% of the 28% predicted variation), along (26%), Secchi (27%) and chlorophyll (46%).

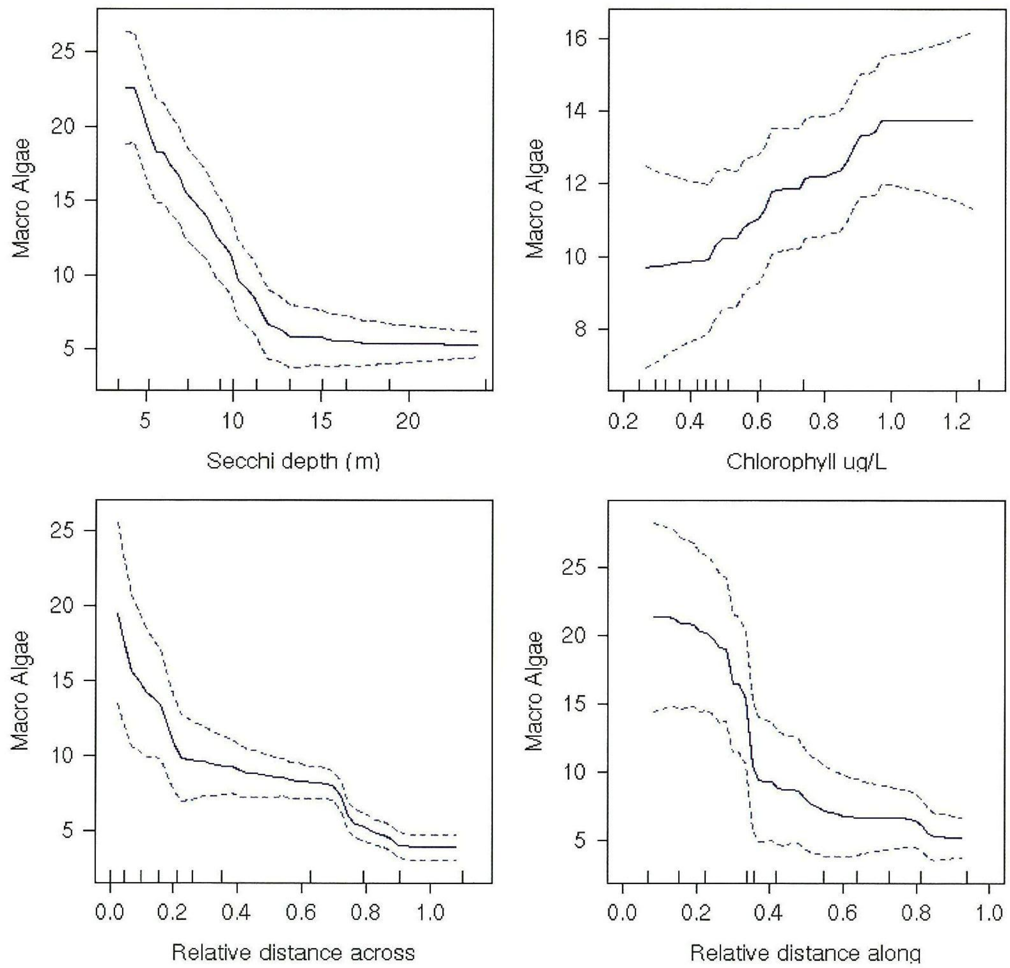


Figure 25: Partial effects plots of changes of macroalgal cover along gradients of water clarity (Secchi depth, in m), chlorophyll (µg $L^{-1}$), and distance across (0 = coast, 1 = offshore) and along the shelf (0 = south, 1 = north).

## b) Hard coral species richness

The species richness of hard corals increased with increasing water clarity by 24% (from 87 to 108 taxa; Fig. 26). Additionally, richness increased with decreasing chlorophyll by 14% (from 88 to 100 taxa). The greatest changes occurred when Secchi depth was in the range 8 – 13 m and chlorophyll was 0.25 – 0.4 µg $L^{-1}$. Richness was unrelated to water clarity and chlorophyll in clearer water. Hard coral richness declined by ~16% towards the coast and fluctuated between 60 and 120 taxa per reef along the GBR.

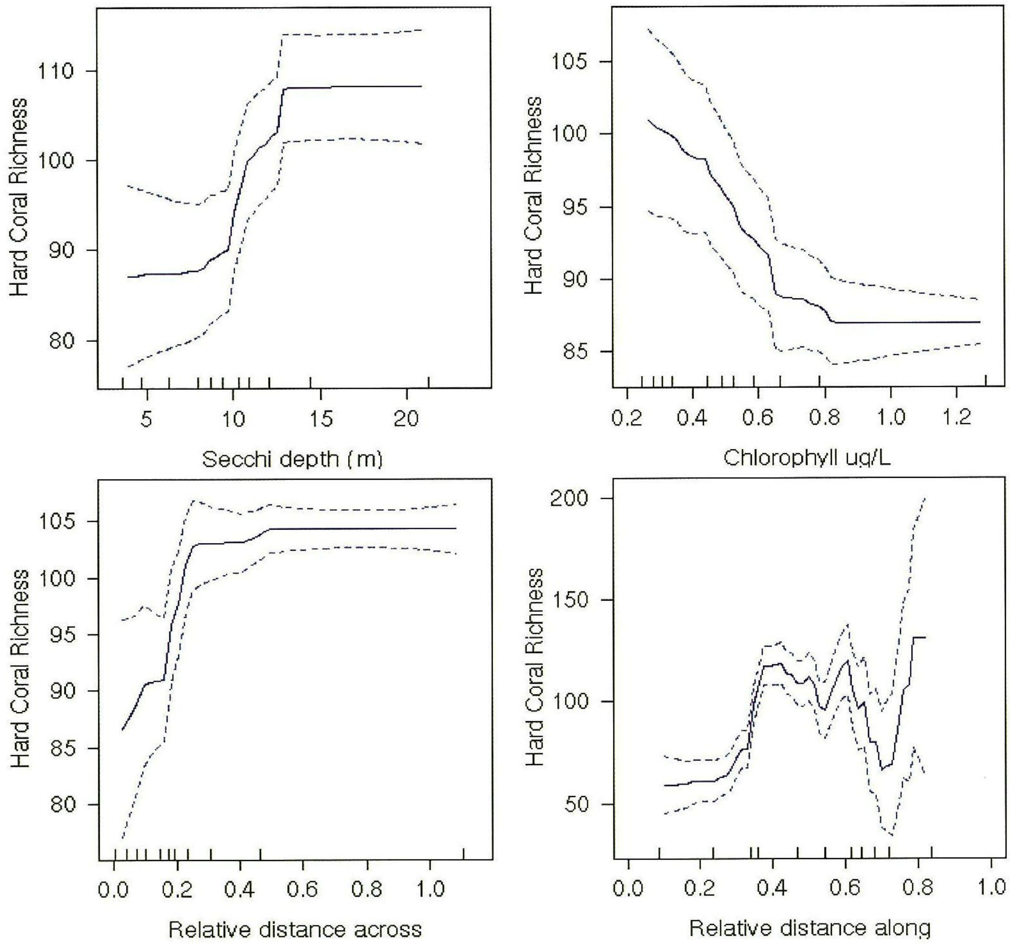


Figure 26: Partial effects plots of changes of the species richness of hard corals along gradients of water clarity (Secchi depth, in m), chlorophyll (µg $L^{-1}$), and distance across (0 = coast, 1 = offshore) and along the shelf (0 = south, 1 = north).

## c) Richness of phototrophic octocorals

The taxonomic richness of phototrophic octocorals increased by ~30% as water clarity increased from 5 to 15 m, and steeply declined by ~40% as chlorophyll increased from 0.25 to 0.5 g $L^{-1}$ (Fig. 27). Richness was unaffected by water quality at Secchi depth >15 m and chlorophyll levels below 0.35. Richness declined steeply towards the inner shelf (<0.4 across) and increased to the north. The model predicted 43% of variation, with chlorophyll and Secchi being useful predictors, accounting for 14% and 28% of the predicted variation, respectively (Table 5).

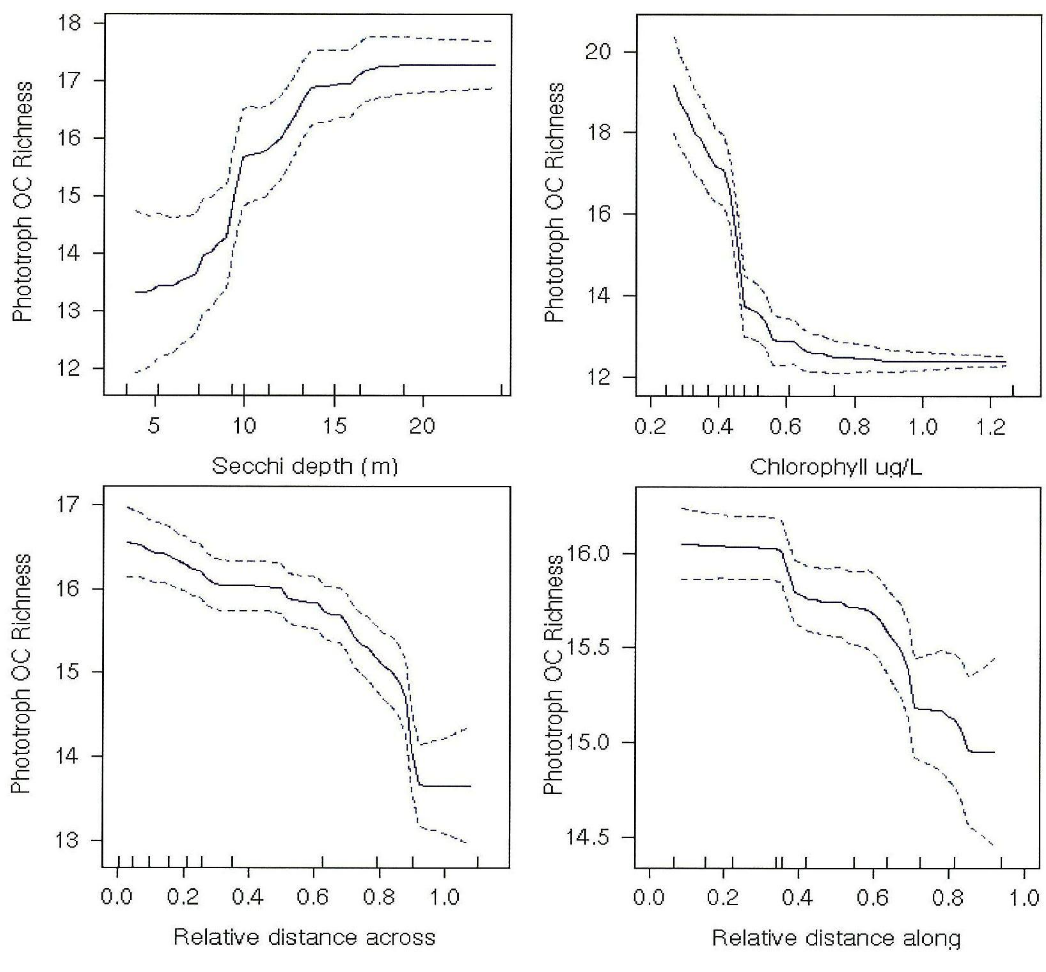


Figure 27: Partial effects plots of changes in the species richness of phototrophic octocorals along gradients of water clarity (Secchi depth, in m), chlorophyll (µg $L^{-1}$), and distance across (0 = coast, 1 = offshore) and along the shelf (0 = south, 1 = north).

## d) Richness of heterotrophic octocorals

The taxonomic richness of heterotrophic octocorals decreased by ~25% with increasing water clarity, and declined by ~20% with increasing chlorophyll (Fig. 28). Heterotrophic richness increased towards the coast and towards the north. Over 40% of variation was predicted by this model, with the spatial factors predicting most of the variation.

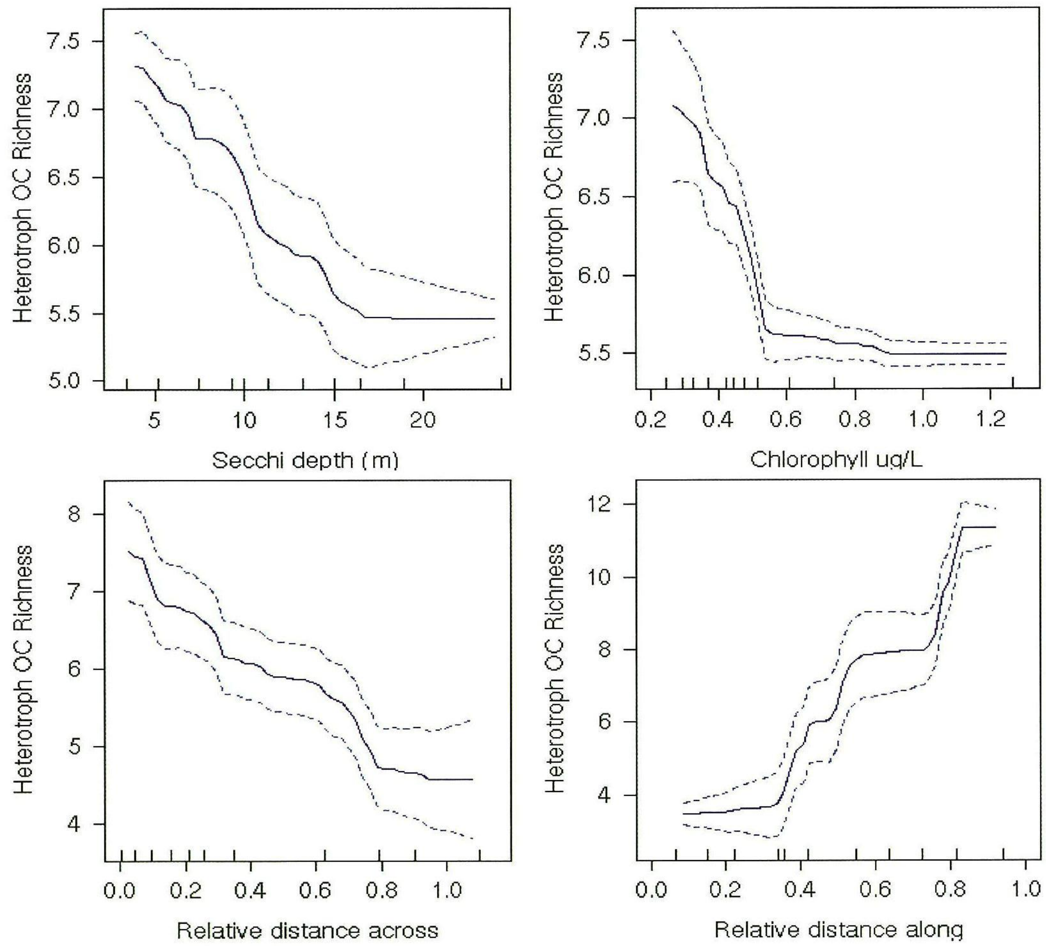


Figure 28: Partial effects plots of changes in the species richness of heterotrophic octocorals along gradients of water clarity (Secchi depth, in m), chlorophyll (µg $L^{-1}$), and distance across (0 = coast, 1 = offshore) and along the shelf (0 = south, 1 = north).

# 6. Suggested guideline trigger values for water clarity and chlorophyll for coastal and inner shelf reefs within the six NRM regions

## *6.1. Guideline trigger values for Secchi and chlorophyll*

We used two independent assessments to define guideline triggers for water quality improvement.

Both the Australian Environmental Protection Agency (2006) and the European Community (2005) recommend that water quality guideline values be calculated as percentiles of values found at Reference sites, and special consideration be given to areas of high ecological values. In the GBR, the Cape York region is assumed to have water quality conditions that are relatively unaltered since western settlement, and this region has been proposed to be used as a Reference Location for the regions further south. The mean values for coastal and inner shelf waters in Cape York are 0.45 µg $L^{-1}$ and 0.40 µg $L^{-1}$ chlorophyll, and 10 m and 11 m Secchi depth, respectively (Table 4). The shape of the response curves that related biotic data to water clarity and chlorophyll (Chapter 4) showed that high macroalgal cover and major reductions in coral and octocoral richness were only found at in the range of 0.3 – 0.6 µg $L^{-1}$ mean annual chlorophyll concentration and 5 – 15 m Secchi depth (Fig. 29).

**Choosing the Cape York values and the means of the ranges in the response curves, we postulate that the ecological condition of the GBR would significantly higher if mean annual water clarity does not drop below 10 m Secchi depth (at shallower depths Secchi will be visible on the seafloor), and mean annual chlorophyll concentration remains below 0.45 µg $L^{-1}$. These values should become the guideline triggers for water quality management. Further reductions in chlorophyll and increases in water clarity would provide additional significant improvement in ecosystem status. These guideline values benefit photosynthetic organisms such as hard corals and phototrophic octocorals, and do not adversely impact on other important reef organisms such as heterotrophic octocorals.**

**Summer chlorophyll values are ~40% higher in summer and ~30% lower in winter than mean annual values. Seasonal chlorophyll guideline triggers should be adjusted accordingly, to 0.63 µg $L^{-1}$ in summer and 0.32 µg $L^{-1}$ in winter. Seasonal adjustments for Secchi depths are presently not available due to lack of seasonal data.**

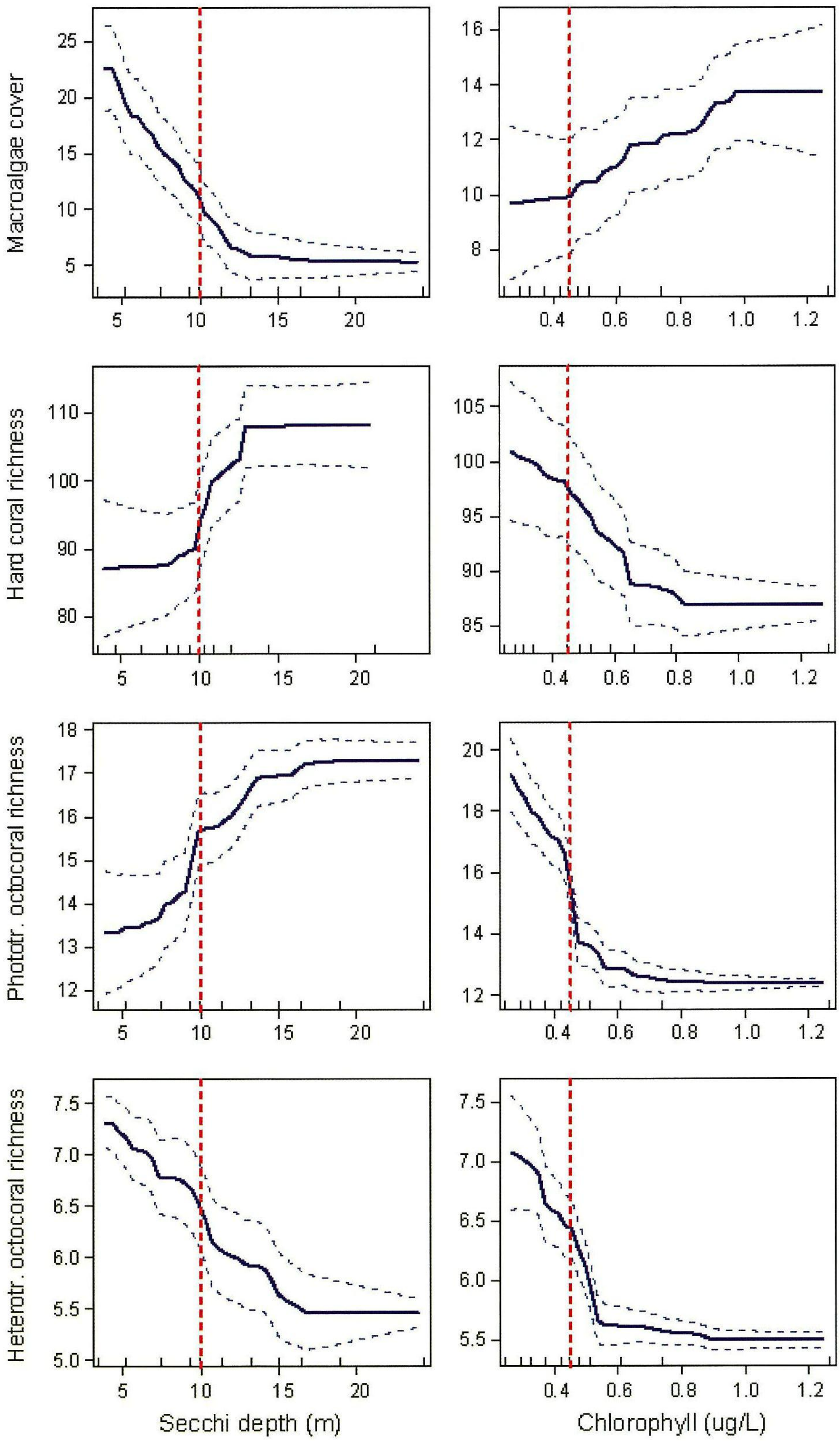


Figure 29: Partial effects of Secchi depth and chlorophyll concentration on the four measures of ecosystem status (from Figs. 25 – 28). Relative distance across and along were included in this model, but not shown here. The red dashed line indicates values found in coastal waters of Cape York. The plots suggest substantial improvement in reef status (higher biodiversity of hard corals and phototrophic octocorals, lower macroalgal cover) at water clarity of 5 - 15 m Secchi depth and chlorophyll of 0.3 – 0.6 µg $L^{-1}$.

## 6.2. Guideline trigger values for SS, PN and PP

Due to the high correlation between PN, PP, SS and Secchi, it is not possible to resolve their individual effects on ecosystem status, and inclusion of all variables simultaneously leads to spurious conclusions about such effects. To obtain approximate trigger values, we therefore analysed the correlations of biota to each of the water quality variables SS, PN and PP separately, with relative distance across and along being included in all models (Fig. 30). Note that in contrast to the previous analyses, the effects of these analyses are not additive. Partial effects plots for biotic responses and predictive errors for biotic responses to Secchi and chlorophyll were similar when both variables were analysed separately compared to when both were included in the model simultaneously (not shown).

Macroalgal cover increased about four-fold with SS increasing from 1.2 to 2.0 mg $L^{-1}$, and remained high above 2.0 mg $L^{-1}$. Macroalgal cover also increased by >50% (from 7 to 11%) with PN increasing from 0.9 to 1.6 µmol $L^{-1}$ (12.6 – 16.8 µg $L^{-1}$), and by ~40% (from 8 to 11%) with PP increasing from 0.04 to 0.14 µmol $L^{-1}$ (1.24 – 4.34 µg $L^{-1}$).

Hard coral richness declined with increasing SS, with highest values at <0.8 mg $L^{-1}$ SS and low richness at >2.0 mg $L^{-1}$. It also declined with increasing PN and PP, with highest values at <1.0 µmol $L^{-1}$ PN (14 µg $L^{-1}$) and <0.06 µmol $L^{-1}$ PP (<1.86 µg $L^{-1}$) and low richness at >1.8 µmol $L^{-1}$ PN and >0.10 µmol $L^{-1}$ PP (25.2 and 3.1 µg $L^{-1}$).

The declines in phototrophic octocoral richness were much steeper than those of the hard corals. Richness was highest at <1 mg $L^{-1}$ SS, 1.0 µmol $L^{-1}$ PN, and 0.05 µmol $L^{-1}$ PP (14 and µg $L^{-1}$ 1.55). Richness was up to 50% lower when SS exceeded 2.0 mg $L^{-1}$ SS, 1.6 µmol $L^{-1}$ PN and 0.10 µmol $L^{-1}$ PP (22.4 and 3.1 µg $L^{-1}$).

The richness of heterotrophic octocorals did not respond much to SS and PN, and only weakly declined with PP increasing above 0.08 µmol $L^{-1}$ (2.48 µg $L^{-1}$)

In coastal and inner shelf waters of the Cape York region, mean annual SS is 2.24 and 1.39 mg $L^{-1}$, respectively (Table 4), PN averages 1.49 and 1.48 µmol $L^{-1}$ (20.86 and 20.71 µg $L^{-1}$), respectively, and PP values are 0.090 and 0.080 µmol $L^{-1}$ (2.79 and 2.48 µg $L^{-1}$).

**Based on the biotic responses, and the concentrations found in the Cape York region, we propose the following maximum annual means as trigger values: 2.0 mg $L^{-1}$ SS, 1.5 µmol $L^{-1}$ (= 20 µg $L^{-1}$ ) PN, and 0.09 µmol $L^{-1}$ (2.8 µg L-1) PP. A choice of lower nutrient concentrations as triggers would likely lead to further reduction in macroalgal cover and substantial increases coral biodiversity.** For PN and PP, the suggested trigger values are supported by both the concentrations found at the reference region and those obtained from the response curves. For SS, the response curves suggested that trigger values should be lower than the concentrations presently found in the coastal zone of Cape York, to prevent extensive macroalgal cover and loss of biodiversity.

**Seasonal adjustments for SS, PN and PP are approximately 20% of mean annual values. Seasonally adjusted guideline triggers are therefore 2.4 mg $L^{-1}$ SS in summer and 1.6 mg $L^{-1}$ SS in winter. For PN, they are 1.8 µmol $L^{-1}$ (25 µg $L^{-1}$) in summer and 1.25 µmol $L^{-1}$ (17.5 µg $L^{-1}$) in winter. Seasonally adjusted trigger values for PP are 0.11 µmol $L^{-1}$ (3.3 µg $L^{-1}$) in summer and 0.075 µmol $L^{-1}$ (2.3 µg $L^{-1}$) in winter.**

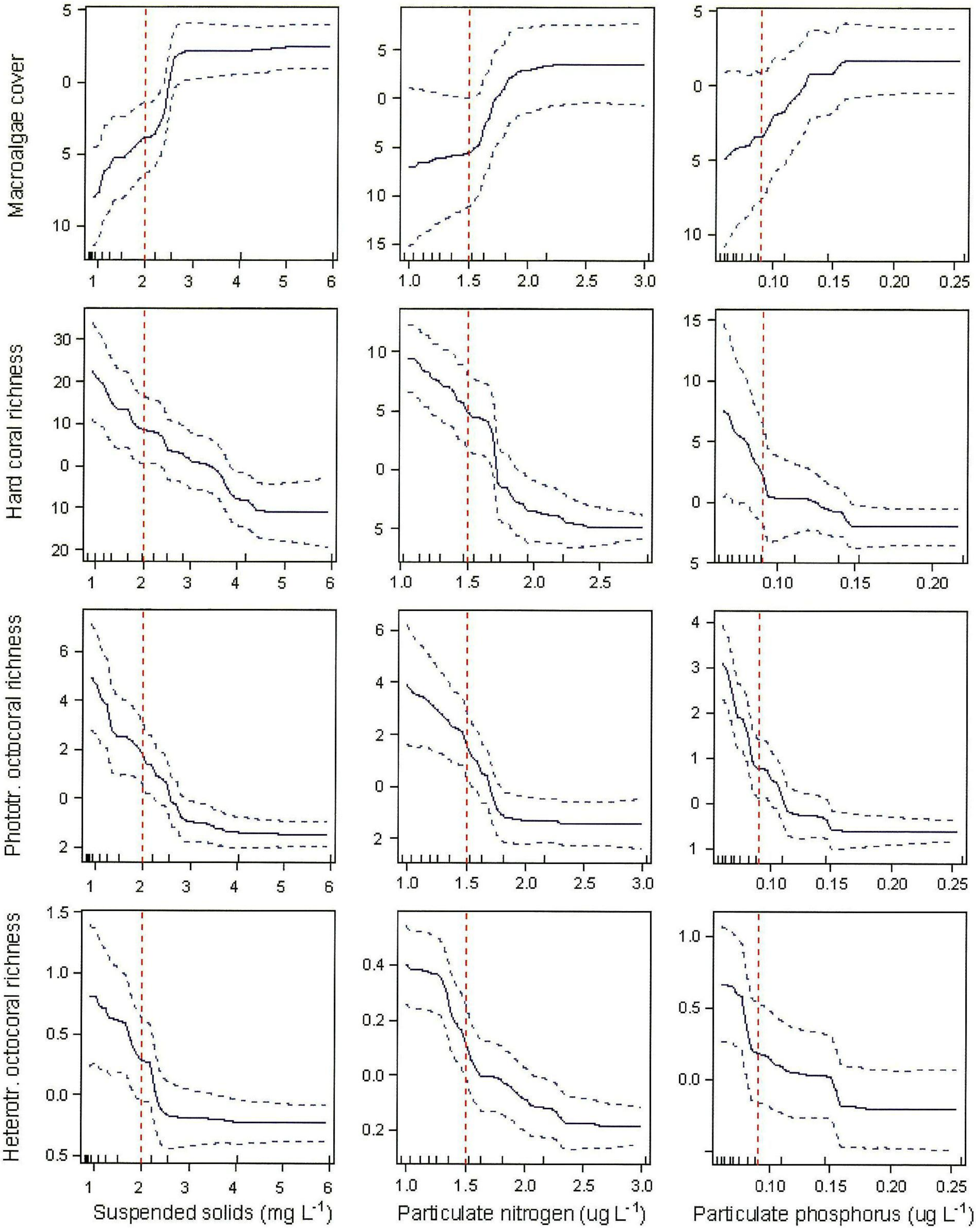


Figure 30: Partial effects of SS, PN and PP on the four measures of ecosystem status. SS, PN and PP were analysed separately, with across and along included in each of these 3 models (not shown). As SS, PN and PP were analysed separately, their effects as displayed here are not additive. Dashed red lines show suggested trigger values (see text).

# 7. Effects of improved water quality of reef biodiversity

## *7.1. Predicted changes in reef status after implementation of triggers*

Table 6 shows the changes in reef status predicted by the models for coastal and inner shelf reefs in each region if mean Secchi depth is >10 m, and mean chlorophyll concentration remains at <0.45 µg $L^{-1}$. As stated before the models simultaneously control for changes across and along the GBR. As indicated above, Secchi depth is highly correlated with SS, PN and PP and therefore can be used here as a proxy for the latter three water quality variables. The analyses suggest that:

**a) Macroalgal cover:** In coastal reefs of all regions other than Cape York, macroalgal cover would approximately halve if water clarity and chlorophyll were to be simultaneously improved. Water clarity has a greater effect on macroalgal cover than changes in chlorophyll. Benefits are also great for inner shelf reefs of the Mackay Whitsundays and Fitzroy reefs. Due to the natural north-south gradient in macroalgal cover, macroalgal cover would still be higher in the southern three regions than the northern regions after water quality improvements were implemented. Values in Cape York would remain similar to present values.

**b) Hard coral richness:** The simultaneous improvement of water clarity and chlorophyll would have greatest benefits in the southern regions. Coral richness on coastal reefs in the Burnett Mary, Fitzroy and Wet Tropics would increase by 44 – 47% compared to present-day values, and in the Mackay Whitsundays and Burdekin by ~30%. Changes in water clarity would have slightly greater benefits for coral richness than changes in chlorophyll. On inner shelf reefs, hard coral richness would still increase by about 20 – 25% in the Fitzroy and Mackay Regions, and 4 – 11% in the northern regions.

**c) Richness of phototrophic octocorals:** The simultaneous improvement of water clarity and chlorophyll concentrations would increase the richness of phototrophic octocorals on coastal reefs in all regions except Cape York by 63 – 84% compared to present-day values. On inner shelf reefs, the benefits would still be substantial (44 – 51%) in the Fitzroy and Mackay Whitsundays region, and 5 – 15% further north. Changes in chlorophyll will have a far greater effect on coral richness than changes in water clarity.

**d) Richness of heterotrophic octocorals:** A reduction in chlorophyll would lead to gains in the richness of heterotrophic octocorals, while increased water clarity would lead to slight losses of heterotrophic taxa. The simultaneous improvement of chlorophyll and water clarity would lead to 13 – 34% gains in the southern three regions (greater gains inner shelf than on coastal reefs), and small changes (ranging from 6% gains to 9% losses) on coastal and inner shelf reefs of the three northern regions.

Table 6: Present reef conditions, and predicted changes in conditions of coastal (C) and inner shelf (I) reefs if the water quality guideline trigger values of ≤0.45 μg $L^{-1}$ chlorophyll, and ≥10 m Secchi depth, or both, were met. MA = % Macroalgal cover, HC = hard coral richness, SC-phot = Richness of phototrophic octocorals, SC-het = Richness of heterotrophic octocorals.

| Biota | Shelf | WQ Status | Burnett Mary | Fitzroy | Mackay W | Burdekin | Wet Tropics | Cape York |
|---|---|---|---|---|---|---|---|---|
| MA | C | Present | 42 | 39 | 39 | 28 | 20 | 11 |
| MA | C | Secchi | 25 | 22 | 19 | 15 | 11 | 8.5 |
| MA | C | Chl | 40 | 37 | 37 | 25 | 19 | 11 |
| MA | C | Secchi+Chl | 21 | 19 | 16 | 11 | 10 | 8.1 |
| MA | I | Present | na | 26 | 28 | 6.9 | 6.1 | 3.8 |
| MA | I | Secchi | na | 17 | 12 | 4.2 | 4.1 | 2.7 |
| MA | I | Chl | na | 25 | 27 | 6.7 | 5.6 | 3.7 |
| MA | I | Secchi+Chl | na | 15 | 11 | 4.0 | 3.7 | 2.6 |
| HC | C | Present | 43 | 45 | 64 | 91 | 76 | 110 |
| HC | C | Secchi | 54 | 56 | 76 | 104 | 94 | 120 |
| HC | C | Chl | 51 | 53 | 72 | 103 | 93 | 112 |
| HC | C | Secchi+Chl | 63 | 64 | 85 | 116 | 110 | 122 |
| HC | I | Present | na | 59 | 68 | 122 | 111 | 129 |
| HC | I | Secchi | na | 65 | 79 | 125 | 118 | 135 |
| HC | I | Chl | na | 65 | 72 | 122 | 116 | 129 |
| HC | I | Secchi+Chl | na | 71 | 84 | 126 | 123 | 134 |
| SC-phot | C | Present | 12 | 12 | 11 | 11 | 11 | 14 |
| SC-phot | C | Secchi | 14 | 14 | 14 | 13 | 14 | 15 |
| SC-phot | C | Chl | 17 | 17 | 17 | 16 | 16 | 16 |
| SC-phot | C | Secchi+Chl | 19 | 19 | 19 | 19 | 19 | 18 |
| SC-phot | I | Present | na | 13 | 13 | 17 | 16 | 17 |
| SC-phot | I | Secchi | na | 14 | 14 | 18 | 17 | 18 |
| SC-phot | I | Chl | na | 18 | 17 | 18 | 18 | 17 |
| SC-phot | I | Secchi+Chl | na | 19 | 19 | 19 | 19 | 18 |
| SC-het | C | Present | 4.0 | 3.9 | 4.8 | 7.2 | 9.4 | 12 |
| SC-het | C | Secchi | 3.5 | 3.4 | 3.9 | 6.0 | 8.0 | 11 |
| SC-het | C | Chl | 5.5 | 5.4 | 6.1 | 8.4 | 10 | 12 |
| SC-het | C | Secchi+Chl | 5.0 | 4.9 | 5.4 | 7.6 | 9.0 | 11 |
| SC-het | I | Present | na | 3.2 | 3.6 | 6.9 | 8.0 | 11 |
| SC-het | I | Secchi | na | 2.9 | 3.1 | 6.7 | 7.8 | 10 |
| SC-het | I | Chl | na | 4.6 | 5.1 | 7.1 | 8.2 | 11 |
| SC-het | I | Secchi+Chl | na | 4.3 | 4.6 | 7.0 | 8.0 | 10 |

## 7.2. Water quality changes required to achieve trigger values

The changes in chlorophyll and water clarity necessary to achieve the proposed guideline trigger values are listed in Table 7. The table shows that in coastal waters, and increases in water clarity by 56 – 170% and reductions in chlorophyll by 22 – 63% will be necessary to re-establish highly diverse coral communities reduced abundances of macroalgae. On inner shelf reefs, water clarity is close to the guideline trigger value in all regions except the Mackay Whitsunday, where water clarity would need to improve by 16% to improve biodiversity. On inner shelf reefs, chlorophyll would need to be reduced by 46% in the Burnett Mary and by 8% in the Burdekin, while the other regions require no changes. Given the strong correlation between chlorophyll, SS, PN and PP, reductions in chlorophyll and Secchi depth may also be achieved by reductions in SS, PN and PP.

Within individual NRM regions and zones, some areas of coastline already meet or are near the trigger values, while other areas should be considered priority areas for management intervention (Figs. 31 and 32). Most noticeable is that coastal nutrient concentrations greatly exceed the trigger values in the areas north of the Burnett, Burdekin, Fitzroy, Herbert, Tully and Johnstone rivers, likely due to influences of river discharges. Water clarity in the Broad Sound is partly determined by the high tidal ranges leading to intense resuspension regimes. As nutrient levels in this zone are low, it appears advisable to relax the guideline trigger values for water clarity by 20% for areas with a >5 m tidal range (Fig. 33).

The offshore zone in the Pompeys reefs, which are known for their naturally high levels of chlorophyll, also experience 4 – 5 m tidal ranges, and complex hydrodynamic features promote nutrient injection from the shelf break. High chlorophyll levels in this region are therefore independent of terrestrial sources. Reefs in this region are marginal for reef growth and dominated by filter feeders (bryozoans, sponges, ascidians and bivalves; Fabricius, unpublished data). Because our proposed guideline trigger values have been developed for coastal and inner shelf regions that are likely to be influenced by human activities, tehy do not apply to the offshore Pompeys.

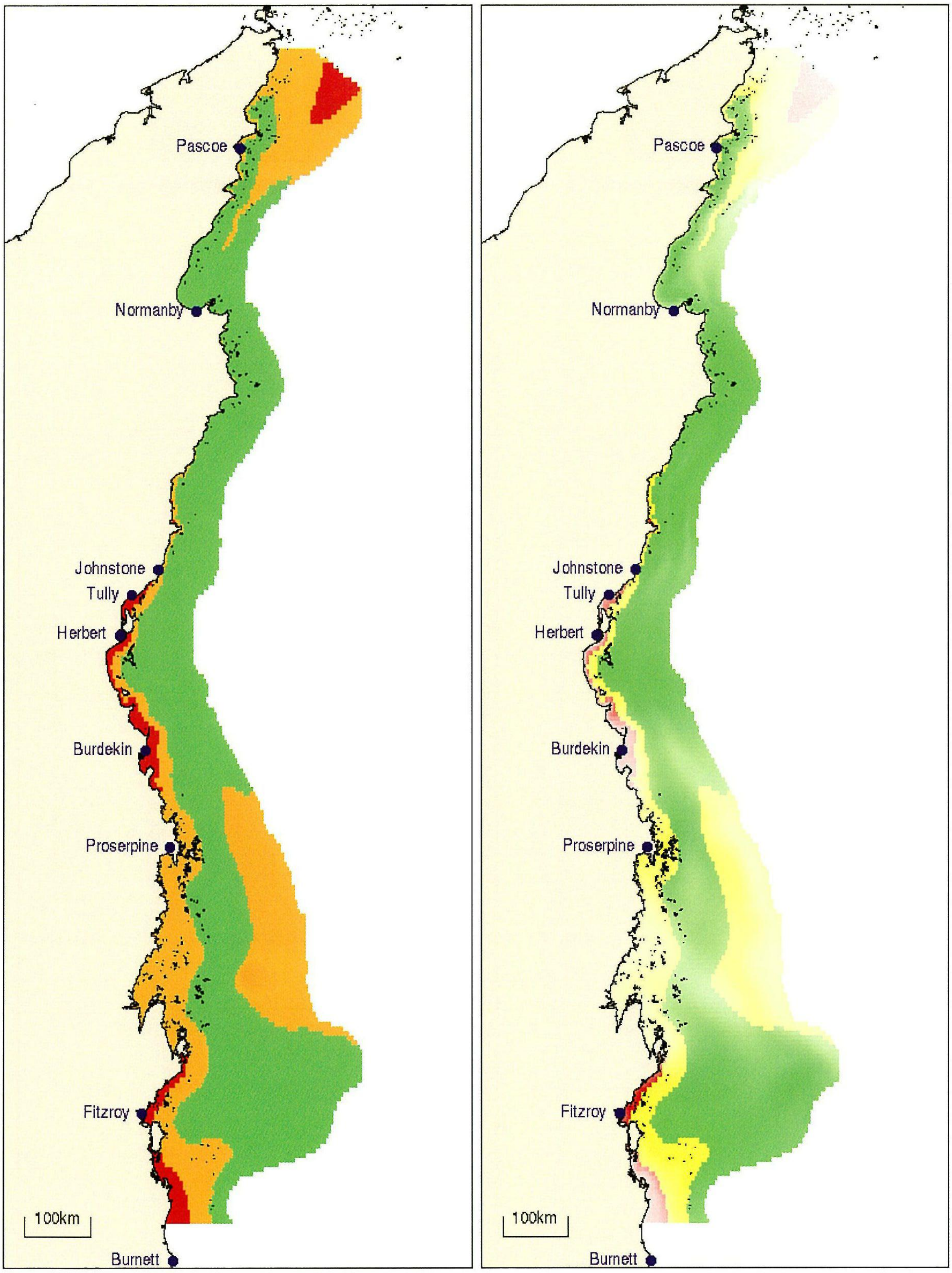


Figure 31: Locations that are presently at less than (green) or exceed (orange and red) the water quality guideline trigger value of a maximum annual mean of 0.45 µg $L^{-1}$ chlorophyll. Orange zones show areas that exceed the guideline trigger values, having chlorophyll values of 0.45 – 0.8 µg $L^{-1}$. Red zones show areas of greatest concern with >0.8 µg $L^{-1}$ chlorophyll. The level of fading (right panel) indicates the level of confidence in the estimates with faded areas being more uncertain.

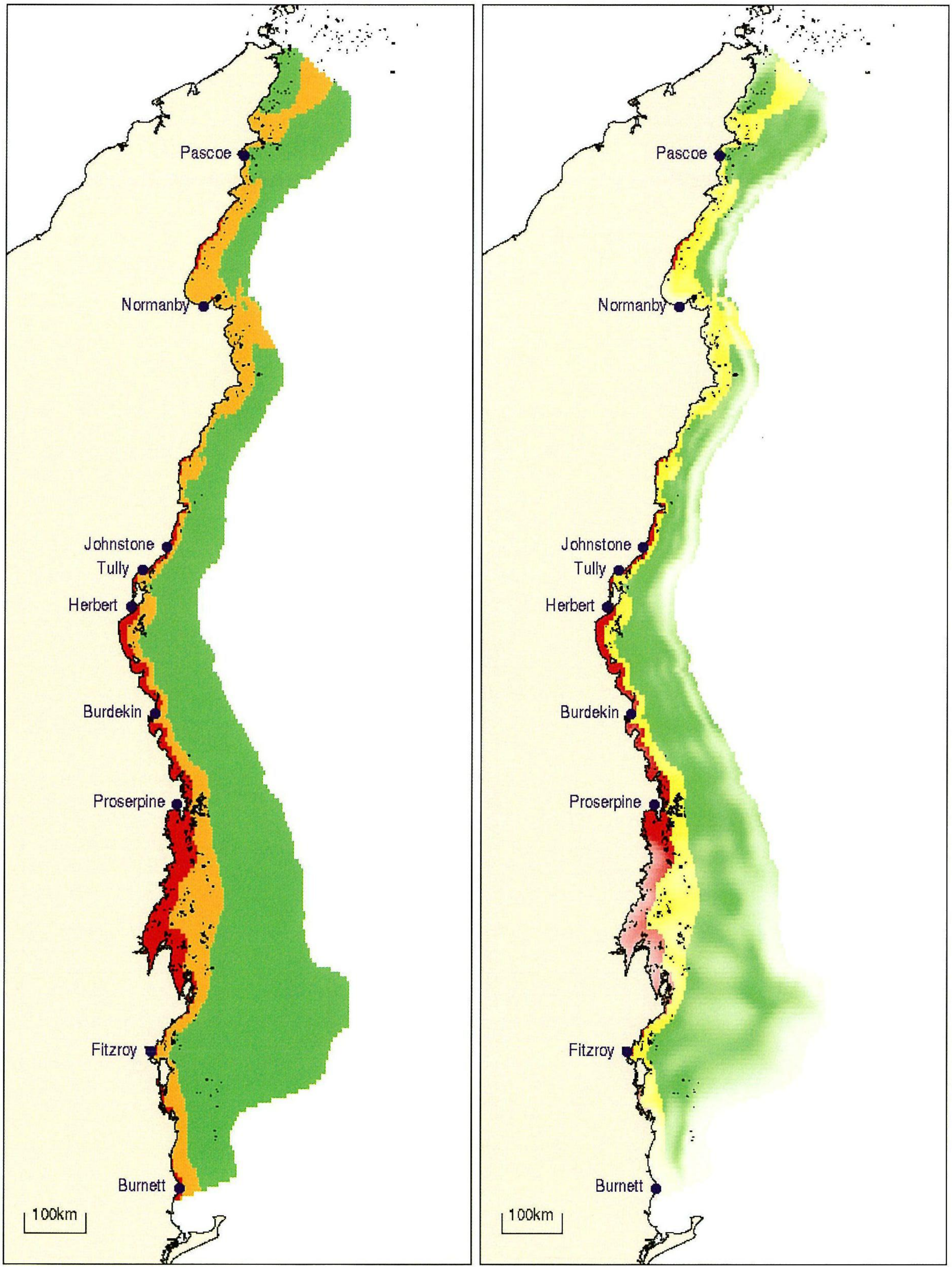


Figure 32: Locations that are presently at less than (green) or exceed (orange and red) the water quality guideline trigger value of a minimum annual mean of 10 m Secchi depth. Orange zones show areas that exceed the guideline trigger values, having Secchi depths of 5 – 10 m. Red zones show areas of greatest concern with Secchi depth <5 m. The level of fading (right panel) indicates the level of confidence in the estimates with faded areas being more uncertain.

Table 7: Percentage changes required for each region to achieve a mean annual water clarity target of 10 m Secchi depth and a mean annual chlorophyll level of 0.45 μg $L^{-1}$.

| a) Coastal Reefs | Secchi | | Chlorophyll | |
|---|---|---|---|---|
| | Present value (m) | % Increase | Present value (μg $L^{-1}$) | % Reduction |
| Burnett Mary | 6.4 | 56 | 1.20 | 63 |
| Fitzroy | 5.5 | 81 | 0.72 | 38 |
| Mackay Whitsundays | 4.4 | 130 | 0.58 | 22 |
| Burdekin | 3.7 | 170 | 0.93 | 52 |
| Wet Tropics | 4.7 | 113 | 0.87 | 48 |
| Cape York | 10.2 | (no change) | 0.45 | 0.9 |

| b) Inner shelf Reefs | Secchi | | Chlorophyll | |
|---|---|---|---|---|
| | Present value (m) | % Increase | Present value (μg $L^{-1}$) | % Reduction |
| Burnett Mary | 11.4 | (no change) | 0.83 | 46 |
| Fitzroy | 14.3 | (no change) | 0.45 | (no change) |
| Mackay Whitsundays | 8.7 | 16 | 0.45 | 0.1 |
| Burdekin | 13.3 | (no change) | 0.49 | 7.8 |
| Wet Tropics | 11.0 | (no change) | 0.45 | (no change) |
| Cape York | 10.9 | (no change) | 0.40 | (no change) |

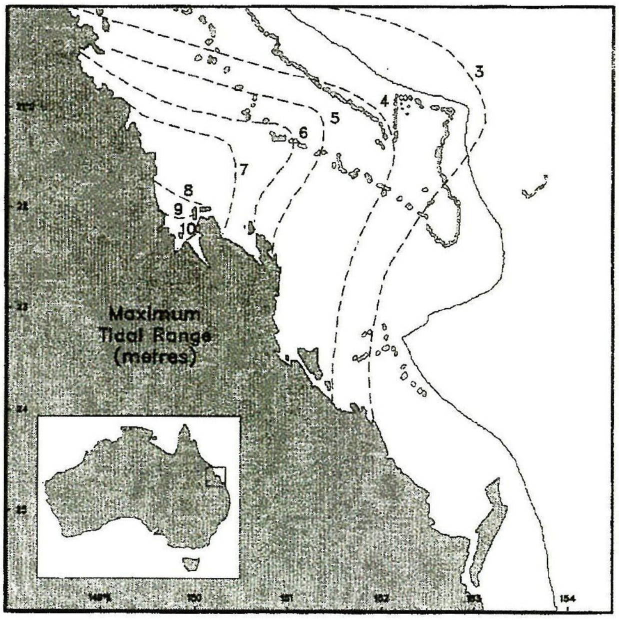


Figure 33: The high tidal ranges in the Broad Sound result in high turbidity while nutrient levels are generally low (from Pickard, 1977).

# 8. Discussion

## a) Proposed water quality trigger values

We have shown the relationship of a number of biotic measures (indicators) to the distribution of mean annual chlorophyll and water clarity in the GBR, and we have used these relationships to predict how ecosystem status would change with changing water quality (other factors remaining unchanged). Other forms of disturbance (such as crown-of-thorns, bleaching etc) would affect this relationship and more complex ecological models would be required to factor in such responses and interactions into the analyses. The analyses are based on the spatially most comprehensive data presently available. Response relationships of other key biotic measures (such as microbial communities or coral recruitment) to changing water quality will need to be investigated as a priority to assess the adequacy of the proxies used here.

For chlorophyll, Secchi depth, PN and PP, the suggested trigger values were supported both by the concentrations found in Cape York (the only remaining reference region) and by the biotic responses. For SS, the response curves suggested that trigger values should be lower than the concentrations presently found in the coastal zone of Cape York in order to prevent extensive macroalgal cover and loss of biodiversity. It is unknown whether coastal and inner shelf water clarity in Cape York is still similar to 'pristine' conditions despite its low-intensity cattle grazing industry in parts of the catchments. As historic water quality data are not available from any of the catchments, long-term records of water quality indicators preserved in cores of massive corals, sediment or coral reef communities should be investigated as a matter of priority to assess whether and where water quality and coral reef conditions have changed since agricultural expansion.

## b) Potential additional guideline trigger values for sedimentation and benthic irradiance

A number of independent experiments have shown that a chronic exposure to <10 mg $cm^{-2}$ $d^{-1}$ sedimentation induces significant coral recruit mortality (Appendix 1b). Rogers (1990) proposed a threshold for healthy reefs at 10 mg $cm^{-2}$ $d^{-1}$ sedimentation, moderate to severe effects on corals at 10 to 50 mg $cm^{-2}$ $d^{-1}$, and severe to catastrophic effects at >50 mg $cm^{-2}$ $d^{-1}$. Other studies have shown that chronic levels of sedimentation higher than 3 mg $cm^{-2}$ $d^{-1}$ induces mortality in coral recruits, while levels higher than 10 mg $cm^{-2}$ $d^{-1}$ reduce coral species richness, coral cover, coral growth rates, calcification, net productivity of corals, and reef accretion (Appendix 1b). Fabricius et al. (2003) and Weber et al. (2006) have shown that sedimentation effects not only increase with the amount of sediment but also with its organic and nutrient contents and with decreasing grain size. Experimental evidence therefore suggests that 10 mg $cm^{-2}$ $d^{-1}$ sedimentation is acceptable in areas with coarse calcareous sediments, but trigger levels need to be substantially lower where sediments are largely of terrigenous origin or of small grain size or high in organic contents. **Based on existing experimental and field evidence, it is proposed to set a sedimentation trigger value to a maximum mean annual value of 3 mg $cm^{-2}$ $d^{-1}$, a value that would guard against excessive coral recruit mortality and accommodates an uncertainty factor for higher organic contents or small grain sizes.** More field data on ecosystem responses in relation to sediment quality and quantity are needed to test this proposed trigger value. Hydrodynamic settings determine to what extent ecosystem stress is due to sedimentation and to what extent due to turbidity. In areas of low hydrodynamic energy, stress due to sedimentation will exceed the stress due to light attenuation, while at high hydrodynamic energy where sediments tend to remain in suspension, the reverse is true. In the longer term, sediment quality guidelines should be developed for the GBR, following recommendations by ANZECC (2000). Such guidelines should also include trigger values for sediment nutrient concentrations, which at elevated levels may cause toxicity through the development of excess porewater ammonia and hydrogen sulphide.

The relationship between benthic irradiance, suspended solid concentrations and turbidity (water clarity, measured either with nephelometers or as Secchi depth) depends on the nature of the particulate matter (Te 1997), and this relationship is not yet fully understood for the GBR. Secchi depth was used here as proxy for light penetration, due to the good spatial coverage of the data, and because light attenuation data (e.g., from CTD casts) have not yet been compiled and analysed for the GBR. Benthic irradiance is a key resource for marine ecosystems, as corals and many other key groups are phototrophic and growth their growth is controlled by the availability of benthic irradiance (Anthony et al. 2004). There is a substantial research need to better understand the distribution of benthic irradiance, in order to quantify the relationship between benthic irradiance and coral growth, and how benthic irradiance shapes reef communities. Achituv (1990) found that light availability below 10% of surface irradiance limits the growth of corals, while 30 – 40% of surface irradiance is the lower limit for reef development in the Red Sea. Kleypas (1997) concluded from work in the Broad Sound that the minimum PAR necessary for reef growth is 250 µE $m^{-2}$ $s^{-1}$ for 3 hours at noon on the GBR (16% of surface irradiance assuming noon light levels of 1500 E $m^{-2}$ $s^{-1}$). Kleypas et al. (1999) reviewed light limits for reef development around the world, and found that marginal reefs were found in a wide range of light environments. Similarly, Titlyanov and Latypov (1991) have investigated the distribution of 64 reef-building scleractinian species in turbid waters of the South China Sea. They concluded that the lowest depth limit of most corals was at 2 – 8% of surface irradiance, and only a few plate, corymbose and encrusting colonies were found at such low light. In the Whitsundays, the lowest depth for coral distribution was at 6 – 8% of surface irradiance, where communities shifted from phototrophic to heterotrophic benthos (Cooper et al. 2007. Cooper (in prep.) suggested that >3.0 NTU can lead to light limitation of *Symbiodinium* hosted by the coral *Pocillopora damicornis* on coastal reefs at a shallow depth (~3 m). Further, the observed limit of reef development at 8% of surface irradiance was correlated with turbidity exceeding 4.5 NTU. On this basis, Cooper tentatively proposed 3.0 NTU as a threshold of turbidity for sub-lethal stress and 4.5 NTU for the absolute limit for reef development, emphasizing that more data on the light environment on the GBR and the photophysiology and light adaptation in corals and seagrass are needed to substantiate this threshold value. Finally, for seagrass, the deepest depth of seagrass distribution in Moreton Bay was defined by a $K_d$ value of 0.9 $m^{-1}$ (Abal and Dennison 1996); it is not known whether these findings would also apply to GBR species. **Before adequate light penetration targets can be set, further work is needed to analyse the spatial distribution of benthic irradiance, its relationship to Secchi depth and turbidity, and its role in shaping the ecosystems of the GBR.**

## c) Recommendations for research and monitoring

In this Report, we have related four measures of ecosystem status (algae cover and richness of hard corals, heterotrophic and phototrophic soft corals) to two measures of water quality (Secchi depth as a measure of water clarity, and chlorophyll). The two measures of water quality were shown to be strongly related to ecosystem status, suggesting that improvement in these two measures will lead to improvements in ecosystem status. Furthermore, we have suggested trigger values for the measures in coastal and inner shelf regions, and have estimated the likely improvements in the four measures of ecosystem status if the trigger values are met. These improvements would be substantial. This work thus constitutes a sound basis for management of water quality in the GBR coastal and inner shelf regions.

In order to implement policies that will lead to improvements in water quality and hence ecosystem health, effective monitoring of WQ and biotic responses is required, and such monitoring should be conducted at the same locations in a coordinated manner. The two measures proposed in this Report have distinct advantages over other possible water quality measures addressed in this Report and in De'ath (2007b). Of the measures considered in the two Reports, Secchi and chlorophyll are the best currently available predictors for our measures of ecosystem status. Though the two measures are moderately correlated, they do reflect different aspects of coral reef status as the four biotic measures respond in different ways and with varying intensity to the two water quality measures (see earlier analyses). Chlorophyll is highly correlated with particulate WQ measures including particulate nitrogen, particulate phosphorous and suspended solids, and thus it can act as a surrogate for these measures (De'ath 2007b). The measurement error for Secchi depth is low compared to all other water quality measures, and thus fewer observations are required to give a precise estimate of this water quality measure. On the other hand all the dissolved nutrients are highly variable and would provide limited information if used in a long-term monitoring program. Finally, turbidity (as alternative measure to Secchi depth to measure water clarity) and chlorophyll can be measured directly using automated sensors, thereby reducing cost and, most importantly, returning high-frequency data that can be used to assess both spatial and temporal dynamics.

The points outlined above suggest that an effective monitoring program could be implemented on a cost-effective basis on a relatively short term basis, with the main effort focusing on the coastal and inner shelf zone. Biological monitoring would then complement the water quality monitoring at the same locations, focusing on indicators that are relatively specific to water quality changes. Macroalgal abundances, hard coral and octocoral richness, coral recruitment and recruit survivorship, macrobioeroder densities in living massive *Porites*, the photosynthetic performance of corals, and nature of biofilms on natural substrata have been suggested as useful indicators in such a program (Fabricius et al. 2007b). Future work will be required for the design of such a program and consideration should be given to include Cape York into such program.

Further research will be needed to relate land use intensity in individual catchments to river pollutant loads and to water quality conditions and ecosystem status in the estuaries, and in the coastal and inshore seagrass meadows and coral reefs of the GBR. Given that rivers are the main source of new nutrients, sediments and pesticides to the lagoon and given the natural variability in flow, loads and concentrations, long-term river data are crucial for such analyses. Detailed and comprehensive long-term river monitoring programs therefore remain essential to improve pressure and trend estimates in response to changing catchment management.

Within the marine environment, a fine resolution grid of environmental conditions should be developed for each NRM region based on measurements and hydrodynamic models. Such data will improve models on flood plume dilution and dispersal, deposition and resuspension of sediments, on biological and chemical transformations and help identifying areas of greatest risk (e.g., exposure to highest loads, highest concentrations or greatest retention). Similarly, a research project linking river discharge to pollutant dispersal in the GBR lagoon, and spatial and seasonal changes of lagoonal water quality will be essential to understand residency times of these pollutants. Finally, additional data and models are needed to identify the main factors responsible for inter- and intra-annual variability in concentrations of nutrients and suspended solids, such as the effects of river floods, wind- and wave-driven resuspension, and blooms of the nitrogen-fixing *Trichodesmium*. These factors are not well understood but should be incorporated into future models. To determine the frequency and duration of such extreme values, long-term instrumental measurements of chlorophyll, benthic irradiance and turbidity samplers and remote sensing need to be employed.

Priority should also be given to compile data and analyse the spatial and temporal distribution of light absorption in the GBR, to relate light to bathymetry, and to establish the relationships between light penetration, turbidity, Secchi depth and rates of sedimentation for specific regions and hydrodynamic conditions within the GBR.

Lastly, the region of Cape York plays an important role in the GBR, being the only remaining coastal and inner shelf Reference region that supports extensive coral reefs. The biodiversity, ecological functions and water quality conditions of the Cape York region should be much better documented and researched as a matter of urgency, before climate change and other intensifying pressures start degrading this part of the GBR ecosystem. Two rare category 4 - 5 cyclones and some bleaching have disturbed some of Cape York's reefs in this region between 2002 and 2007, so it is important to obtain data from this remote region to consolidate future use of this region as reference location. Also, Cape York should be added to any monitoring program to monitor the natural variability of reference conditions.

# Appendices

## *Appendix 1: Review of published ecological data of effect concentrations of nutrients and sediments*

A large number of studies and reviews exist that have shown that high levels of nutrients and sediments lead to deteriorating ecosystem status (reviewed in Fabricius 2005). Some of the studies that quantified exposure levels and physiological and ecological effects on coral reef biota are listed in Table A1, and summarised here.

### a) Effects of water quality on macroalgal cover

Macroalgal communities are an integral and often diverse component of inner shelf reef systems. They cover their carbon demand by photosynthesis, and their nutrient demand by uptake of dissolved inorganic nutrients, plus in some species by decomposing particulate organic matter deposited on their fronds (Schaffelke 1999a). In the absence of grazing control, the growth and productivity of certain groups of macroalgae is nutrient limited and may increase with slight increases in dissolved inorganic nutrients and POM (Schaffelke 1999b, Schaffelke et al. 2005). High standing biomass of fleshy, silt-trapping macroalgae has been reported around many point nutrient sources (reviewed in Fabricius 2005). There is strong evidence that nutrients can limit macroalgal biomass, and that they can have a negative effect on reef development.

There is little doubt remaining that macroalgal cover increases with nutrient availability, despite additional controls by herbivory. The main sets of evidence to support the conclusion of a causal link between increasing macroalgal abundances and nutrient availability are as follows (see also Table A1):

a) Temporal changes:

- Time series data show that macroalgal cover expanded on sites where nutrient concentrations increased due to coastal runoff, but not on control sites (Cuet et al. 1988), and that macroalgal cover decreased after sewage diversion (Smith 1981).
- A 50% local increase in nutrients in the northern-most part of the Red Sea (Eilat, Gulf of Aqaba) coincided with increasing macroalgal cover (Loya et al. 2004).
- Experiments have shown that several GBR macroalgal species are nutrient limited and respond with enhanced productivity to transient pulses of dissolved inorganic nutrients (N and N+P) at environmentally relevant concentrations (Schaffelke 1999b).

Nutrients surplus to immediate metabolic demand are stored in the tissue, and these nutrient stores sustain increased growth for several weeks. *Sargassum* and other species that have a high nutrient demand and the ability to use a variety of nutrient forms are likely to benefit from increased nutrient availability, while species that are nutrient-sufficient in an oligotrophic environment would not benefit from a higher nutrient availability (Delgado and Lapointe, 1994 Delgado and Lapointe 1994; Schaffelke 1999b).

- Experiments have shown that growth rates in several species of macroalgae on the GBR increased when particulate organic matter is deposited on their thalli (Schaffelke 1999a). The nutrient gains from POM remineralisation by epiphytic microbes outweighed potential negative effects of organic particles settling on thalli (e.g. from shading or anoxia), resulting in net growth benefits.

b) Spatial gradients:

- Macroalgal abundances are high in areas of nutrient upwelling, and more prevalent on eastern sides of large land masses from which most rivers originate than on dry western sides (Birkeland 1988)
- Both macroalgal biomass and water column nutrients increase with latitude (Johannes et al. 1983)
- High standing biomass of fleshy, silt-trapping macroalgae has been reported around many point nutrient sources, such as Kaneohe Bay (Smith 1981), Brazil (Costa Jr et al. 2000) or the Bahamas (Lapointe et al. 2004).
- On inner shelf reefs of the central and northern Great Barrier Reef, total macroalgal cover (especially red and green algae) increases by up to 50% from reefs in water with lowest nutrient and particle loads to those in least clean water (van Woesik et al. 1999; Fabricius and De'ath 2004; Fabricius et al. 2005).

These studies, in combination with our data analyses from the GBR (Chapter 5), show conclusively that both dissolved inorganic nutrients and particulate organic matter can stimulate macroalgal productivity, resulting in increased macroalgal cover. Other studies have shown that high macroalgal cover can damage corals by shading, sediment trapping, restricting gas exchange, and creating anoxic conditions when mats age and collapse. A substantial reduction of macroalgal cover to lower than present-day values in the inner shelf regions with the highest lagoon nutrient concentrations (the Burnett Mary, Fitzroy, Mackay Whitsundays, Burdekin and Wet Tropics Regions) is therefore a desirable goal for management aiming at maintaining or improving the ecosystem health of the GBR. Our data and models suggest that macroalgal cover should decrease by ~70% of present values if water clarity improves from 4 to 10 m Secchi depth, and additionally by 25% if chlorophyll decreased from 0.8 to 0.45 µg $L^{-1}$.

## b) Effects of water quality on hard corals and coral recruitment

Corals are the main group of organisms responsible for reef construction. Without corals, other reef-associated organisms would not have a habitat, and although some reef associated organisms may be more or less sensitive to changes in water quality, not much information on their sensitivities presently exists. Hard corals are competitive in low-nutrient environments because of efficient internal recycling of nutrients and energy between host and zooxanthellae.

Poor water quality leads to reduced reef calcification (Loya 2004), a shallower deepest depth of reef development (Cooper et al. 2007), changed coral community structure (Fabricius et al. 2005), and reduced species richness (Fabricius and De'ath 2001b; Fabricius et al. 2005; DeVantier et al. 2006. While hard coral cover is predominantly determined by disturbance history, the species richness of hard corals appears to be a sensitive indicator of the physico-chemical environmental conditions of a site. Hard coral richness has been found to be 50% lower along a 400 km long stretch on inner shelf reefs of the Burdekin and the Wet Tropics compared to reefs further north and south, and repeated disturbance as well as poor water quality retarding recovery from disturbance have been discussed as potential cause for this low species richness (DeVantier et al. 2006).

Coral recruitment is the most sensitive life history stage, and a reduction in coral recruitment arguably represents the most severe direct effect of poor water quality on coral communities (Fabricius 2005). Coral recruitment ultimately depends on three factors: the availability of larvae, the availability of substratum unoccupied by macroalgae and other benthos, and conditions of the physico-chemical environment that foster recruit survival (esp. water quality, sedimentation, benthic irradiance and water flow). Macroalgae are a particularly important factor determining coral recruitment as they inhibit coral recruitment by space occupancy, allelopathy, silt trapping or shading (Connell et al., 1997; Hughes and Tanner, 2000; Szmant, 2002; Schaffelke et al., 2005). Adult corals are also affected by higher levels of exposure to changing water quality (high levels of sedimentation, low benthic irradiance). Hence reef ecosystems increasingly simplify with declining water quality, and show a reduced ability to maintain essential ecosystem functions at increasing frequencies of climate related disturbances.

## c) Effects of water quality on octocorals, and on phototrophic and heterotrophic groups

Octocoral families and genera have repeatedly acquired and lost endosymbiotic dinoflagellates (zooxanthellae) throughout their evolutionary history (van Oppen et al. 2005), resulting in suites of closely related genera with and without zooxanthellae. Octocorals thus separate into two main functional groups: (1) taxa with photosynthetic endosymbionts (phototrophs) that have entered into symbiosis with zooxanthellae and use benthic irradiance for carbon fixation, and (2) taxa without endosymbionts (heterotrophs), that do not require light, but depend on water flow to carry picoplankton and other small suspended particulate food towards their tentacles (Fabricius et al. 1995). With increasing eutrophication, coral reefs are expected to shift from phototrophic to heterotrophic mode (Fabricius 2005). Phototrophic and heterotrophic octocorals, due to their contrasting resource requirements, represent an ideal model to assess changing water quality in this regard. Octocoral communities shift from phototrophic to heterotrophic taxa with increasing nutrient loads and decreasing water clarity (Fabricius and McCorry 2006). Other studies from around the Indo-Pacific (e.g., the Great Barrier Reef, Hong Kong and Palau) have also quantified the effects of water quality on the taxonomic richness of octocorals. The studies have shown that on the GBR, octocoral richness is reduced by 1 taxon with every meter reduction in horizontal visibility (Fabricius and De'ath 2001b) and that richness declines along short water quality gradients on inner shelf reefs of the GBR (Fabricius et al. 2005) and Palau (Fabricius et al. 2007c).

## d) Effects of water quality on outbreaks of crown-of-thorns starfish

The evidence underpinning the relationships between outbreaks of *A. planci* and water quality, especially concentrations of large phytoplankton that are food for the larvae of this sea star, have been reviewed in Brodie et al. (2005). The main finding is that under experimental conditions, the probability of full larval development increases 10-fold with every doubling of chlorophyll (Okaji 1996). Furthermore, an ecological model based on all existing life history data of COTS and coral, long-term chlorophyll and GBR connectivity data, shows how the frequency of outbreaks of crown-of-thorns starfish changes with altered lagoon chlorophyll concentrations (De'ath, in prep.). The model was first run at chlorophyll concentrations such as found off Cairns (0.8 µg $L^{-1}$), and tuned it so that the frequency of primary outbreaks matches that recorded off Cairns (one every 12 - 15 years). By running the models in water quality such as found at inner shelf Cape York reefs (0.4 µg $L^{-1}$), it was shown that outbreak frequencies are reduced to one every 50 - 80 years. The model is complex, but very robust to variations in life history parameters and other assumptions.

## e) Biotic trigger values

Similar to water quality trigger values, trigger values for biotic responses might be established. Based on the changes observed along the chlorophyll and Secchi depth gradients and this review, 'ecological reference conditions' indicative of good ecosystem status can be defined. Such definitions need a dedicated research project, however elements such as the ones listed here might be considered for inclusion:

- Averaged over all inner shelf reefs within each region and cross-shelf zone, mean coral cover recovers to >35% of hard substratum.
  Rationale: As in other parts around the world, average coral cover in the GBR has evidently declined over the past 20 years, and it is likely that this decline started even earlier. GBR coral cover was ~33% averaged over 104 surveys between 1968 and 1983, but has declined to an mean cover of 24% - 25% since 1984 (Bruno and Selig 2007; Sweatman et al., in prep). Crown-of-thorns starfish are the greatest cause of coral loss, followed by climate-change related bleaching (Sweatman et al., in prep). Adherence to water quality guidelines is therefore important to a) reduce the frequency of outbreaks of crown-of-thorns starfish, and b) maximize coral recruitment success to improve the likelihood of coral reef recovery from disturbances.
- Averaged over all inner shelf reefs within a region, mean macroalgal cover does not exceed that on the reference region in Cape York, after adjusting for natural latitudinal and cross-shelf differences (Fig 23).
  Rationale: Our analyses have shown that macroalgal cover of on the GBR increases with increasing chlorophyll and decreasing water clarity. To our knowledge, our analyses are the first to quantify the association between macroalgal cover and water quality on the GBR. Our findings are in agreement with other studies that either conclude causal links between macroalgal abundances and nutrient levels, or quantify these links (see above).
- Averaged over all inner shelf reefs within a region, coral diversity in the Wet Tropics Region increases to levels comparable to current values in the neighboring regions (Fig. 24).

- Averaged over all inner shelf reefs within a region, the density of coral recruits does not decline (as assessed through standardized monitoring programs) compared to present- reference values.
- The frequency of primary crown-of-thorns starfish outbreaks declines to a frequency of one every >30 years (a halving of present-day values).
  Rationale: according to existing models, outbreak frequencies would decline with a decline in chlorophyll levels
- Phototrophic reef communities do not shift to a dominance of heterotrophic filter feeders and heterotrophic foraminifera at anyone site.

Other measures that are presently less supported by available data may be considered due to their ecological relevance to maintain ecosystem health:

- Averaged across reefs within management zones, the maximum sizes, size distributions and biomass of targeted fish species do not decline.
- Algal blooms (including *Trichodesmium* blooms) do not increase in frequency and extent. Algal blooms have previously been defined as >5 µg $L^{-1}$ chlorophyll for temperate waters (Hallegraeff and Jeffrey 1993), however this values appears too high for GBR waters (only 3 of the 3856 GBR chlorophyll samples exceeded 5 µg $L^{-1}$). A value of >1.7 µg $L^{-1}$ (the $98^{th}$ percentile of chlorophyll samples) appears more appropriate to indicate algal blooms in the GBR.
- GBR waters remain free of toxic algal blooms.
- The extent of deep seagrass meadows does not shrink throughout the GBR.
- Epiphyte cover on intertidal and shallow subtidal seagrasses does not show a significant trend to increase over years at anyone site.

## Table A1. Published studies quantifying water quality effects on corals and other reef organisms

### a) Studies quantifying effect concentrations of particulate and dissolved nutrients

| | | | | | | |
|---|---|---|---|---|---|---|
| Lab experiment | 1 or 15 µM $NH_4$ and/or 0.3 or 1.2 µM $PO_4$ | Chronic (8 weeks) | Physiology | After 8 weeks, increased zooxanthellae density, increased chlorophyll and N per zooxanthella, | *Pocillopora damicornis* | Snidvongs and Kinzie 1994 |
| Lab experiment | 0, 1, 2, 5 µM $NO_3$ | Chronic (30 – 40 days) | Physiology | At ≥1 µM: calcification reduced by 50%, increased zooxanthellae density. At ≥5 µM $NO_3$: increased zooxanthellae size, chlorophyll per zooxanthellae, photosynthesis, greater zooxanthellae biomass. | *Porites porites and explants of Montastrea annularis* | Marubini and Davies 1996 |
| Lab experiment | 10 µM and 20 µM $NH_4$ | 9 weeks | Physiology | At 10 µM: unaltered buoyant weight gain, At 20 µM: 60% reduced buoyant weight gain in corals. | | Ferrier-Pages et al. 2000 |
| Lab experiment | 2 µM $NO_3$ | 3 weeks | Physiology | No change in zooxanthellae density or rate of photosynthesis, but -34% reduced buoyant weight gain | | Ferrier-Pages et al. 2001 |
| ENCORE experiment | 10 or 20 µM $NH_4$ | Chronic (1 year) | Physiology | 10 to 20% reduction, or no effect, or slight increase in coral growth. Reduced lipids. | | Koop et al. 2001 |
| Lab experiment | 15 µM $NO_3$ | Chronic (2 | Physiology | Reduced coral primary production, unaltered zooxanthellae density and | | Nordemar et al. 2003 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | weeks) | | chlorophyll concentrations. | | |
| Lab experiment | 2 μM $PO_4^{3-}$ | | Physiology | Increased coral photosynthesis, reduced calcification. | | Kinsey and Davies, 1979 |
| Lab experiment | 1.2 μM $PO_4^{3-}$ | | Physiology | Slowed coral calcification, unaltered zooxanthellae density, lower C and P per zooxanthella. | | Snidvongs and Kinzie 1994 |
| Lab experiment | 0, 0.2, 1, 5 μM $PO_4^{3-}$ | 30 days | Physiology | No change in coral photosynthesis, organic productivity, zooxanthellae density or size, tissue biomass; calcification reduced by up to 20% in one species, unaltered in another. | | Marubini and Davies 1996 |
| ENCORE experiment | 2 or 4 μM $PO_4^{3-}$ | 1 year | Physiology | Inconsistent effects on coral growth rates: increased calcification, linear extension and/or reduced skeletal density in some species. Increased lipids. | | Koop et al. 2001 |
| Lab experiment | 10 or 20 μM $NH_4$, and/or 2 μM $PO_4^{3-}$ | | Physiology | 60% reduction in coral growth, up to +150% increase in gross photosynthesis. | | Ferrier-Pages et al. 2000 |
| ENCORE experiment | 20 μM $NH_4$ plus 4 μM $PO_4^{3}$ | 1 year | Mortality | Increased coral mortality. | *Pocillopora damicornis* | Koop et al. 2001 |
| Field study | Increased | | Physiology | Increased linear extension | | Meyer and |

| | | | | | | |
|---|---|---|---|---|---|---|
| | particulate and dissolved nutrients from fish excretions | | | in coral. | | Schultz 1985 |
| | *Artemia* food | | Physiology | No effect on density of zooxanthellae. | | Muscatine et al. 1989 |
| Field study | Particulate and dissolved nutrients released from fish farm | Chronic | Physiology | In adult corals, increased growth, oocyte and testes numbers, unaltered survival. In coral fragments, reduced growth probably due to burial by settled particules and light reduction. | *Stylophora pistillata* | Bongiorni et al. 2003a; Bongiorni et al. 2003b |

## b) Studies quantifying the effects of exposure to sedimentation

| Method | Exposure concentration | Exposure duration | Endpoint | Effect concentration and response | Species | Reference |
|---|---|---|---|---|---|---|
| Field experiment with fine sand/ silt | 2 – 12 mg cm$^{-2}$ d$^{-1}$ | 8 months | Recruitment / Mortality | 30% reduction in settlement, 60% reduction in recruit survival. | *Acropora millepora* | Babcock and Smith 2002 |
| Lab experiment | 12 and 20 mg cm$^{-2}$ without TEP ('marine snow') | 43 h | Minor | 0% and 4% recruit mortality, respectively. | *Acropora willisae* | Fabricius et al. 2003 |
| Lab experiment | 12 and 20 mg cm$^{-2}$ d$^{-1}$ with TEP ('marine snow') | 43 h | Mortality | 33% and 98% recruit mortality, respectively. | *Acropora willisae* | Fabricius et al. 2003 |
| Lab experiments | 3 mg cm$^{-2}$ d$^{-1}$ | 2 days | Recruitment | ~84% reduction in recruitment on upper surfaces. | *Acropora millepora* | Babcock and Davies 1991 |

| Method | Exposure concentration | Exposure duration | Endpoint | Effect concentration and response | Species | Reference |
|---|---|---|---|---|---|---|
| Lab experiments | 8 mg $cm^{-2}$ $d^{-1}$ | 2 days | Recruitment | ~96% reduction in recruitment on upper surfaces. | *Acropora millepora* | Babcock and Davies 1991 |
| Literature review, recommendation of <10 mg $cm^{-2}$ $d^{-1}$ as sedimentation threshold for healthy reefs | >10 mg $cm^{-2}$ $d^{-1}$ | Long-term | Mortality / Community | Reduction in coral species richness, coral cover, coral growth rates, calcification, net productivity of corals, and reef accretion; increased proportion of branching forms. Species-specific capability for particle rejection and survival at lower light. | *(coral reefs)* | Rogers 1990 |
| Terrestrial runoff/ resuspension of sand/ fine mud | 0.3 – 64 mg $cm^{-2}$ $d^{-1}$ | | Mortality | Partial mortality: sediment smothering caused significant tissue mortality at deep depths. | *Siderastrea sidera* | Nugues and Roberts 2003 |
| Terrestrial runoff/ resuspension of sand/ fine mud | 0.3 – 64 mg $cm^{-2}$ $d^{-1}$ | | Mortality | Injury and partial mortality: significant mortality at deep depth at 1 site, no differences between depths elsewhere. | *Colpophyllia natans* | Nugues and Roberts 2003 |
| Lab experiments | 33, 66, 100, 133 mg DW $cm^{-2}$ with silt sized sediments and varying nutrient contents. | 12, 20, 36 and 44 h of exposure | Physiological / mortality | Stress: decreased *Fv/F*m, and partial mortality. Severity of effect increased with the amount of organic contents, and with amount and duration of exposure. | *Montipora peltiformis* | Weber et al., 2006 |
| Lab experiment with fine grained sediment | 79 – 234 mg $cm^{-2}$ $d^{-1}$ | Up to 40 h | Physiological / mortality | Severity of effect increased from photophysiological stress to partial mortality with increasing amount and duration of exposure. | *Montipora peltiformis* | Philipp and Fabricius 2003 |
| Field experiment | 200 mg $cm^{-2}$ | One | No effect | No effect. | *Diploria stringosa* | Rogers 1983 |

| Method | Exposure concentration | Exposure duration | Endpoint | Effect concentration and response | Species | Reference |
|---|---|---|---|---|---|---|
| with bottom sand | | application | | | *Montastrea annularis* | |
| Field experiment with bottom sand | 200 mg $cm^{-2}$ | One application | Mortality | Partial mortality. | *Acropora palmata* | Rogers 1983 |
| Dredging | 200 – 300 mg $cm^{-2}$ $d^{-1}$ | Days to weeks | Physiological | Stress: decreased growth. | *Acropora formosa* | Simpson 1988 |
| Lab experiment | 50 – 200 mg $cm^{-2}$ of 70/30% calcium carbonate/ quartz sediment at <63 µm to 1 – 3 mm particle sizes | 6 days | Physiological | Effects depended on species, turbulence and grain size, ranging from no effect to tissue bleaching. | 42 species | Stafford-Smith and Ormond 1992; Stafford-Smith 1993 |
| Lab experiment with carbonate sand | 200 mg $cm^{-2}$ $d^{-1}$ | Days | Mortality | Partial mortality: tissue necrosis. | Scleractinia and Alcyonacea | Riegl 1995 |
| Lab experiment with bottom sand | 430 mg $cm^{-2}$ $d^{-1}$ | >24 hr | Physiological | Stress: reduced horizontal growth. | *Acropora palmata, Acropora cervicornis, Porites astreoides, Agaricia agaricites* | Bak 1976 |
| Field experiment with bottom sediment | 600 mg $cm^{-2}$ $d^{-1}$ | | Physiological | Stress: decreased production, increased respiration. | *Acropora palmata Montastrea annularis Diploria stringosa* | Abdel-Salam et al. 1988 |
| Field experiment with bottom sand | 800 mg $cm^{-2}$ $d^{-1}$ | One application? | Mortality | Partial mortality. | *Montastrea annularis* | Rogers 1983 |

## c) Studies quantifying the effects of turbidity and shading

| Method | Exposure concentration | Exposure duration | Endpoint | Effect concentration and response | Species | Reference |
|---|---|---|---|---|---|---|
| SPM | 4 – 7 mg $l^{-1}$ | Chronic | Physiological | Increased linear extension at moderate SPM, decreased linear extension at high SPM. | *Montastrea annularis* | Tomascik and Sander 1985 |
| SPM | 1 – 30 mg $l^{-1}$ | Hours | Physiological | Inner shelf colonies: SPM feeding capacity increases at high SPM concentrations, this capacity covers approx. 50% carbon and 30% nitrogen required for tissue growth. | *Porites cylindrica, Pocillopora damicornis, Montipora digitata, Acropora millepora* | Anthony 1999 |
| SPM | 1 – 30 mg $l^{-1}$ | Days | Physiological | Inner shelf species more heterotrophic compared with conspecifics from less turbid, inner shelf reefs. | *Acropora millepora Pocillopora damicornis* | Anthony 2000 |
| SPM/Shading | 0, 1, 4, 16 mg $l^{-1}$ SS,<br>30% and 100% of irradiance at 3 m depth | 2 months | Physiological | Sediment feeding compensated fully for the 35–47% lower phototrophy in the shaded treatment, but skeletal growth slightly reduced at 30% irradiance. | *Goniastrea retiformis* | Anthony and Fabricius 2000 |
| SPM/Shading | 0, 1, 4, 16 mg $l^{-1}$ SS,<br>30% and 100% of irradiance at 3 m depth | 2 months | Physiological | Skeletal growth slightly reduced at 30% irradiance, tissue biomass greatly reduced at 30% irradiance and 16 mg $L^{-1}$ SPM. | *Porites cylindrica* | Anthony and Fabricius 2000 |
| Terrestrial runoff, recommendation of <10 mg $L^{-1}$ $d^{-1}$ as threshold for healthy reefs | > 10 mg $l^{-1}$ | Years | Community | Stress: reduced coral cover, species diversity, net productivity and reef accretion, more branching corals. | (Literature review) | Rogers 1990 |

| Method | Exposure concentration | Exposure duration | Endpoint | Effect concentration and response | Species | Reference |
|---|---|---|---|---|---|---|
| Lab experiment | > 50 mg $l^{-1}$ | Days | Reproduction / Mortality | Reduced fertilisation, larval survival and settlement | *Acropora* | Gilmour 1999 |
| Dredging inner shelf Pilbara | 20 – 70 mg $l^{-1}$ | Weeks | Mortality | Stress: 80% mortality. | Coral community | Stoddart and Anstee 2005 |
| SPM/Marine snow | 170 mg $l^{-1}$ | Hours | Physiological | Mucus production in response to increases in the rates and size (200 - 2000 µm diameter) of flocs of marine snow. | *Acropora* spp. | Fabricius and Wolanski 2000 |
| Dredging | Up to 286 mg $l^{-1}$ | Months | Community | Reduced coral cover, species diversity. | Coral community | Brown et al. 1990 |
| Drilling mud | 1 ppm | | No effect | No effect. | *Montastrea annularis* | Szmant-Froelich et al. 1981 |
| Drilling mud | 10 ppm | | Physiological | Stress: decreased calcification. | *Montastrea annularis* | Szmant-Froelich et al. 1981 |
| Drilling mud | 100 ppm | | Physiological/ mortality | Bleaching, decreased calcification, respiration and feeding, partial mortality, and some whole-colony mortality. | *Montastrea annularis* | Szmant-Froelich et al. 1981 |
| Turbidity | 0 – 2 NTU | Weeks | Physiological | No effect on P:R ratio. | *Meandrina meandrites, Dichocoenia stokesii* | Telesnicki and Goldberg 1995 |
| Turbidity | 7 – 9 NTU | Weeks | Physiological | No effect on P:R ratio. | *Meandrina meandrites, Dichocoenia stokesii* | Telesnicki and Goldberg 1995 |
| Turbidity | 14 – 16 NTU | Weeks | Physiological | Mucus production, P:R ratio <1 after 6 days exposure. | *Meandrina meandrites,* | Telesnicki and Goldberg 1995 |

| Method | Exposure concentration | Exposure duration | Endpoint | Effect concentration and response | Species | Reference |
|---|---|---|---|---|---|---|
| | | | | | *Dichocoenia stokesii* | |
| Turbidity | 28 – 30 NTU | Weeks | Physiological | Mucus production, P:R ratio <1 after 3 days exposure. | *Meandrina meandrites, Dichocoenia stokesii* | Telesnicki and Goldberg 1995 |
| Turbidity, recommendation of <4.5 NTU as threshold for healthy reefs | 3 NTU | Chronic | Physiological | Saturation irradiance reached at 3 m depth. | *Pocillopora damicornis* | T. Cooper, submitted |
| Turbidity | <8% surface irradiance | Chronic | Community | Lower edge of reef development, transition from phototrophic to heterotrophic community. | Coral reefs in the Whitsundays | Cooper et al. 2007 |
| | 2 - 8% surface irradiance | Chronic | Community | Lowest distribution limit for corals; few species and growth forms found at such low light. | Coral communities in South China Sea; | Titlyanov and Latypov 1991 |
| | Shading, simulating extreme turbidity | 5 weeks | Mortality | Reduced coral growth, net primary productivity, respiration. Bleaching and death in several species leads to altered community structure. | *Acropora cervicornis,* coral community | Rogers 1979 |
| | Shading (equivalent to 10 – 13 m depth) | Chronic | Reproduction | Reduced fecundity and recruitment at low light. | *Favia fragum* | Carlon 2002 |
| | Shading | | | Species-specific effects on settlement and metamorphosis. | | Babcock and Mundy 1996; Mundy and Babcock 1998 |

## *Appendix 2: Mean annual values of nutrients (µg $L^{-1}$), predicted across the 6 regions and 3 cross-shelf positions*

(See Table 2 for molar concentrations).

| | **Coastal** | | **Inner shelf** | | **Offshore** | | **Across all zones** | |
|---|---|---|---|---|---|---|---|---|
| | mean | SE | **mean** | SE | **mean** | SE | **mean** | SE |
| **(d) PN (µg $L^{-1}$)** | | | | | | | | |
| GBR Mean | **27.02** | 1.79 | **22.82** | 1.51 | **17.16** | 1.76 | **20.89** | 0.28 |
| Burnett Mary | **27.47** | 3.89 | **22.48** | 3.67 | **10.82** | 2.38 | **13.26** | 2.62 |
| Fitzroy | **27.58** | 2.23 | **25.72** | 2.06 | **15.57** | 1.64 | **19.24** | 1.79 |
| Mackay W | **24.19** | 1.55 | **21.63** | 1.39 | **17.04** | 1.55 | **19.24** | 1.51 |
| Burdekin | **36.81** | 2.09 | **26.40** | 1.40 | **18.90** | 1.79 | **22.90** | 1.72 |
| Wet Tropics | **31.67** | 1.19 | **20.44** | 0.84 | **14.49** | 1.02 | **17.37** | 1.02 |
| Cape York | **20.92** | 1.40 | **20.73** | 1.32 | **21.28** | 2.35 | **20.51** | 1.92 |
| **(e) PP (µg $L^{-1}$)** | | | | | | | | |
| GBR Mean | **3.596** | 0.279 | **2.511** | 0.217 | **1.922** | 0.248 | **2.945** | 0.062 |
| Burnett Mary | **3.689** | 0.651 | **2.976** | 0.558 | **1.705** | 0.434 | **1.984** | 0.465 |
| Fitzroy | **2.852** | 0.310 | **2.325** | 0.248 | **1.736** | 0.217 | **1.984** | 0.248 |
| Mackay W | **3.348** | 0.248 | **2.294** | 0.186 | **1.922** | 0.217 | **2.201** | 0.217 |
| Burdekin | **5.518** | 0.341 | **3.193** | 0.186 | **2.108** | 0.248 | **2.790** | 0.248 |
| Wet Tropics | **4.991** | 0.186 | **2.604** | 0.124 | **1.984** | 0.155 | **2.356** | 0.155 |
| Cape York | **2.790** | 0.217 | **2.480** | 0.186 | **2.170** | 0.310 | **2.263** | 0.248 |
| **(f) TDN (µg $L^{-1}$)** | | | | | | | | |
| GBR Mean | **85.51** | 4.76 | **78.58** | 3.91 | **70.06** | 4.09 | **74.13** | 4.26 |
| Burnett Mary | **69.68** | 8.18 | **67.61** | 6.40 | **66.36** | 4.93 | **66.75** | 5.49 |
| Fitzroy | **75.26** | 6.26 | **71.82** | 4.93 | **67.42** | 3.47 | **69.29** | 4.10 |
| Mackay W | **80.70** | 4.24 | **79.55** | 3.98 | **71.97** | 3.72 | **75.21** | 3.86 |
| Burdekin | **93.66** | 4.27 | **81.77** | 3.49 | **68.92** | 4.17 | **75.15** | 4.02 |
| Wet Tropics | **106.65** | 3.12 | **90.31** | 2.69 | **75.33** | 3.70 | **81.37** | 3.54 |
| Cape York | **85.76** | 4.17 | **77.50** | 3.54 | **71.40** | 5.38 | **74.54** | 4.76 |
| **(g) TDP (µg $L^{-1}$)** | | | | | | | | |
| GBR Mean | **10.881** | 1.302 | **8.711** | 0.961 | **5.921** | 0.837 | **7.254** | 1.023 |
| Burnett Mary | **8.649** | 1.984 | **7.874** | 1.519 | **7.688** | 1.333 | **7.781** | 1.457 |
| Fitzroy | **11.687** | 1.767 | **9.734** | 1.302 | **6.944** | 0.868 | **8.091** | 1.054 |
| Mackay W | **11.098** | 1.271 | **10.137** | 1.116 | **6.293** | 0.837 | **7.998** | 0.961 |
| Burdekin | **12.059** | 1.209 | **10.075** | 0.961 | **5.549** | 0.837 | **7.502** | 0.899 |
| Wet Tropics | **10.695** | 0.682 | **8.494** | 0.589 | **6.076** | 0.744 | **6.975** | 0.713 |
| Cape York | **8.649** | 0.961 | **5.921** | 0.682 | **3.720** | 0.775 | **4.929** | 0.775 |

(Appendix 2, cont.)

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **(h) TN (µg $L^{-1}$)** | | | | | | | | |
| GBR Mean | **109.47** | 6.62 | **102.44** | 5.82 | **97.51** | 8.08 | **100.21** | 6.85 |
| | | | | | | | | |
| Burnett Mary | **83.36** | 11.55 | **82.46** | 11.79 | **78.02** | 13.12 | **78.48** | 12.88 |
| Fitzroy | **96.32** | 8.23 | **99.16** | 7.62 | **95.59** | 7.69 | **96.53** | 7.71 |
| Mackay W | **102.58** | 6.10 | **103.61** | 5.88 | **103.26** | 7.56 | **103.26** | 6.90 |
| Burdekin | **122.07** | 6.45 | **104.10** | 5.05 | **101.30** | 8.44 | **104.33** | 7.34 |
| Wet Tropics | **139.59** | 4.59 | **114.37** | 3.92 | **95.33** | 5.57 | **103.39** | 5.25 |
| Cape York | **109.09** | 5.80 | **99.11** | 4.96 | **97.48** | 9.13 | **98.69** | 7.70 |
| | | | | | | | | |
| **(i) TP (µg $L^{-1}$)** | | | | | | | | |
| GBR Mean | **15.159** | 1.798 | **11.656** | 1.333 | **9.207** | 1.674 | **10.540** | 1.612 |
| | | | | | | | | |
| Burnett Mary | **14.601** | 3.503 | **13.082** | 3.348 | **8.401** | 2.759 | **9.300** | 2.883 |
| Fitzroy | **14.229** | 2.170 | **12.958** | 1.829 | **9.052** | 1.581 | **10.509** | 1.705 |
| Mackay W | **15.004** | 1.736 | **12.989** | 1.457 | **11.470** | 1.798 | **12.338** | 1.705 |
| Burdekin | **18.135** | 1.798 | **14.260** | 1.333 | **10.168** | 1.829 | **12.121** | 1.674 |
| Wet Tropics | **16.058** | 1.054 | **11.501** | 0.837 | **8.091** | 1.085 | **9.579** | 1.023 |
| Cape York | **13.206** | 1.488 | **7.657** | 0.837 | **7.285** | 1.643 | **8.308** | 1.488 |

## *Appendix 3: Mean water quality values for the summer and winter quarters in the GBR*

Table A3a: Predicted values of chlorophyll (µg $L^{-1}$), SS (mg $L^{-1}$), PN, PP, TDN, TDP, TN and TP **(µmol $L^{-1}$).** across all regions and zones (Fig. 18). 1Q = Summer (January – March), 3Q = Winter (July – September). C = Coastal (≤0.1 across); I = inner shelf (0.1 - 0.4 across); O = offshore (>0.4 – 1.3 across). hi, lo = upper and lower 95% confidence intervals.

| Season | Shelf | Region | chltot | chltot.hi | chltot.lo | SS | ss.hi | ss.lo | PN | pn.hi | pn.lo | TDN | tdn.hi | tdn.lo |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1Q | C | Fitzroy | **1.40** | 1.71 | 1.14 | **2.21** | 4.24 | 1.15 | **2.64** | 3.22 | 2.17 | **7.50** | 10.56 | 5.33 |
| 3Q | C | Fitzroy | **0.32** | 0.58 | 0.17 | **3.30** | 6.87 | 1.58 | **1.00** | 1.62 | 0.62 | **4.34** | 6.41 | 2.94 |
| 1Q | I | Fitzroy | **0.73** | 0.99 | 0.54 | **1.47** | 3.35 | 0.64 | **1.49** | 1.99 | 1.12 | **5.45** | 8.14 | 3.65 |
| 3Q | I | Fitzroy | **0.35** | 0.60 | 0.20 | **2.17** | 5.36 | 0.88 | **0.90** | 1.45 | 0.55 | **4.78** | 6.78 | 3.37 |
| 1Q | O | Fitzroy | **0.46** | 0.58 | 0.36 | **0.72** | 1.73 | 0.30 | **0.99** | 1.24 | 0.79 | **6.20** | 7.38 | 5.21 |
| 3Q | O | Fitzroy | **0.50** | 0.62 | 0.41 | **0.55** | 1.34 | 0.23 | **0.96** | 1.20 | 0.77 | **5.22** | 6.07 | 4.49 |
| 1Q | C | Mackay W | **1.00** | 1.15 | 0.88 | **4.17** | 5.58 | 3.11 | **2.41** | 2.77 | 2.09 | **5.61** | 6.61 | 4.76 |
| 3Q | C | Mackay W | **0.40** | 0.53 | 0.30 | **2.46** | 3.92 | 1.54 | **1.11** | 1.39 | 0.88 | **5.60** | 6.69 | 4.69 |
| 1Q | I | Mackay W | **0.65** | 0.74 | 0.58 | **1.86** | 2.51 | 1.38 | **1.93** | 2.21 | 1.69 | **5.21** | 5.81 | 4.67 |
| 3Q | I | Mackay W | **0.32** | 0.42 | 0.24 | **1.72** | 2.84 | 1.04 | **1.06** | 1.30 | 0.87 | **4.69** | 5.58 | 3.94 |
| 1Q | O | Mackay W | **0.62** | 0.70 | 0.56 | **0.71** | 1.07 | 0.47 | **1.17** | 1.41 | 0.97 | **4.51** | 4.96 | 4.10 |
| 3Q | O | Mackay W | **0.37** | 0.54 | 0.25 | **0.96** | 2.86 | 0.32 | **0.90** | 1.28 | 0.64 | **5.28** | 6.84 | 4.08 |
| 1Q | C | Burdekin | **1.39** | 1.68 | 1.15 | **4.68** | 7.01 | 3.13 | **3.95** | 5.04 | 3.10 | **5.25** | 7.48 | 3.68 |
| 3Q | C | Burdekin | **0.67** | 0.91 | 0.49 | **3.49** | 6.18 | 1.97 | **1.81** | 2.66 | 1.23 | **5.81** | 7.42 | 4.54 |
| 1Q | I | Burdekin | **0.79** | 0.90 | 0.70 | **4.24** | 5.23 | 3.44 | **2.01** | 2.30 | 1.76 | **4.92** | 5.70 | 4.25 |
| 3Q | I | Burdekin | **0.28** | 0.36 | 0.21 | **2.08** | 3.17 | 1.36 | **1.49** | 1.88 | 1.19 | **5.28** | 6.08 | 4.59 |
| 1Q | O | Burdekin | **0.34** | 0.52 | 0.22 | **2.22** | 4.44 | 1.11 | **1.43** | 1.94 | 1.06 | **4.99** | 6.63 | 3.75 |
| 3Q | O | Burdekin | **0.18** | 0.29 | 0.12 | **0.70** | 1.86 | 0.26 | **1.08** | 2.08 | 0.56 | **5.13** | 6.31 | 4.17 |
| 1Q | C | Wet Tropics | **0.77** | 0.82 | 0.72 | **5.66** | 6.32 | 5.06 | **2.27** | 2.42 | 2.13 | **8.63** | 9.09 | 8.19 |
| 3Q | C | Wet Tropics | **0.41** | 0.47 | 0.35 | **3.49** | 4.36 | 2.80 | **1.53** | 1.73 | 1.35 | **5.67** | 6.22 | 5.17 |
| 1Q | I | Wet Tropics | **0.53** | 0.57 | 0.49 | **1.92** | 2.35 | 1.57 | **1.75** | 1.88 | 1.62 | **7.00** | 7.41 | 6.62 |
| 3Q | I | Wet Tropics | **0.26** | 0.30 | 0.22 | **1.67** | 2.25 | 1.24 | **1.13** | 1.27 | 1.00 | **5.80** | 6.26 | 5.37 |
| 1Q | O | Wet Tropics | **0.43** | 0.49 | 0.37 | **0.84** | 1.36 | 0.52 | **1.15** | 1.37 | 0.97 | **5.25** | 5.80 | 4.74 |
| 3Q | O | Wet Tropics | **0.23** | 0.30 | 0.18 | **0.56** | 1.31 | 0.24 | **0.73** | 0.91 | 0.59 | **6.65** | 7.46 | 5.93 |
| 1Q | C | Cape York | **0.63** | 0.72 | 0.56 | **1.68** | 2.36 | 1.20 | **1.60** | 1.82 | 1.40 | **6.59** | 7.26 | 5.98 |
| 3Q | C | Cape York | **0.29** | 0.38 | 0.22 | **2.62** | 4.08 | 1.68 | **1.29** | 1.59 | 1.04 | **5.65** | 6.55 | 4.86 |
| 1Q | I | Cape York | **0.43** | 0.47 | 0.39 | **1.61** | 2.04 | 1.27 | **1.38** | 1.50 | 1.26 | **6.73** | 7.15 | 6.33 |
| 3Q | I | Cape York | **0.24** | 0.30 | 0.20 | **2.52** | 3.56 | 1.78 | **1.40** | 1.59 | 1.23 | **5.74** | 6.32 | 5.21 |
| 1Q | O | Cape York | **0.57** | 0.66 | 0.50 | **0.92** | 1.59 | 0.53 | **1.70** | 1.96 | 1.47 | **5.28** | 5.98 | 4.66 |
| 3Q | O | Cape York | **0.23** | 0.34 | 0.15 | **0.88** | 2.15 | 0.36 | **0.73** | 1.50 | 0.36 | **4.53** | 5.73 | 3.58 |

Table Appendix 3a (cont).

| Season | Shelf | Region | PP | pp.hi | pp.lo | TDP | tdp.hi | tdp.lo | TN | totn.hi | totn.lo | TP | totp.hi | totp.lo |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1Q | C | Fitzroy | **0.114** | 0.152 | 0.085 | **0.097** | 0.330 | 0.029 | **8.91** | 12.24 | 6.49 | **0.234** | 0.486 | 0.113 |
| 3Q | C | Fitzroy | **0.057** | 0.106 | 0.031 | **0.593** | 1.058 | 0.332 | **5.34** | 7.62 | 3.74 | **0.650** | 1.087 | 0.389 |
| 1Q | I | Fitzroy | **0.087** | 0.124 | 0.061 | **0.175** | 0.548 | 0.056 | **6.92** | 9.92 | 4.83 | **0.284** | 0.653 | 0.124 |
| 3Q | I | Fitzroy | **0.057** | 0.102 | 0.032 | **0.571** | 0.997 | 0.327 | **5.67** | 7.85 | 4.10 | **0.628** | 1.029 | 0.384 |
| 1Q | O | Fitzroy | **0.055** | 0.075 | 0.040 | **0.171** | 0.305 | 0.096 | **7.08** | 8.35 | 6.00 | **0.223** | 0.356 | 0.139 |
| 3Q | O | Fitzroy | **0.059** | 0.077 | 0.045 | **0.241** | 0.355 | 0.163 | **6.17** | 7.16 | 5.33 | **0.296** | 0.413 | 0.212 |
| 1Q | C | Mackay W | **0.156** | 0.184 | 0.132 | **0.233** | 0.361 | 0.151 | **7.64** | 9.06 | 6.43 | **0.418** | 0.582 | 0.300 |
| 3Q | C | Mackay W | **0.072** | 0.096 | 0.055 | **0.438** | 0.621 | 0.309 | **6.65** | 7.84 | 5.64 | **0.510** | 0.689 | 0.378 |
| 1Q | I | Mackay W | **0.109** | 0.130 | 0.092 | **0.189** | 0.263 | 0.137 | **7.31** | 8.49 | 6.30 | **0.362** | 0.495 | 0.265 |
| 3Q | I | Mackay W | **0.057** | 0.076 | 0.043 | **0.330** | 0.474 | 0.230 | **5.75** | 6.74 | 4.91 | **0.387** | 0.528 | 0.284 |
| 1Q | O | Mackay W | **0.073** | 0.093 | 0.058 | **0.151** | 0.211 | 0.108 | **5.92** | 6.88 | 5.09 | **0.269** | 0.386 | 0.187 |
| 3Q | O | Mackay W | **0.049** | 0.080 | 0.030 | **0.353** | 0.611 | 0.204 | **6.19** | 7.88 | 4.87 | **0.402** | 0.649 | 0.250 |
| 1Q | C | Burdekin | **0.273** | 0.362 | 0.206 | **0.149** | 0.382 | 0.058 | **7.63** | 12.39 | 4.70 | **0.487** | 0.919 | 0.258 |
| 3Q | C | Burdekin | **0.131** | 0.197 | 0.087 | **0.478** | 0.766 | 0.298 | **7.59** | 10.44 | 5.52 | **0.858** | 1.342 | 0.548 |
| 1Q | I | Burdekin | **0.108** | 0.129 | 0.090 | **0.322** | 0.437 | 0.237 | **6.83** | 7.80 | 5.99 | **0.463** | 0.597 | 0.359 |
| 3Q | I | Burdekin | **0.086** | 0.112 | 0.066 | **0.300** | 0.415 | 0.216 | **7.02** | 8.40 | 5.87 | **0.401** | 0.569 | 0.282 |
| 1Q | O | Burdekin | **0.090** | 0.130 | 0.062 | **0.303** | 0.559 | 0.164 | **6.48** | 8.34 | 5.03 | **0.406** | 0.677 | 0.244 |
| 3Q | O | Burdekin | **0.048** | 0.123 | 0.018 | **0.313** | 0.496 | 0.197 | **6.08** | 9.74 | 3.80 | **0.584** | 1.259 | 0.271 |
| 1Q | C | Wet Tropics | **0.171** | 0.183 | 0.159 | **0.345** | 0.398 | 0.299 | **11.34** | 11.93 | 10.78 | **0.543** | 0.610 | 0.483 |
| 3Q | C | Wet Tropics | **0.132** | 0.151 | 0.116 | **0.327** | 0.404 | 0.265 | **7.11** | 7.83 | 6.45 | **0.463** | 0.567 | 0.378 |
| 1Q | I | Wet Tropics | **0.104** | 0.114 | 0.095 | **0.247** | 0.291 | 0.209 | **9.16** | 9.70 | 8.65 | **0.378** | 0.435 | 0.328 |
| 3Q | I | Wet Tropics | **0.069** | 0.080 | 0.060 | **0.305** | 0.366 | 0.254 | **6.99** | 7.59 | 6.44 | **0.382** | 0.453 | 0.321 |
| 1Q | O | Wet Tropics | **0.082** | 0.100 | 0.067 | **0.181** | 0.242 | 0.135 | **7.19** | 8.18 | 6.32 | **0.292** | 0.405 | 0.210 |
| 3Q | O | Wet Tropics | **0.060** | 0.076 | 0.048 | **0.208** | 0.298 | 0.145 | **7.72** | 8.73 | 6.83 | **0.230** | 0.330 | 0.161 |
| 1Q | C | Cape York | **0.112** | 0.129 | 0.097 | **0.322** | 0.409 | 0.254 | **8.39** | 9.28 | 7.59 | **0.459** | 0.559 | 0.377 |
| 3Q | C | Cape York | **0.073** | 0.095 | 0.055 | **0.264** | 0.386 | 0.181 | **7.14** | 8.31 | 6.14 | **0.335** | 0.476 | 0.235 |
| 1Q | I | Cape York | **0.081** | 0.090 | 0.073 | **0.249** | 0.296 | 0.209 | **8.19** | 8.70 | 7.71 | **0.332** | 0.385 | 0.286 |
| 3Q | I | Cape York | **0.066** | 0.078 | 0.055 | **0.322** | 0.404 | 0.257 | **7.18** | 7.93 | 6.50 | **0.386** | 0.477 | 0.313 |
| 1Q | O | Cape York | **0.080** | 0.097 | 0.066 | **0.189** | 0.271 | 0.131 | **7.05** | 7.96 | 6.24 | **0.272** | 0.365 | 0.202 |
| 3Q | O | Cape York | **0.027** | 0.084 | 0.009 | **0.095** | 0.232 | 0.039 | **6.55** | 11.05 | 3.88 | **0.247** | 0.965 | 0.063 |

b) As Table Appendix 3a, but all nutrients presented in in **μg L$^{-1}$**.

| Season | Shelf | Region | chltot | chltot.hi | chltot.lo | SS | ss.hi | ss.lo | PN | pn.hi | pn.lo | TDN | tdn.hi | tdn.lo |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1Q | C | Fitzroy | **1.40** | 1.71 | 1.14 | **2.21** | 4.24 | 1.15 | **37.0** | 45.1 | 30.4 | **105.0** | 147.8 | 74.6 |
| 3Q | C | Fitzroy | **0.32** | 0.58 | 0.17 | **3.30** | 6.87 | 1.58 | **14.0** | 22.7 | 8.7 | **60.8** | 89.7 | 41.2 |
| 1Q | I | Fitzroy | **0.73** | 0.99 | 0.54 | **1.47** | 3.35 | 0.64 | **20.9** | 27.9 | 15.7 | **76.3** | 114.0 | 51.1 |
| 3Q | I | Fitzroy | **0.35** | 0.60 | 0.20 | **2.17** | 5.36 | 0.88 | **12.6** | 20.3 | 7.7 | **66.9** | 94.9 | 47.2 |
| 1Q | O | Fitzroy | **0.46** | 0.58 | 0.36 | **0.72** | 1.73 | 0.30 | **13.9** | 17.4 | 11.1 | **86.8** | 103.3 | 72.9 |
| 3Q | O | Fitzroy | **0.50** | 0.62 | 0.41 | **0.55** | 1.34 | 0.23 | **13.4** | 16.8 | 10.8 | **73.1** | 85.0 | 62.9 |
| 1Q | C | Mackay W | **1.00** | 1.15 | 0.88 | **4.17** | 5.58 | 3.11 | **33.7** | 38.8 | 29.3 | **78.5** | 92.5 | 66.6 |
| 3Q | C | Mackay W | **0.40** | 0.53 | 0.30 | **2.46** | 3.92 | 1.54 | **15.5** | 19.5 | 12.3 | **78.4** | 93.7 | 65.7 |
| 1Q | I | Mackay W | **0.65** | 0.74 | 0.58 | **1.86** | 2.51 | 1.38 | **27.0** | 30.9 | 23.7 | **72.9** | 81.3 | 65.4 |
| 3Q | I | Mackay W | **0.32** | 0.42 | 0.24 | **1.72** | 2.84 | 1.04 | **14.8** | 18.2 | 12.2 | **65.7** | 78.1 | 55.2 |
| 1Q | O | Mackay W | **0.62** | 0.70 | 0.56 | **0.71** | 1.07 | 0.47 | **16.4** | 19.7 | 13.6 | **63.1** | 69.4 | 57.4 |
| 3Q | O | Mackay W | **0.37** | 0.54 | 0.25 | **0.96** | 2.86 | 0.32 | **12.6** | 17.9 | 9.0 | **73.9** | 95.8 | 57.1 |
| 1Q | C | Burdekin | **1.39** | 1.68 | 1.15 | **4.68** | 7.01 | 3.13 | **55.3** | 70.6 | 43.4 | **73.5** | 104.7 | 51.5 |
| 3Q | C | Burdekin | **0.67** | 0.91 | 0.49 | **3.49** | 6.18 | 1.97 | **25.3** | 37.2 | 17.2 | **81.3** | 103.9 | 63.6 |
| 1Q | I | Burdekin | **0.79** | 0.90 | 0.70 | **4.24** | 5.23 | 3.44 | **28.1** | 32.2 | 24.6 | **68.9** | 79.8 | 59.5 |
| 3Q | I | Burdekin | **0.28** | 0.36 | 0.21 | **2.08** | 3.17 | 1.36 | **20.9** | 26.3 | 16.7 | **73.9** | 85.1 | 64.3 |
| 1Q | O | Burdekin | **0.34** | 0.52 | 0.22 | **2.22** | 4.44 | 1.11 | **20.0** | 27.2 | 14.8 | **69.9** | 92.8 | 52.5 |
| 3Q | O | Burdekin | **0.18** | 0.29 | 0.12 | **0.70** | 1.86 | 0.26 | **15.1** | 29.1 | 7.8 | **71.8** | 88.3 | 58.4 |
| 1Q | C | Wet Tropics | **0.77** | 0.82 | 0.72 | **5.66** | 6.32 | 5.06 | **31.8** | 33.9 | 29.8 | **120.8** | 127.3 | 114.7 |
| 3Q | C | Wet Tropics | **0.41** | 0.47 | 0.35 | **3.49** | 4.36 | 2.80 | **21.4** | 24.2 | 18.9 | **79.4** | 87.1 | 72.4 |
| 1Q | I | Wet Tropics | **0.53** | 0.57 | 0.49 | **1.92** | 2.35 | 1.57 | **24.5** | 26.3 | 22.7 | **98.0** | 103.7 | 92.7 |
| 3Q | I | Wet Tropics | **0.26** | 0.30 | 0.22 | **1.67** | 2.25 | 1.24 | **15.8** | 17.8 | 14.0 | **81.2** | 87.6 | 75.2 |
| 1Q | O | Wet Tropics | **0.43** | 0.49 | 0.37 | **0.84** | 1.36 | 0.52 | **16.1** | 19.2 | 13.6 | **73.5** | 81.2 | 66.4 |
| 3Q | O | Wet Tropics | **0.23** | 0.30 | 0.18 | **0.56** | 1.31 | 0.24 | **10.2** | 12.7 | 8.3 | **93.1** | 104.4 | 83.0 |
| 1Q | C | Cape York | **0.63** | 0.72 | 0.56 | **1.68** | 2.36 | 1.20 | **22.4** | 25.5 | 19.6 | **92.3** | 101.6 | 83.7 |
| 3Q | C | Cape York | **0.29** | 0.38 | 0.22 | **2.62** | 4.08 | 1.68 | **18.1** | 22.3 | 14.6 | **79.1** | 91.7 | 68.0 |
| 1Q | I | Cape York | **0.43** | 0.47 | 0.39 | **1.61** | 2.04 | 1.27 | **19.3** | 21.0 | 17.6 | **94.2** | 100.1 | 88.6 |
| 3Q | I | Cape York | **0.24** | 0.30 | 0.20 | **2.52** | 3.56 | 1.78 | **19.6** | 22.3 | 17.2 | **80.4** | 88.5 | 72.9 |
| 1Q | O | Cape York | **0.57** | 0.66 | 0.50 | **0.92** | 1.59 | 0.53 | **23.8** | 27.4 | 20.6 | **73.9** | 83.7 | 65.2 |
| 3Q | O | Cape York | **0.23** | 0.34 | 0.15 | **0.88** | 2.15 | 0.36 | **10.2** | 21.0 | 5.0 | **63.4** | 80.2 | 50.1 |

Table Appendix 3b (cont).

| Season | Shelf | Region | PP | pp.hi | pp.lo | TDP | tdp.hi | tdp.lo | TN | totn.hi | totn.lo | TP | totp.hi | totp.lo |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1Q | C | Fitzroy | **3.53** | 4.71 | 2.64 | **0.10** | 0.33 | 0.03 | **124.7** | 171.4 | 90.9 | **7.3** | 15.1 | 3.5 |
| 3Q | C | Fitzroy | **1.77** | 3.29 | 0.96 | **0.59** | 1.06 | 0.33 | **74.8** | 106.7 | 52.4 | **20.2** | 33.7 | 12.1 |
| 1Q | I | Fitzroy | **2.70** | 3.84 | 1.89 | **0.18** | 0.55 | 0.06 | **96.9** | 138.9 | 67.6 | **8.8** | 20.2 | 3.8 |
| 3Q | I | Fitzroy | **1.77** | 3.16 | 0.99 | **0.57** | 1.00 | 0.33 | **79.4** | 109.9 | 57.4 | **19.5** | 31.9 | 11.9 |
| 1Q | O | Fitzroy | **1.71** | 2.33 | 1.24 | **0.17** | 0.31 | 0.10 | **99.1** | 116.9 | 84.0 | **6.9** | 11.0 | 4.3 |
| 3Q | O | Fitzroy | **1.83** | 2.39 | 1.40 | **0.24** | 0.36 | 0.16 | **86.4** | 100.2 | 74.6 | **9.2** | 12.8 | 6.6 |
| 1Q | C | Mackay W | **4.84** | 5.70 | 4.09 | **0.23** | 0.36 | 0.15 | **107.0** | 126.8 | 90.0 | **13.0** | 18.0 | 9.3 |
| 3Q | C | Mackay W | **2.23** | 2.98 | 1.71 | **0.44** | 0.62 | 0.31 | **93.1** | 109.8 | 79.0 | **15.8** | 21.4 | 11.7 |
| 1Q | I | Mackay W | **3.38** | 4.03 | 2.85 | **0.19** | 0.26 | 0.14 | **102.3** | 118.9 | 88.2 | **11.2** | 15.3 | 8.2 |
| 3Q | I | Mackay W | **1.77** | 2.36 | 1.33 | **0.33** | 0.47 | 0.23 | **80.5** | 94.4 | 68.7 | **12.0** | 16.4 | 8.8 |
| 1Q | O | Mackay W | **2.26** | 2.88 | 1.80 | **0.15** | 0.21 | 0.11 | **82.9** | 96.3 | 71.3 | **8.3** | 12.0 | 5.8 |
| 3Q | O | Mackay W | **1.52** | 2.48 | 0.93 | **0.35** | 0.61 | 0.20 | **86.7** | 110.3 | 68.2 | **12.5** | 20.1 | 7.8 |
| 1Q | C | Burdekin | **8.46** | 11.22 | 6.39 | **0.15** | 0.38 | 0.06 | **106.8** | 173.5 | 65.8 | **15.1** | 28.5 | 8.0 |
| 3Q | C | Burdekin | **4.06** | 6.11 | 2.70 | **0.48** | 0.77 | 0.30 | **106.3** | 146.2 | 77.3 | **26.6** | 41.6 | 17.0 |
| 1Q | I | Burdekin | **3.35** | 4.00 | 2.79 | **0.32** | 0.44 | 0.24 | **95.6** | 109.2 | 83.9 | **14.4** | 18.5 | 11.1 |
| 3Q | I | Burdekin | **2.67** | 3.47 | 2.05 | **0.30** | 0.42 | 0.22 | **98.3** | 117.6 | 82.2 | **12.4** | 17.6 | 8.7 |
| 1Q | O | Burdekin | **2.79** | 4.03 | 1.92 | **0.30** | 0.56 | 0.16 | **90.7** | 116.8 | 70.4 | **12.6** | 21.0 | 7.6 |
| 3Q | O | Burdekin | **1.49** | 3.81 | 0.56 | **0.31** | 0.50 | 0.20 | **85.1** | 136.4 | 53.2 | **18.1** | 39.0 | 8.4 |
| 1Q | C | Wet Tropics | **5.30** | 5.67 | 4.93 | **0.35** | 0.40 | 0.30 | **158.8** | 167.0 | 150.9 | **16.8** | 18.9 | 15.0 |
| 3Q | C | Wet Tropics | **4.09** | 4.68 | 3.60 | **0.33** | 0.40 | 0.27 | **99.5** | 109.6 | 90.3 | **14.4** | 17.6 | 11.7 |
| 1Q | I | Wet Tropics | **3.22** | 3.53 | 2.95 | **0.25** | 0.29 | 0.21 | **128.2** | 135.8 | 121.1 | **11.7** | 13.5 | 10.2 |
| 3Q | I | Wet Tropics | **2.14** | 2.48 | 1.86 | **0.31** | 0.37 | 0.25 | **97.9** | 106.3 | 90.2 | **11.8** | 14.0 | 10.0 |
| 1Q | O | Wet Tropics | **2.54** | 3.10 | 2.08 | **0.18** | 0.24 | 0.14 | **100.7** | 114.5 | 88.5 | **9.1** | 12.6 | 6.5 |
| 3Q | O | Wet Tropics | **1.86** | 2.36 | 1.49 | **0.21** | 0.30 | 0.15 | **108.1** | 122.2 | 95.6 | **7.1** | 10.2 | 5.0 |
| 1Q | C | Cape York | **3.47** | 4.00 | 3.01 | **0.32** | 0.41 | 0.25 | **117.5** | 129.9 | 106.3 | **14.2** | 17.3 | 11.7 |
| 3Q | C | Cape York | **2.26** | 2.95 | 1.71 | **0.26** | 0.39 | 0.18 | **100.0** | 116.3 | 86.0 | **10.4** | 14.8 | 7.3 |
| 1Q | I | Cape York | **2.51** | 2.79 | 2.26 | **0.25** | 0.30 | 0.21 | **114.7** | 121.8 | 107.9 | **10.3** | 11.9 | 8.9 |
| 3Q | I | Cape York | **2.05** | 2.42 | 1.71 | **0.32** | 0.40 | 0.26 | **100.5** | 111.0 | 91.0 | **12.0** | 14.8 | 9.7 |
| 1Q | O | Cape York | **2.48** | 3.01 | 2.05 | **0.19** | 0.27 | 0.13 | **98.7** | 111.4 | 87.4 | **8.4** | 11.3 | 6.3 |
| 3Q | O | Cape York | **0.84** | 2.60 | 0.28 | **0.10** | 0.23 | 0.04 | **91.7** | 154.7 | 54.3 | **7.7** | 29.9 | 2.0 |

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