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# Assessment of the eutrophication status of the Great Barrier Reef lagoon (Australia)

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**Abstract** Current scientific consensus is that inshore regions of the central and southern Great Barrier Reef, Australia, are at risk of impacts from increased nutrient (as well as sediment and pesticide) loads delivered to Reef waters. Increases in the discharge of water quality contaminants to the Reef are largely a consequence of the expansion of agricultural practices in northern Queensland catchments following European settlement in the 1850s. In particular, the presence of elevated chlorophyll *a* and nutrient concentrations in many parts of the inshore Great Barrier Reef together with intense and extensive phytoplankton blooms following the discharge of nutrient-rich river flood waters suggest that the central and southern inshore area of the Great Barrier Reef is likely to be significantly impacted by elevated nutrient loads. The biological consequences of this are not fully quantified, but are likely to include changes in reef condition including hard and soft coral biodiversity, macroalgal abundance, hard coral cover and coral recruitment, as well as change in seagrass distribution and tissue nutrient status. Contemporary government policy is centered around promotion and funding of better catchment management practices to minimize the loss of catchment nutrients (both applied and natural) and the maintenance of a Reef wide water quality and ecosystem monitoring program. The monitoring program is designed to assess trends in uptake of management practice improvements and their associated impacts on water quality and ecosystem status over the next 10 years. A draft set of quantitative criteria to assess the eutrophication status of Great Barrier Reef waters is outlined for further discussion and refinement.

**Keywords** Eutrophication · Great Barrier Reef · Nutrients · Water quality management

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## Introduction

The Great Barrier Reef (GBR), the world's largest coral reef ecosystem, is situated on the north-east coast of Australia (Fig. 1). It has the status of a Marine Park under joint Australian and Queensland State Government arrangements and has been a declared World Heritage Area since 1981. The "Reef" is globally recognised as a managed (for multiple uses)

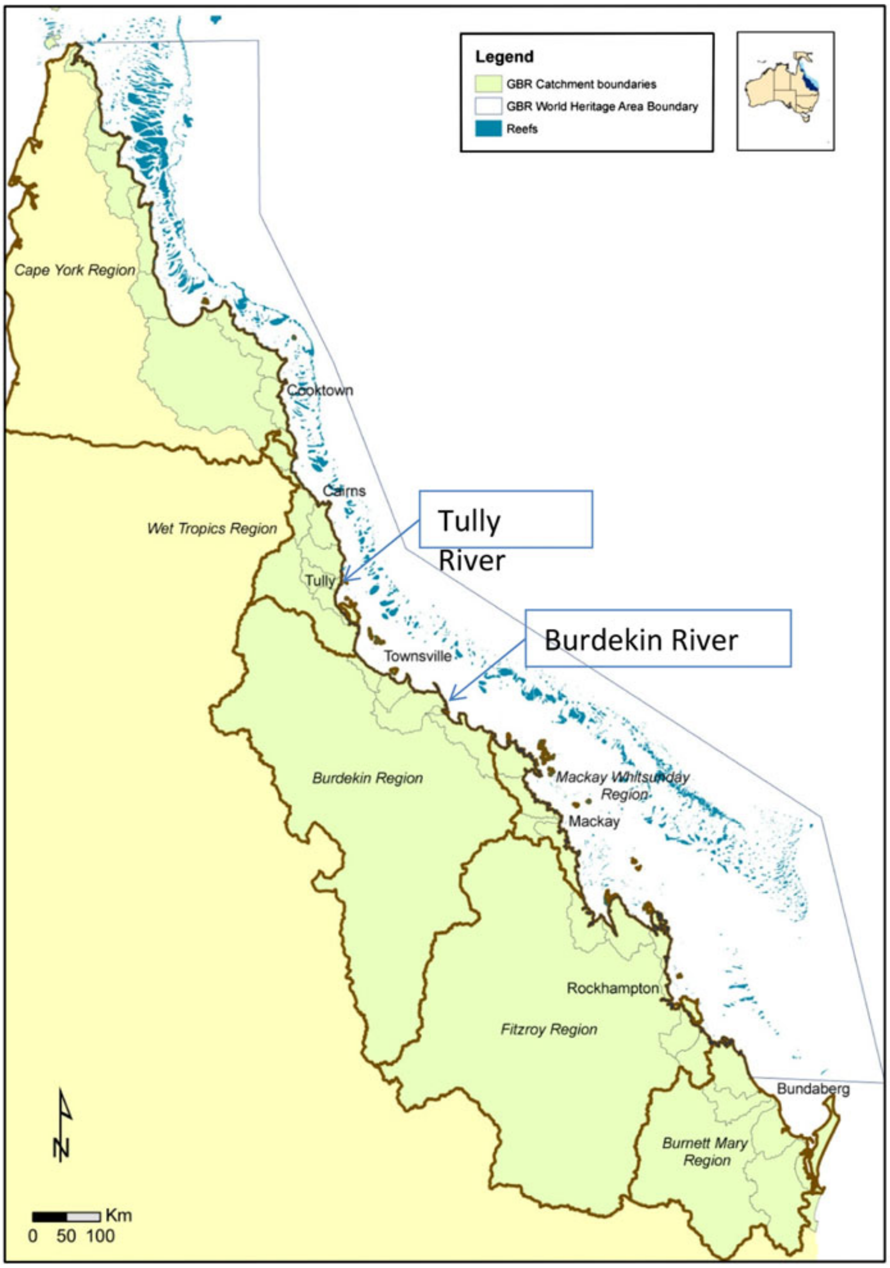


**Fig. 1** Drainage basins discharging into the Great Barrier Reef and the associated Regional Natural Resource Management boundaries

*Large Marine Ecosystem* (Brodie 2003). An extensive catchment area containing multiple river basins drains to the GBR (Fig. 1). This catchment area covers a total area of over 424,000 km$^2$ and includes both large dry tropical catchments as well as smaller wet tropical catchments (Furnas 2003). Important catchment land uses include rangeland beef grazing (314,000 km$^2$), sugarcane cultivation (5,700 km$^2$), horticulture (630 km$^2$), other cropping including grain and cotton cultivation (11,600 km$^2$), urban areas (2,600 km$^2$) and native forest (55,900 km$^2$) (Gilbert and Brodie 2001; Waterhouse et al. 2009). The dominance of grazing and cropping agriculture in the region has promoted the hypothesis that nutrient (and other pollutant) discharge from adjacent catchments to the GBR has increased greatly due to agricultural development over the last 150 years (Furnas 2003; McKergow et al. 2005; Haynes et al. 2007).

Examination of a growing collection of data from GBR waters prompted discussion and debate about the status of GBR waters in the 1990s and helped elevate the perception of importance of management of water quality (Kinsey 1991). Preliminary conclusions at the time varied widely of the scale and the severity of the problems. One side of the debate claimed no evidence of large scale or severe effects of terrestrial runoff of sediments and nutrients (Walker 1991) while the opposing view presented evidence of widespread nutrient enrichment, eutrophication and related undesirable impacts in the GBR (Bell 1991). In a series of papers, Bell and colleagues postulated that nearshore waters of the GBR were already eutrophic based on comparisons of GBR waters with those elsewhere (particularly the Caribbean), as nutrient concentrations, drawn from historic studies as well as their own current studies, exceeded nutrient threshold guidelines for coral reefs (Bell 1991, 1992; Bell and Elmetri 1995). Bell's conclusions were not completely accepted by the scientific community at the time due to disagreements over the validity of the nutrient threshold guidelines used, as well as concerns around the relatively small data sets available for analysis. However, as more data was subsequently accumulated, there was eventual consensus that inshore regions of the GBR adjacent to catchments south of Cooktown (refer Fig. 1) were at risk of eutrophication (Brodie 1997) and from land-sourced sediment and pesticide impacts (Haynes et al. 2007).

In more recent times, a series of studies have linked terrestrial runoff with degraded GBR health. In a pioneering study in the Whitsunday Islands, van Woesik and co-workers determined that corals were recruiting into localities close to the mouths of major rivers, but recruits were failing to survive. This was in contrast to reefs at larger distances from riverine and terrigenous influences in the same region which were actively accreting (van Woesik et al. 1999). Similar gradients in a range of water quality parameters were detectable in the region 10 years later, with water clarity believed to play a critical role in structuring the reef matrix (Cooper et al. 2007). Udy et al. (1999) concluded that a pattern of gradual increase in seagrass distribution at Green Island (in the northern Wet Tropics Region) since the 1950s was most likely caused by a regional increase in nutrient availability due to anthropogenic activity. Data collected along the north Queensland coast also suggests that the tissue nutrient status of the seagrass *Halophila ovalis* has increased over a 20 year period in concert with increasing fertiliser usage by the local agricultural industry, and that this seagrass species could be a good bioindicator of local nutrient conditions (Mellors et al. 2005). Differences in reef condition including hard and soft coral biodiversity and algal abundance have been attributed to water quality differences between reefs in Princess Charlotte Bay which is adjacent to relatively pristine rivers, and reefs in the Wet Tropics Region adjacent to polluted rivers (Fabricius and De'ath 2004; Fabricius et al. 2005). Comparative studies on a wider set of reefs in the northern GBR concluded that reduced hard coral species diversity and cover in the region between Cardwell and Cape Flattery (15° to 18°S) was due to elevated terrestrial pollutant input into this region (Devantier et al. 2006). All five studies implicated elevated concentrations of terrestrial pollutants (suspended sediment, nutrients and pesticides) as factors in observed reef degradation, but (except for Mellors et al. 2005), could not specifically link which of the pollutants was the primary causal agent.

Overall, reefs of the GBR are considered to be in relatively 'good' condition compared to other reefs around the world, but are declining due to stress from fishing, water quality impacts and climate change (Pandolfi et al. 2003; Fabricius et al. 2005; Wilkinson 2008). Whether this relatively good condition is related to good management through institution of the Great Barrier Reef Marine Park Authority, or is a consequence of relatively low adjacent human population pressures and distance from the coast compared to South East Asian and Caribbean reefs, is not proven (Bruno and Selig 2007). What is known is that the current water quality management regime for catchments adjacent to the GBR has not been effective in improving catchment or Reef water quality (Brodie et al. 2008a).

The purpose of this paper is to consider the influences of nutrients on ecosystems in the GBR, and to propose a set of criteria to assess whether the GBR is eutrophic given the spatial variability of the water body and the temporal variability in nutrient delivery. These draft criteria are modelled on those developed and used for assessment in European and United States waters (Bricker et al. 2003; Devlin et al. 2007; Foden et al. 2010), but adapted for the very different climatic conditions and ecosystems of the GBR. The second purpose is to assess current management response to these conditions and its effectiveness. The paper presents an overview of the effects of elevated nutrients on coral ecosystems in a global setting, then with a focus on the GBR, reviews the primary sources of nutrients, the current nutrient status, fate and transformation of nutrients in the lagoon, impacts on Reef ecosystems and evidence of eutrophication in the GBR. Based on this information, a set of preliminary criteria for assessing eutrophication in the GBR are proposed. Finally, the options for management of nutrient enrichment in the GBR including an overview of the current setting and shortfalls are discussed.

## Influences of nutrients on reef ecosystems

Contemporary disturbances of coral reefs are caused by a complex combination of stressors including those arising from climate change, disturbance and degraded water quality. Land sourced runoff containing elevated nutrient concentrations may result in a range of impacts on coral communities (Tomascik and Sander 1985; Grigg 1995; Ward and Harrison 1997; Koop et al. 2001; Fabricius and De'ath 2004; Loya et al. 2004; Fabricius et al. 2005, Fabricius 2007) and under extreme situations, can result in coral reef community collapse (Smith et al. 1981). Impacts can include reduced coral recruitment (Loya 1976; Babcock and Davies 1991; Loya et al. 2004), modified trophic structures (Lapointe 1997; Fabricius 2005), altered biodiversity (van Woesik et al. 1999) and coral mortality (Ward and Harrison 2000; Harrison and Ward 2001; Kline et al. 2006). Interactions between increased coral bioerosion and nutrient enrichment have been postulated over many years (e.g. Hallock 1988) with a number of studies showing a correlation between bioerosion and the nutrient gradient across the GBR shelf (Sammarco and Risk 1990; Risk et al. 1995), as well as under experimental conditions (Kiene and Hutchings 1994; Kiene 1997; Hutchings et al. 2005).

The role of increased nutrient regimes on coral reefs and macroalgal structuring is a complex, and as yet, not completely resolved interaction between herbivoury and nutrient limitation (McCook 1999, 2001; McCook et al. 2001; Hughes et al. 2007; Jompa and McCook 2002, 2003; Bellwood et al. 2004, 2006), with grazing pressure typically the dominant controlling factor (Sotka and Hay 2009).

Further complicating these coral—algal—water quality interactions are results which indicate that organic compounds released by algae enhance microbial activity on coral surfaces cause coral mortality and algal overgrowth (Smith et al. 2006). Other water quality factors such as dissolved organic carbon concentrations and increased rates of bioerosion have also been shown to be important in reef degradation (Tribollet and Golubic 2005; Hutchings et al. 2005; Kline et al. 2006).

Elevated nutrient concentrations can also be deleterious to seagrasses by lowering ambient light levels via the proliferation of local light absorbing algae (including water column phytoplankton, benthic macro algae or algal epiphytes). This loss of light can reduce the amount of photosynthesis in seagrasses, particularly in deeper water (Walker et al. 1999). Elevated nutrient concentrations can also cause deleterious disruptions to nitrogen and phosphorus metabolism in seagrass (Touchette and Burkholder 2000), although Australian seagrasses are generally regarded as being nitrogen-limited.

Critically, more recent research shows that direct interactions between nutrients species such as nitrate and enhanced coral bleaching susceptibility will be important as a clear example of direct synergy between climate change stress and nutrient enrichment stress (Wooldridge 2009a, b; Wooldridge and Done 2009).

## Eutrophication and coral reefs

The consequences of enhanced nutrient loading on coral reefs, and hence 'eutrophication', have been extensively studied following the well known case in Kaneohe Bay, Hawaii (Smith et al. 1981). Large scale sewage effluent inputs into Kaneohe Bay, which has limited oceanic flushing, led to blooms of phytoplankton (Caperon et al., 1971), increased benthic macroalgae biomass (Smith et al. 1981), increased filter and deposit feeders (tube worms, sponges) biomass (Kinsey 1988) and cryptofauna biomass (Brock and Smith 1983) and consequent loss of live coral (Smith et al. 1981). Removal of outfalls allowed an improvement in water quality (Laws and Allen 1996) and some regeneration of the reef (Hunter and Evans 1995), although there had not been a complete return to pre-outfall conditions by 2001 (Stimson et al. 2001). Subsequently, macroalgae abundance in the Bay may have declined permanently (Stimson and Conklin 2008).

The Relative Dominance Model (RDM) (Littler and Littler 1984) was derived from the Kaneohe situation and numerous laboratory and field studies of the effects of nutrients on coral reefs. In this model, coral reefs respond to changing nutrient status and grazing pressure to move to alternative states. These alternative states include coralline algal dominance with high grazing and high nutrients; fleshy macro-alagal dominance with low grazing and high nutrients; and turf algal dominance with low nutrients and low grazing. The model has been tested many times since its development in controlled field situations (Smith et al. 2001; Lapointe et al. 2004; Littler et al. 2006), but its uniform applicability is still in dispute (Hughes et al. 1999; Aronson and Precht 2000; McClanahan and Graham 2005). One criticism of the RDM is that the model ignores other consequences of nutrient enrichment in coral reef ecosystems such as increased phytoplankton biomass (blooms) and subsequent benthic species composition shifts towards filter feeders (such as sponges, tube worms and ascidians) which can take advantage of increased food supplies. In addition, the consequences of changes in phytoplankton species composition resulting from nutrient enrichment such as population shifts in organisms dependent on phytoplankton type and biomass (including crown-of-thorns starfish (*Acanthaster planci*) (Brodie et al. 2005, 2007)) are not reflected in the model.

## Eutrophication and the Great Barrier Reef

For the purposes of this paper, the term eutrophication refers to situations where nutrient enrichment, increased algal growth and/or increased organic production rates have resulted in change in benthic community structure This definition is derived from Bell et al. (2007) and international eutrophication assessments (Foden et al. 2010). Recent discussions and legal rulings within the uptake of European directives have identified that eutrophication is a multi-step process and therefore management focus is on the detection of the potential undesirable ecological consequences of nutrient enrichment rather than the confirmation of desirable attributes of a well-balanced naturally enriched system (Tett et al. 2007; Foden et al. 2010). Thus the following discussion presents examples of enrichment, increased production and ecological disturbance as measured within GBR waters.

## Nutrient supply to GBR marine waters

Nutrient supply to the GBR includes a range of sources including river discharges (Mitchell et al. 1997); urban stormwater and wastewater run-off (Brodie 1995; Mitchell and Furnas 1997); atmospheric inputs following rainfall events (Furnas et al. 1995); planktonic and microphytobenthic nitrogen fixation (Furnas and Brodie 1996); deeper ocean supply following Coral Sea upwelling (Furnas and Mitchell 1986); deposition of dust from storms generated in the interior of Australia (Shaw et al. 2008) and wind resuspension of nearshore sediments and their associated nutrients (Walker and O'Donnell 1981; Gagan et al. 1987). However of these, riverine discharge is the single largest source of nutrients to inshore areas of the GBR (Furnas et al. 1997). This nutrient increase is largely driven by the application of fertilizer to crops grown in adjacent GBR catchments. A proportion of the applied nutrients are subsequently lost to surface and groundwaters and eventually to the GBR (Rayment 2003). Additional losses of particulate bound nutrients occur from agricultural catchments where soil tillage, vegetation clearing and reduced pasture cover leads to the loss of natural nitrogen and phosphorus from the soil to catchment waterways (Brodie and Mitchell 2005; McKergow et al. 2005).

Contemporary estimates suggest that the total nitrogen discharge to the GBR has increased from 14,000 tonnes year$^{-1}$ in pre-development times (prior to 1850) to a current discharge of 58,000 tonnes year$^{-1}$; a four-fold increase (Brodie et al. 2009a). The predominant form of the nitrogen that is delivered to the GBR has also changed. Discharge of nitrogen from natural landscapes is predominantly in the form of dissolved organic nitrogen (DON) (Harris 2001; Brodie and Mitchell 2005). This is still the case in undisturbed forest stream runoff in the GBR catchment area (Brodie and Mitchell 2006), however, nitrogen discharge from agricultural and urban lands is dominated by dissolved inorganic nitrogen (DIN = nitrate + nitrite + ammonium) derived from fertiliser and sewage wastes, and particulate nitrogen (PN) derived from soil erosion (Brodie and Mitchell 2005). The shift from a predominantly DON discharge in pre-1850 times to a predominantly (bioavailable) PN and DIN discharge in modern times has important consequences for the effects of discharged nitrogen (Fabricius 2005). Change in land use has also led to the increase in nitrate discharge in some individual catchments being much larger relative to the increase in total nitrogen discharge (e.g. in the Wet Tropics Region, it is estimated to be 6 times in the Johnstone River (Hunter and Walton 2008) and 10 times in Tully River (Armour et al. 2009)). The larger increases in the inorganic nitrogen fraction are associated with intensive fertiliser use on sugarcane and banana crops in these catchments.

Discharge of nutrients to the GBR, both particulate and dissolved, occurs overwhelmingly during the large river flood flows of the wet season (Mitchell et al. 1997, 2005; Packett et al. 2009). More than 90% of the nutrients sourced from the land enter the GBR lagoon during this time as waterway concentrations of the different forms of nitrogen and phosphorus peak, and waterway flows are maximised (Mitchell et al. 1997, 2005). At other times there is minimal nutrient discharge from the land. High river flows occur at a frequency of 0.25 per year for dry tropics rivers including the Fitzroy and Burdekin Rivers to 3

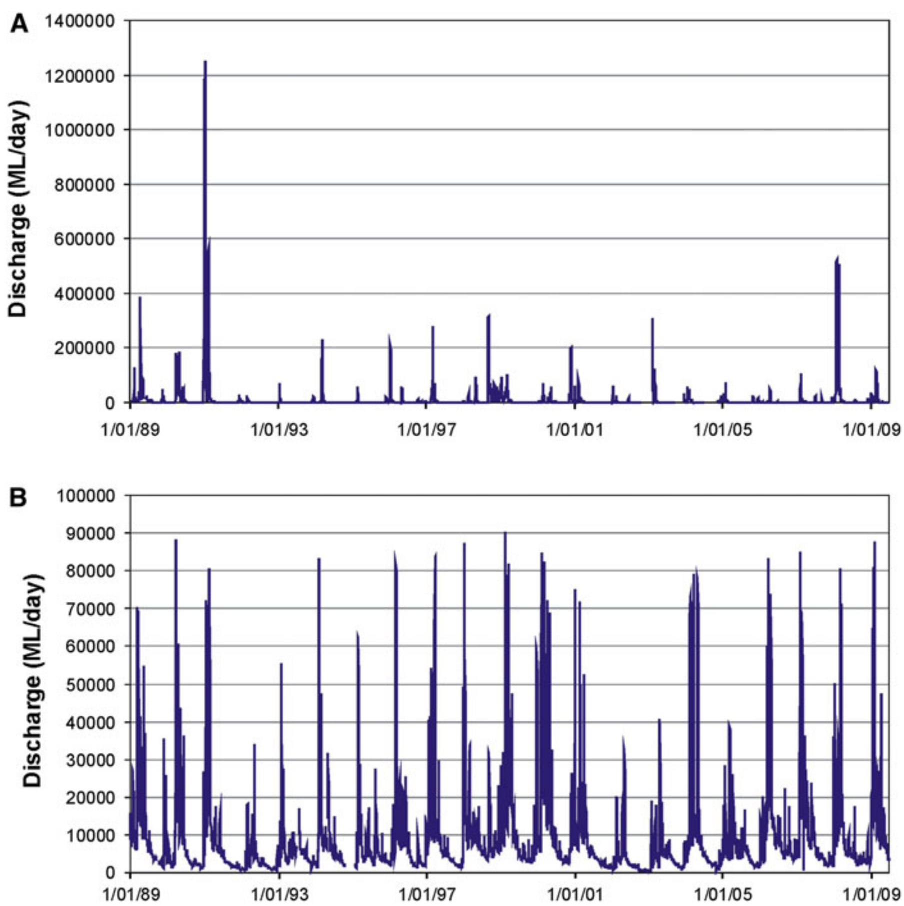


**Fig. 2** Hydrographs for the Burdekin River (*top panel*) and Tully River (*bottom panel*) from 1989 to 2009 showing large infrequent and variable events in the Burdekin River (dry tropics) versus annual, comparatively smaller, similar sized events in the Tully River (wet tropics)

flows per year for wet tropics rivers such as the Tully. These differences are evident in the hydrographs shown in Fig. 2. High flow periods last only a few weeks per year in all GBR rivers. During this period, more than 80% of the nutrient load is discharged from the Tully River and more than 98% of the nutrient load from the Burdekin River. Strong patterns of nutrient concentration within the high flow periods are also obvious with high concentrations in small first flush events at the beginning of the wet season, high concentrations on the rising limb of the hydrograph in major flows and lower concentrations on the falling limb, and higher concentrations in general in early wet season flows compared to late wet season flows (Furnas 2003). All these factors make nutrient loading to the GBR from rivers a highly temporally variable process.

## Fate and transformation of nutrients in the GBR lagoon

Flooding river discharges into the GBR lagoon typically form extensive plumes (Devlin et al. 2001), images of which are now regularly captured by a wide variety of satellite sensors including SeaWiFS, MODIS and MERIS (Brodie et al. 2010; Devlin and Schaffelke 2009). Short-term concentrations of both particulate and dissolved nutrients are extreme (in the range 2–30 µM nitrogen and 0.1–1 µM phosphorus) (Devlin and Brodie 2005). Particulate nutrients are initially transported only short distances from the river mouth before ‘settling out’ from the plume through gravity controlled processes, as well as through flocculation of fine particles into larger ones which then also settle out (Lewis et al. 2006). In contrast, dissolved nutrients from the river discharge disperse widely in the GBR lagoon before being taken up as biomass in phytoplankton blooms which are transported across the shelf and into the Coral Sea. Figure 3 shows the progression of a plume arising from multiple rivers in the Wet Tropics region into the Coral Sea over about 6 days. The plume is initially dominated by terrestrial particulate matter which settles out and the plume becomes defined by a dissolved nutrient driven phytoplankton bloom. The plume is visible due to the presence of suspended sediment, phytoplankton and Coloured Dissolved Organic Matter (CDOM).

Inner-shelf reefs of the Wet Tropics region are exposed regularly (one to three times per year) to a mixture of land sourced particulate and dissolved inorganic nutrients. Reefs situated a greater distance offshore in the same region are exposed less frequently to particulate nutrient fluxes, However, they are exposed regularly to nutrients derived mainly from secondary algal growth driven by terrestrially sourced dissolved nutrients (Devlin and Schaffelke 2009). In contrast, mid and outer shelf reefs in the drier southern part of the GBR are rarely exposed to terrestrial nutrients due to larger distances from the coast and lower ambient rainfall regimes.

## Effects of elevated nutrients in the GBR

The waters of the GBR are characterised by high ambient light intensities and water temperatures and as a consequence, available nutrients are rapidly converted to organic matter by phytoplankton, particularly in inter-reef regions (Furnas et al. 2005). These recycled and transformed nutrients largely determine the (nutrient) water quality status of these waters and any impacts on benthic organisms. Phytoplankton biomass measured as chlorophyll *a* concentrations are 2–3 times higher in inshore waters of the central and southern GBR (0.3–0.7 µg $l^{-1}$) compared to areas in the northern GBR (0.2 µg $l^{-1}$) (Brodie et al. 2007). In addition, phytoplankton biomass measured as chlorophyll *a* concentrations in the central and southern GBR in flood plume conditions are typically in the range of 1–20 µg $l^{-1}$ (Devlin and Brodie 2005; Devlin and Schaffelke 2009; Brodie et al. 2010). These values are believed to reflect nutrient enrichment, attributable to terrestrial nutrient discharge from central and southern rivers associated with large scale activities. Increases in land sourced nitrogen and phosphorus flux and the bioavailable nutrient species in the GBR lagoon drive the proliferation of extensive phytoplankton blooms following flood discharge (Fig. 3) (Brodie and Mitchell 2005, 2006).

A change in the speciation of phytoplankton has also probably occurred in GBR waters, although this is a relatively new research area. The ‘normal’ phytoplankton community of the lagoon is dominated by picoplankton, specifically the cyanobacteria *Synechococcus* and *Prochlorococcus* (Crosbie and

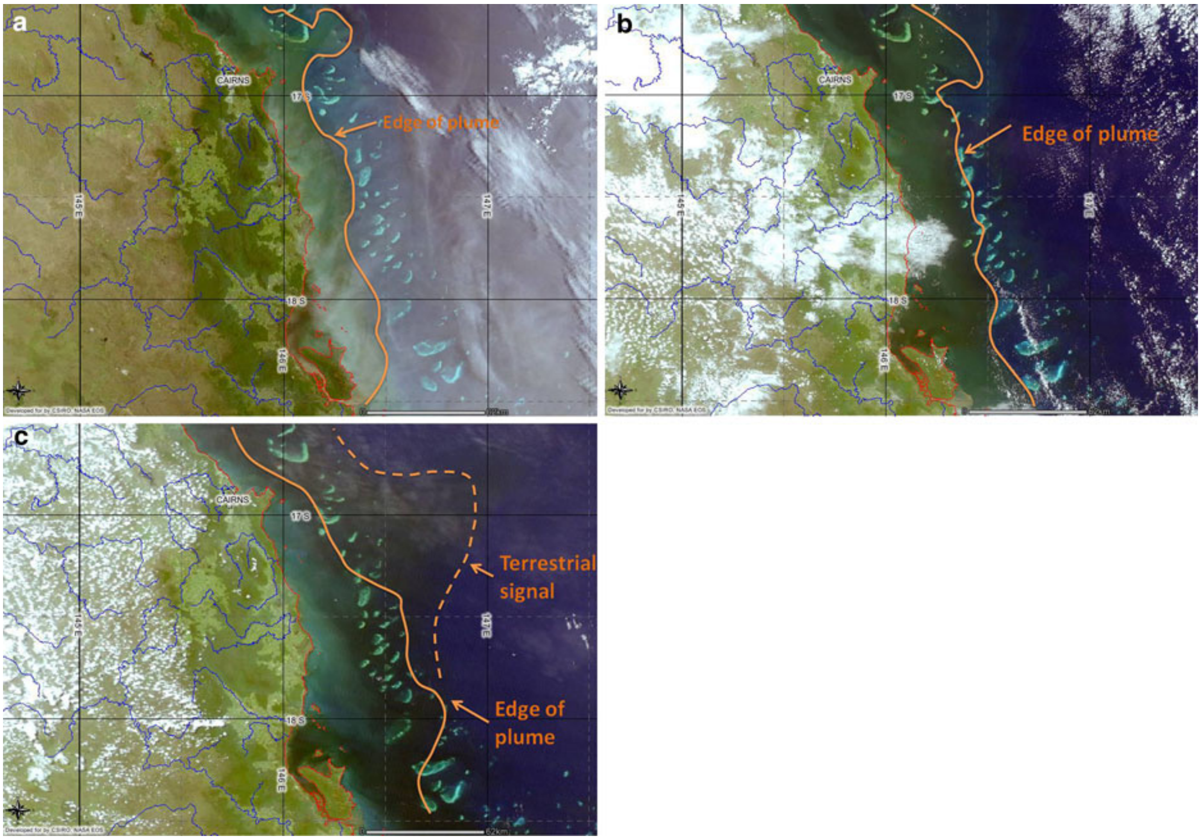


**Fig. 3** Progression (**a**–**c**) of a multiple river plume in the Wet Tropics (Feb, 2007) extending from the coast to beyond the outer reef. The lines show the outer edge of the plume made visible due to Coloured Dissolved Organic Matter and phytoplankton. Images (**a**–**c**) show the transformation from a plume dominated by terrestrial particulate matter into a plume dominated by a dissolved nutrient driven phytoplankton bloom. Image courtesy of CSIRO

Furnas 2001; Furnas et al. 2005). The larger cyanobacteria *Trichodesmium* sp. are also common in slicks at certain times of the year. It is postulated that nitrogen fixation by *Trichodesmium* could be stimulated by increases in river borne nutrients such as phosphorus and iron thus leading to even greater inputs of 'new' nitrogen to the system (Bell et al. 1999). It has been clearly shown that *Trichodesmium* blooms follow nitrogen and phosphorus enrichment events and temperatures above 26°C in Pacific lagoons (Rodier and Le Borgne 2008). In the past, low concentrations of bioavailable nitrogen and phosphorus in river discharges would have had minimal impact on phytoplankton speciation shifts. Increased contemporary concentrations of DIN and sometimes dissolved inorganic phosphorus (DIP) in flood plumes tend to promote phytoplankton species shifts to larger species of diatoms and dinoflagellates (Furnas et al. 2005; Heimann pers com). This nutrient induced shift which is most obviously seen and documented in flood plume conditions is similar to that noted in similar situations in tropical locations including Singapore (Gin et al. 2000), Japan (Tada et al. 2003), Curacao (van Duyl et al. 2002), New Caledonia (Jacquet et al. 2006; Tenório et al. 2005), Hawaii (Cox et al. 2006), Moorea (Delesalle et al. 1993) and in experimental studies (Hopcroft and Roff 2003). The shift in phytoplankton species composition under nutrient enriched conditions has implications for other trophic levels, the most important in the GBR is likely to be the promotion of crown of thorns starfish larval survival (Brodie et al. 2005; Fabricius et al. 2010).

Increased delivery of nutrients to the GBR is also believed to have enriched the central and southern sections of the Marine Park. This is shown most clearly by chlorophyll *a* concentrations (Brodie et al. 2007) where the more 'pristine' coastal waters adjacent to the Northern Cape York catchment have similar relatively low mean chlorophyll *a* concentrations in both inshore and offshore waters (0.2 μg $l^{-1}$). In contrast, inshore areas south of Cooktown have elevated mean chlorophyll *a* concentrations (0.3–0.7 μg $l^{-1}$). Other indicators using direct nutrient concentrations (Nutrient Threshold Criteria) also suggest much of the inshore GBR is nitrified (Bell et al. 2007) and that chlorophyll *a* concentrations normally exceed water quality guideline values across large areas of the GBR (Fig. 4) (De'ath and Fabricius 2008; Great Barrier Reef Marine Park Authority 2009). It is estimated that the area of the GBR that exceeds the guideline value of 0.45 μg $l^{-1}$ for chlorophyll *a* is 10–15% (approximately 50,000 $km^2$) of the total area of the Marine Park and 40–50% of the defined inshore area.

Currently macroalgal abundance is high on many inshore reefs of the GBR in the monitored area south of Cooktown, (Thompson et al. 2010; Schaffelke et al. 2009; De'ath and Fabricius 2008; Wismer et al. 2009) but controversy still exists as to its cause. This includes areas within the Wet Tropics (offshore from the Tully and Herbert Rivers) and Burdekin Regions

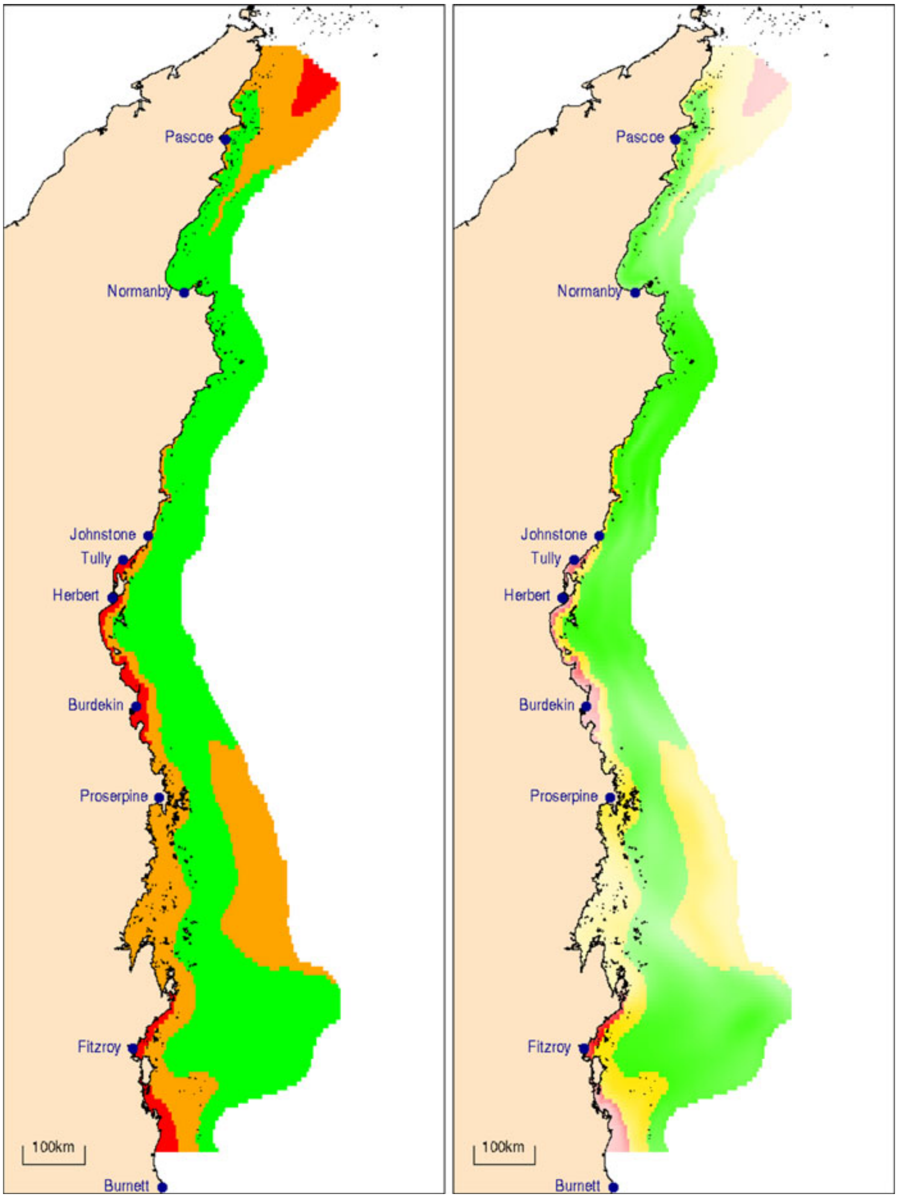


**Fig. 4** Chlorophyll concentrations in reference to the GBR Water Quality Guideline. Locations that are presently at less than (*green/dark grey*) or exceed (*orange/light grey* and *red/black*) the guideline trigger value of a maximum annual mean of 0.45 μg $l^{-1}$ chlorophyll. *Orange/light grey zones* show areas that exceed the guideline trigger values, having chlorophyll values of 0.45–0.8 μg $l^{-1}$. *Red/black 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. Extracted from De'ath and Fabricius (2008) (Color figure online)

where high levels of macroalgal cover and low coral cover (and coral biodiversity) dominates inshore reefs and water quality is characterised by high chlorophyll values and sporadic high turbidity due to wind-driven resuspension (Thompson et al. 2010). This contrasts with inshore reefs off Cape York in a lower nutrient environment which typically have low macroalgal cover and higher coral cover (Fabricius et al. 2005; Devantier et al. 2006). In the Mackay Whitsunday region reefs typically have higher macroalgal cover in areas of river sourced high nutrient status (but low river sourced suspended sediment status) in comparison to reefs further offshore not strongly affected by river sourced nutrients (Jupiter et al. 2008; Thompson et al. 2010). An analysis of macroalgal cover versus fish herbivore biomass on transects across the central and north-central GBR showed that macroalgal cover was high inshore and lower offshore in contrast to fish herbivore biomass which was lower on inshore reefs (Wismer et al. 2009). The range of opinions as to why high macroalgal cover exists on inshore reefs in some areas south of Cooktown include (a) represents a natural state, (b) a result of nutrient enrichment (Bell et al. 2007), (c) a result of reduced grazing fish populations, (d) a combination of nutrient enrichment and reduced grazing fish populations, or (e) a more complex situation involving combined effects of acute coral mortality following cyclone damage, bleaching and COTs outbreaks followed by rapid macro and turf algal growth and subsequent failure of coral recovery due to poor water quality (Thompson et al. 2010; Schaffelke et al. 2009; Fabricius et al. 2005).

## Assessing eutrophication in the GBR

A more complete analysis of the complex effects of nutrient loading in coral reef ecosystems has been reviewed by Fabricius (2005) and includes other confounding terrestrial pollutants such as suspended sediments. Overall it is clear that nutrification and subsequent eutrophication present quite different symptoms and consequences in tropical coral reef ecosystems compared with temperate marine ecosystems (Rabalais 2002). This has to be considered when looking for 'traditional' (i.e. temperate) indicators of eutrophication e.g. dissolved oxygen sags, in a tropical coral reef system versus the known indicators of coral reef response. A number of parameters that can indicate eutrophication are presented in Table 1 and demonstrate the difference between temperate and tropical systems. This list is not exhaustive but presents the most well known and visible symptoms of nutrient enrichment.

Eutrophication in temperate marine waters is a distinctly different phenomenon than in tropical coral reef waters with a strong seasonal influence. Temperate waters experience strong spring and summer growth periods and lower production in the colder shorter days. Tropical monsoonal climates are strongly influenced by the change from dry to wet seasons. These climatic differences have a substantive impact on the eutrophication process and the changes that may occur. These differences have been analysed to identify appropriate indicators for the assessment of eutrophication in coral reef waters.

The problems of defining exactly when a system is 'eutrophic' remain, especially in tropical and coral reef systems where a different set of criteria need to be used compared to temperate systems. Bell et al. (2007) defines eutrophication from the Nutrient Threshold Criteria (NTC) as 'a situation where nutrient enrichment increases algal growth/organic production rates to the extent that changes in the benthic community structure have begun e.g., replacement of hermatypic corals with coralline algae, filamentous algae, macroalgae, and/or a variety of filter feeders'. Given the proposed link between nutrient enrichment and crown-of-thorns starfish outbreaks (Brodie et al. 2005, 2007; Fabricius et al. 2010), and nutrient enrichment and increases in some forms of bioerosion (Hutchings et al. 2005) it is possible to collate a list of coral reefs eutrophication criteria (Table 2). These preliminary criteria provide a first assessment of the characteristics of eutrophication in the GBR. Preliminary thresholds have been defined and included, and are based on reliability of measurement, strong correlative link with nutrient enrichment and where possible, are linked to indicators that are measured in current research programs (e.g. Cooper et al. 2007, 2008), such as the Reef Rescue Marine Monitoring Program (Schaffelke et al. 2009; McKenzie and Unsworth 2009) and the Great Barrier Reef Long Term Monitoring Program (Sweatman et al. 2005). The proposed thresholds are preliminary and will be refined over time. The approach is comparable to assessments in other

**Table 1** Comparison of drivers, impacts and responses between coastal and nearshore temperate and tropical systems

| Parameter | Temperate water response | Tropical water response |
|---|---|---|
| DIN | Higher winter concentrations. Depletion in spring/summer periods | High, episodic pulses experienced during wet summer (high flow) season. Low concentrations for majority of year |
| Phytoplankton | Natural systems have low winter biomass with high spring concentrations, and variable summer/autumnal blooms. Enriched (impacted) systems promote growth of phytoplankton that may not be easily grazed (e.g. shift from diatom to dinoflagellates dominating in bloom periods). Trophic transfer will be poor with unconsumed algal biomass stimulating microbial decomposition and oxygen consumption | GBR coral reefs are typically dominated by picoplankton (pico cyanobacteria) with low biomass. Nutrient enrichment potentially shifts to a larger phytoplankton community (dinoflagellates and diatoms) with higher biomass. This can lead to increases in Crown of Thorns starfish or zooplankton trophic shifts |
| Macroalgae | Macroalgae response can be seen in the proliferation of opportunistic macroalgal blooms (green algal blooms) | Increased competition from macroalgae species in seagrass and coral reef communities |
| Dissolved Oxygen (DO) | Development of hypoxic (and anoxic) conditions due to decomposition of the accumulated biomass, and changes in the community structure of benthic animals due to oxygen deficiency with many recorded cases of DO depletion such as dead zones. DO is one of the main attributes of any temperate eutrophication assessment | DO is not a reliable indicator in tropical coral reef waters due to the shallow, well mixed nature of the waters |
| Seagrass | Less species, longer turnover rate. Measures of seagrass health measured by reduction and expansion in area and biomass concentrations | Tropical species can turn over leaves every year, used as a measure of seagrass health identified by reduction and expansion in area and biomass concentrations |
| Seasonal response/change | Typically phytoplankton growth limited in winter months. High growth periods in spring and summer. Potential change from interactions between climate change and nutrient enrichment may be to increase phytoplankton growth in winter months, changing the trophic structure of system | System responses driven by high flow conditions. Changing land practices has resulted in significantly higher pollutant loads entering nearshore waters in high flow events. Altered water quality drives higher inshore turbidity, higher nutrient availability, increases in macroalgal and filter feeders abundance |
| Undesirable disturbance | Ultimate end response to prolonged nutrient enrichment includes blooms of toxic algae, increased growth of epiphytic algae and nuisance macroalgae, the loss of submerged vegetation, depletion of dissolved oxygen (DO) due to decomposition of accumulated biomass which leads to the development of hypoxic conditions<br>This leads to include large scale dead zones (e.g. Mississippi R), massive proliferation of nuisance species and red tides | In coral reefs, a complicated relationship exists between macroalgal growth and coral cover, mediated through grazing fish populations<br>Ultimate end response to prolonged nutrient enrichment, increased organic matter and increased turbidity is total loss of coral cover and a shift to a macroalgal, filter feeder and bioeroder dominated system |

locations, i.e. based on thresholds values of relevant indicators (e.g. Bricker et al. 2003; Tett et al. 2007; Foden et al. 2010; Devlin and Brodie 2005) and has been tailored to be specifically relevant to tropical reef ecosystems.

Data from the Reef Plan Marine Monitoring Program (Schaffelke et al. 2009), and chlorophyll values (measured in Bell et al. 2007; Brodie et al. 2007; De'ath and Fabricius 2008, 2010) suggest strongly that parts of the inshore GBR, south of Cooktown, and small areas of the mid-shelf and outer-shelf GBR could be considered eutrophic at certain times of the year. A preliminary assessment of the eutrophication status of the inshore area south of Cooktown (Fig. 1) was applied against the potential criteria as listed in Table 2. Many of the criteria (Table 3) are exceeded although evidence is sometimes incomplete and difficult to assess against the current accepted guidelines. Also the situation is potentially complicated by the large flow events, and the presence of other water quality stress factors such as suspended sediment, turbidity and the presence of pesticides (Haynes et al. 2000; Cooper et al. 2008; Lewis et al. 2009), as well as additional larger scale

**Table 2** Preliminary indicators and thresholds for establishing a set of criteria to assess eutrophication in the GBR

| Type of impact | Potential criteria for the assessment of eutrophication on reef ecosystems | Numerical value of the threshold | GBR evidence |
|---|---|---|---|
| Driver | Nutrient concentrations above the Nutrient Threshold Concentration (NTC) | DIN 1 μM<br>DIP 0.2 μM | Bell et al. (2007), Lapointe (1997) |
| Primary impact | Annual average (ambient and pulsed) chlorophyll *a* concentrations above the NTC and for the GBR above the GBR water quality guidelines (evidence of long term regime shift) | Chl 0.5 μg $l^{-1}$ (NTC)<br>0.45 μg $l^{-1}$ (GBRMPA guidelines) | Bell et al. (2007), Brodie et al. (2005), GBRMPA (2009), De'ath and Fabricius (2008, 2010) |
| Primary impact | Seasonal peak concentrations: intense and extensive phytoplankton blooms following nutrient enriched river discharge events with chlorophyll *a* concentrations 4–100 times above the GBR water quality guidelines. Measurement of severity of exceedance (threshold under development) | Chl 2.0 μg $l^{-1}$ (draft guideline under development)<br>Area and period of exposure will be developed from ongoing spatial assessments of terrestrial influence. | De'ath and Fabricius (2010), Devlin and Brodie (2005), Brodie et al. (2010) |
| Primary impact | Excessive macroalgal abundance on reefs with high nutrient inputs | Threshold exceeded if macroalgal cover is stable at >15% or cover increased from the previous year, or cover decreased from a cover >20% | Schaffelke et al. (2009), Thompson et al. (2010), De'ath and Fabricius (2008), Jupiter et al. (2008), Wismer et al. (2009) |
| Secondary impact | Coastal seagrass tissue nutrient concentrations—Burdekin and Wet Tropics Regions (refer Fig. 1 for locations) | C:N below 20 (low light)<br>C:P below 500 (large P pool)<br>N:P above 30 = high N<br>N:P below 25 = high P | Mellors et al. (2005), McKenzie and Unsworth (2009) |
| Secondary impact | Replacement of corals with coralline algae, filamentous algae, macroalgae and/or a variety of filter feeders | These thresholds consisting of measured coral cover and species diversity versus algal cover versus filter feeder abundance are still under development | van Woesik et al. (1999), Cooper et al. (2007), Fabricius et al. (2005), Devantier et al. (2006), Schaffelke et al. (2009), Thompson et al. (2010) |
| Tertiary impact | Bioerosion of coral in nutrient enriched areas | Total internal bioerosion of *Acropora* highly variable with differences between nearshore (4%), mid-shelf (12%)<br>Internal bioerosion in living *Porites* 11% on nearshore reefs, 1.3% on outer reefs<br>Thresholds could be developed based on these values | Risk et al. (1995), Hutchings et al. (2005), Sammarco and Risk (1990) |

**Table 2** continued

| Type of impact | Potential criteria for the assessment of eutrophication on reef ecosystems | Numerical value of the threshold | GBR evidence |
|---|---|---|---|
| Tertiary impact | Outbreaks of the crown-of-thorns starfish | Presence of an outbreak. An ‘incipient’ outbreak is the density of starfish at which coral damage is likely: $>\sim 1500$ starfish $km^2$ equivalent to an average 0.22 starfish per 2-min manta tow. During an ‘active’ outbreak, densities reach $>1.0$ starfish per 2-min tow which would certainly damage reefs | Brodie et al. (2005), Moran and De’ath (1992) |
| Tertiary impact | Slow recovery from macroalgal dominance following an acute coral mortality event back to coral dominance. Recovery of coral can be fast on reefs with apparent high resilience e.g. Keppel Island reefs (Diaz-Pulido et al. 2009) where coral recovered from a bleaching and subsequent macroalgal bloom within a year | Threshold will be a measure of resilience based on a combination of status indicators including e.g. Coral cover, macroalgae cover, juvenile density and coral spat settlement/recruitment | Fabricius et al. (2005), Devantier et al. (2006) |

stresses such as fishing and climate change (Pandolfi et al. 2003). Despite the limitations of the initial assessment, it does suggest that this area, particularly in the wet season, can be considered as exhibiting eutrophic conditions. There is also some suggestion of a long term baseline increase in chlorophyll for this inshore region south of Cooktown. This preliminary eutrophication assessment does show that nutrient enrichment, increased primary production and impacts on GBR ecosystems are occurring in the inshore GBR, an area that supports a rich, diverse system of coral reefs, seagrass beds and fish communities. It is also the area most accessible to the community and the economically important tourism industry.

## Managing nutrients in the GBR

Based on scientific evidence and consensus, the Australian and Queensland Governments agree that there is an overwhelming case for halting and reversing the decline in water quality in the waterways entering the GBR. The value of the GBR and the sustainable development of its catchment are seen to be of sufficient ecological and economical importance that early action is justified to reduce these risks. The results of several research programs during the 1990s (Haynes et al. 2001) identified GBR water quality as a major management issue for Government and precipitated the production of the *Great Barrier Reef Catchment Water Quality Action Plan* (Brodie et al. 2001). The Plan identified end of catchment pollutant load reduction targets for all catchments in the GBR and generated significant political interest. Since 2003, the Australian and Queensland Governments jointly implemented a Reef Water Quality Protection Plan (Reef Plan; Queensland Department of the Premier and Cabinet 2003) as the primary framework under which water quality issues in the GBR are addressed. The goal of the Reef Plan is to “halt and reverse the decline in water quality entering the Reef within 10 years” (i.e., by 2013). The Reef Plan identifies strategies and actions to address degraded water quality entering the GBR across several areas of interest including self management, education, economic incentives, planning, regulatory frameworks, research, partnerships, priorities and targets and monitoring. The actions are focused on

**Table 3** Preliminary eutrophication assessment of the inshore GBR region south of Cooktown

| Criteria | Exceedance value | Data source | Eutrophication assessment |
|---|---|---|---|
| DIN > 1.0 μM (long term average value) | Not exceeded | Johnson et al. (2010), Schaffelke et al. (2009) | No evidence |
| DIN > 1.0 μM (seasonal peak) | Wet Tropics = 3.2 μM<br>Burdekin = 5.2 μM<br>Mackay WS = 0.5 μM<br>Fitzroy = 5.7 μM<br>Burnett Mary = insufficient data (ID) | Devlin et al. (2009) | Evidence of short term, elevated nutrient pulses above the draft guideline in four regions |
| Chl > 0.45 (long term annual average) | Mean (WT + Burd + MWS + Fitz) = 0.54 μg $L^{-1}$ | Brodie et al. (2007) | Evidence of a long term shift in ambient concentrations for central/south inshore GBR waters |
| Chl > 2.0 μg $l^{-1}$ (seasonal peak) | Wet tropics = 21 μg $l^{-1}$<br>Burdekin = 0.9 μg $l^{-1}$<br>Mackay WS = 1.2 μg $l^{-1}$<br>Fitzroy = 4.8 μg $l^{-1}$<br>Burnett Mary = ID | Devlin et al. (2001, 2009, 2010a), Johnson et al. (2010) | Evidence of seasonal peaks in chlorophyll biomass driven by nutrient enriched plume waters |
| Macroalgal<br>Threshold exceeded if macroalgal cover is stable at > 15% | Wet tropics<br>Daintree = 2.6% Not Exceeded (NE)<br>Johnstone = 3.8% (NE)<br>Tully = 29% Exceeded (E)<br>Burdekin = 20% (E)<br>Mackay WS = 2.1% (NE)<br>Fitzroy = 14% (NE) | Johnson et al. (2010), Thompson et al. (2010) | Evidence of increased production of macroalgal in some areas above guidelines |
| Coastal seagrass tissue nutrient concentrations<br>C:N below 20<br>C:P below 500<br>N:P above 30 = high N<br>N:P below 25 = high P | Locations where all these criteria are met exist in the Wet Tropics and Burdekin Regions from 2008/2009 monitoring results | McKenzie and Unsworth (2009) | Evidence of nutrient saturated conditions in several locations in the GBR. Quantitative assessment of these changes ongoing |
| Replacement of corals with coralline algae, filamentous algae, macroalgae and/or a variety of filter feeders (qualitative thresholds) | Measurements of coral health (diversity, juvenile mortality, recruitment and settlement) show that corals have been negatively impacted in parts of the central and southern GBR | Devantier et al. (2006), Thompson et al. (2010), Fabricius et al., 2005, Cooper et al. (2008), De'ath and Fabricius (2010) | Strong qualitative evidence of negative impacts on coral reefs driven by nutrient enrichment. Quantitative assessment of these changes ongoing |

**Table 3** continued

| Criteria | Exceedance value | Data source | Eutrophication assessment |
|---|---|---|---|
| Bioerosion of coral in nutrient enriched areas | No ongoing assessment data | Risk et al. (1995), Hutchings et al. (2005) | Some qualitative evidence of bioerosion occurring in central GBR reefs |
| Outbreaks of the crown-of-thorns starfish | Multiple outbreaks occurred between Lizard Island and Mackay in the third wave of COTS outbreaks (1993–2008) | Brodie et al. (2005), Moran and De'ath (1992), Sweatman et al. (2008) | Strong evidence on the increase in phytoplankton biomass and the shift between smaller picoplankton community to larger phytoplankton (diatoms and dinoflagellates) resulting in increases in preferential food for COTS larvae |
| Slow recovery from macroalgal dominance following an acute coral mortality event back to coral dominance | Ongoing assessment of recovery under Marine Monitoring program. Not quantified and published as yet | | |

Criteria are taken from the potential Criteria listed for the assessment of eutrophication on reef ecosystems (Table 2)

sediment, nutrient and pesticide management in the GBR catchments. As the Reef Plan approached its five-year (half-way) mark there was recognition of the need to begin to implement land management actions rather than just further planning. This was proposed to be done through improved partnership arrangements and an injection of significant funding. In late 2007, the Australian Government committed A$200 million over 5 years for a Reef Rescue program 'to tackle climate change and improve water quality in the Great Barrier Reef' (Australian Government 2007). This package included substantial funding (A$146 million) for a Water Quality Grants Scheme (for improved land management practices), and supporting monitoring, reporting and research programs, with additional funding to build partnerships. Many of the land management practices supported through the program are targeted at reducing nutrient runoff to the GBR.

In 2009 the Reef Plan was revised and updated (DPC 2009). This was supported by a scientific discussion paper, which updated current consensus of the status of water quality in the GBR (Brodie et al. 2008a, b). The statement reiterated the importance of water quality to ensure long term resilience of the GBR, particularly in the face of climate change, and presented evidence of the need to increase efforts to reduce the amount of nutrients, sediments and pesticides entering the GBR. In response to this evidence, the 2009 Reef Plan includes an additional long term goal to ensure that by 2020 the quality of water quality entering the GBR from adjacent catchments has no detrimental impact on the health and resilience of the GBR. Achievement of the Reef Plan goals will be assessed against quantitative targets established for land management and water quality outcomes (defined as end of catchment pollutant load reductions). These are largely complimentary to a set of targets designed to assess performance of the Reef Rescue investment and set a 50% reduction in nitrogen and phosphorus loads at end of catchments by 2013 (relative to the flow normalized loads estimated in 2009). The Reef Rescue targets specify different reductions for dissolved and particulate nutrients (25 and 10% respectively) to reflect management priorities. Within GBR waters, water quality guidelines that have been defined to sustain the health of GBR ecosystems have been developed included regionally specific and cross shelf guidelines for nutrients and chlorophyll (Great Barrier Reef Marine Park Authority 2009).

As part of the revision of the Reef Plan, the Queensland Government pursued the development of regulation for the management of agriculture in GBR catchments, with a focus on sugar cane and grazing land management practices. The Reef Protection Act has now been passed through the Queensland Parliament and implementation of the Regulations which accompany the Act are now underway.

## Monitoring and evaluation

Several monitoring programs have been operating in the GBR to measure the presence and fate of nutrients in the ecosystem, coupled with measurements of the source and delivery of nutrients to the GBR. Continuations of these programs are critical to evaluate the outcomes of Reef Plan implementation and Reef Rescue investment, and are critical for the long term assessment of the eutrophication status of the GBR.

Catchment based programs measure nutrient concentrations and loads delivered to the GBR and include catchment and end of catchment load water quality monitoring with sampling in major runoff events, when these exports predominantly occur (Hunter and Walton 2008), and several smaller scale regionally specific monitoring programs to support natural resource management plans (e.g. Bainbridge et al. 2007; Rohde et al. 2008; Packett et al. 2009). Many of these programs encourage community participation. These programs are critical for estimating the load of nutrients delivered to the GBR, however, an inadequacy of sampling sites in some locations and application of inconsistent methods over time (and between programs) has resulted in highly uncertain estimates to date. To demonstrate these limitations, specific examples are highlighted here. In the Tully River catchment Wallace et al. (2008, 2009) showed that a large proportion (up to 30%) of the total load of nitrogen and suspended sediment was present in waters in overbank flow on the floodplain and this was not included in load calculation made at the lowest gauging station in the river channel. Similarly it is clear that much of the nitrate lost from sugarcane fertiliser in many coastal catchments reaches the GBR via small stream discharge and possibly groundwater discharge and is thus not included in loads measured at the gauging station near the end of the river (Brodie and Bainbridge 2008; Rohde et al. 2008). Similarly, there is poor understanding of the role of, or impact of, discharges of contaminants from the coastal floodplain in dry season conditions. These chronic discharges are likely to include natural stream discharge and drainage from irrigation, and may contribute to nutrient enriched conditions in the GBR. The consequence of these shortfalls in nutrient load estimations is that management interventions cannot be fully evaluated, and quantification of the relationship between the delivery of nutrients to the GBR and ecosystem response is highly uncertain.

Other challenges in measurement and evaluation of nutrient management techniques, and transport, fate and impact of nutrients in the GBR, are related to geographic scales, temporal variability and system noise (Haynes et al. 2007; Bainbridge et al. 2009). A major limitation in detecting improvements in practices and measurable outcomes in GBR ecosystem health is the ability to detect the signal of change in the system and the effects of time lags (Bainbridge et al. 2009). Noise in the signal is due to system variability, natural occurrence of nutrients and sediments in the system and limitations of the capacity to monitor and model material transport and fate (Waterhouse et al. 2009). A good example of demonstrated time lags in system response to management changes is recorded in the Tully River catchment. The Tully River catchment is the least variable river in the GBR catchments, and yet very large increases in fertiliser use took 14 years to be robustly manifest (i.e. be detectable) as increasing nitrogen levels in the lower Tully River (Mitchell et al. 2001, 2009). This highlights the importance of the need for innovative monitoring and modelling techniques, and an improved understanding of the system dynamics to inform management decisions relating to eutrophication in the GBR.

Some of the limitations outlined above are being addressed through a new, comprehensive monitoring, modeling and reporting program to assess the progress of the Reef Plan and Reef Rescue initiatives (outlined above). The program uses a combination of monitoring and modeling techniques to inform progress on achieving load reduction targets by 2013. Specifically, monitoring and modelling results are used to report end-of-catchment loads of key pollutants (including dissolved and particulate nutrients) for each catchment in the GBR for current condition (2009) and changes relative to this condition every year thereafter (2010–2013). The program, known as the *Reef Plan Paddock to Reef Integrated Monitoring, Modelling and Reporting Program*, incorporates activities across geographic regions and scales—from paddock scale to sub catchment and catchment scale, to coastal and inshore reef environments. It involves monitoring and modelling a range of attributes ultimately relevant to the assessment of the status of the GBR, including management practices for reducing nutrient runoff and runoff water quality at the paddock, sub catchment, catchment and marine scales, and GBR ecosystem status. This approach relies on linking monitoring and modelling outputs at each scale and then across scales, and is described in further detail in Bainbridge et al. (2009). It is anticipated that this program could provide a large proportion of the information required to undertake an eutrophication assessment of the GBR based on the criteria proposed in Table 2 in the coming years.

## Conclusions

The presence of elevated chlorophyll *a* concentrations are indicative of elevated phytoplankton biomass in the inshore GBR lagoon south of Cooktown with chlorophyll *a* concentrations exceeding GBR water quality guidelines over this area (Table 3). Nutrient concentrations are above the Nutrient Threshold Criteria (Lapointe 1997; Bell et al. 2007) during high flow conditions in many parts of the inshore GBR. In addition, intense and extensive phytoplankton blooms follow nutrient-rich river discharge associated with agricultural activities with chlorophyll *a* regularly exceeding guidelines. Secondary impacts include shifts to macroalgal dominance on some inshore reefs and more intense COTS outbreaks.

From this preliminary assessment (Table 3) of eutrophication status of the inshore GBR south of Cook town, based on the suggested criteria, we conclude that this area is significantly enriched and possibly eutrophic at certain times of the year. Ongoing spatial risk assessments (e.g. Devlin et al. 2010), exposure maps (e.g. Maughan and Brodie 2009), water quality gradients and spatial mapping of impact (e.g. Cooper et al. 2008; De'ath and Fabricius 2010) all show an area of enrichment, higher production and changes in benthos and fish distribution.

This assessment is preliminary and based on data that was not collected to assess eutrophication status, however they are based on the current best available knowledge and incorporate the outcomes of many years of research related to nutrient status and impact in the GBR. Further effort to develop these criteria in collaboration with other scientific experts will generate a highly valuable tool for managers of the GBR.

Given the major management response to this risk has been commenced, it is still unclear as to whether the correct pollutants (i.e. between sediments, nitrogen, phosphorus and pesticides) are being prioritized for appropriate management in individual catchments. Analysis to be able to better prioritized across catchments and regions continues (Brodie and Waterhouse 2009, Brodie et al. 2009b) but further work in a risk analysis framework is required. It is also unclear as to whether the Reef Plan 2009 targets for reduced nutrient inputs (50% reduction in Nitrogen and Phosphorus discharge by 2013) or the Reef Rescue targets (25% reduction in dissolved nitrogen and phosphorus and 10% reduction in particulate nitrogen and phosphorus by 2013) will be enough to achieve the desired end point for the GBR. One of the possible end points for reducing the probability of eutrophication occurring would be that all GBR waters meet water quality guidelines for chlorophyll (Brodie et al. 2009a, b). Further research on the validity of the current targets is planned.

The next 10 years will be vital for the protection and rehabilitation of the inshore reef system from the detrimental impacts of poor water quality. Continued monitoring and assessment are essential in the evaluation of these ongoing management actions and the delivery of a "cleaner" GBR in respect to water quality and associated impacts. A more robust GBR may be more resilient to the combined impacts and increasing climate change stresses.

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