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Assessment of the Water Quality and Ecosystem Health of the Great Barrier Reef (Australia): Conceptual Models

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Abstract Run-off containing increased concentrations of sediment, nutrients, and pesticides from land-based anthropogenic activities is a significant influence on water quality and the ecologic conditions of nearshore areas of the Great Barrier Reef World Heritage Area, Australia. The potential and actual impacts of increased pollutant concentrations range from bioaccumulation of contaminants and decreased photosynthetic capacity to major shifts in community structure and health of mangrove, coral reef, and seagrass ecosystems. A detailed conceptual model underpins and illustrates the links between the main anthropogenic pressures or threats (dry-land cattle grazing and intensive sugar cane cropping) and the production of key contaminants or stressors of Great Barrier Reef water quality. The conceptual model also includes longer-term threats to Great Barrier Reef water quality and ecosystem health, such as global climate change, that will potentially confound direct model interrelationships. The model recognises that system-specific attributes, such as monsoonal wind direction, rainfall intensity, and flood plume residence times, will act as system filters to modify the effects of any water-quality system stressor. The model also summarises key ecosystem responses in ecosystem health that can be monitored through indicators at catchment, riverine, and marine scales. Selected indicators include riverine and marine water quality, inshore coral reef and seagrass status, and biota pollutant burdens. These indicators have been adopted as components of a long-term monitoring program to enable assessment of the effectiveness of change in catchment-management practices in improving Great Barrier Reef (and adjacent catchment) water quality under the Queensland and Australian Governments' Reef Water Quality Protection Plan.

Keywords Agricultural runoff · Great Barrier Reef · Conceptual model · Ecosystem status · Monitoring · Water quality

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The Great Barrier Reef is the largest reef system in the world and extends for >2,300 km along the northern Queensland (Australian) continental shelf (Fig. 1). It consists of an archipelagic complex of >2,900 reefs and covers an area of approximately 225,000 km^2. A majority of the reefs are situated on the mid- and outer-continental shelf and are located 40 to 150 km from the mainland. A significant number of reefs (approximately 750) also exist at "inshore" or "nearshore" sites within 40 km of the Queensland coast (Furnas and Brodie 1996).

The Great Barrier Reef was listed on the World Heritage Register in 1981 in recognition of its outstanding universal value (Lucas and others 1997). Protection of the ecologic systems of the Great Barrier Reef World Heritage Area from water-sourced pollutants is recognised as being one the critical issues for management of the World Heritage Area (Haynes and others 2001). Evidence derived from

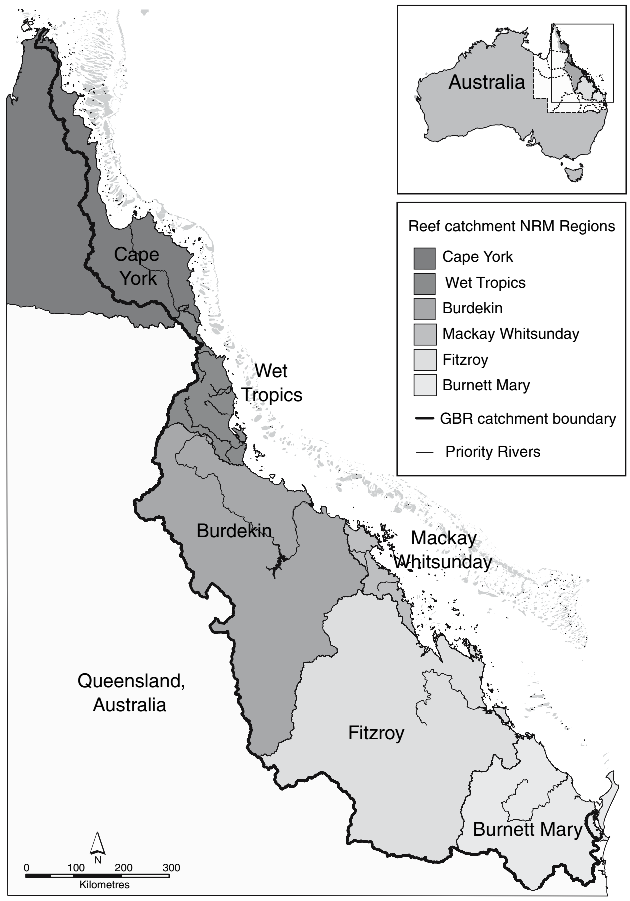

Fig. 1 The Great Barrier Reef and its catchments

modelling and sampling of relatively undisturbed catchments of far-northern Cape York indicate that the export of sediments and nutrients from southern disturbed catchments to the marine environment has increased dramatically during the last 150 years (Furnas 2003; Table 1). There is also increasing evidence concerning the contamination of coastal ecosystems with a range of modern pesticide residues (Haynes and others 2000a; Mitchell and others 2005; Shaw and Műller 2005). Degradation of inshore reefs of the Great Barrier Reef has been associated with increased terrestrial runoff of pollutants in the region between Port Douglas and the Whitsundays (Udy and others 1999; van Woesik and others 1999; Fabricius and De'ath 2004; Fabricius and others 2005; Devantier and others 2006), and damage to both inshore and outer-shelf reefs of the central Great Barrier Reef from Crown of Thorns Starfish (*Acanthaster planci*) outbreaks has been attributed to increased terrestrial nutrient runoff (Brodie and others 2005).

Pollutant loads originating from land-based runoff are predicted to continue to increase, and there is an immediate need to improve current land-management regimes to minimise this runoff (Brodie and others 2001a; Brodie and Mitchell 2005). A key strategy to affect this change is the recently released Reef Water Quality Protection Plan (Anon 2003). This plan builds on existing government policies and industry and community initiatives and aims to assist in halting and reversing the decline in the quality of water entering the Great Barrier Reef. This will help in the overall protection of the ecological health of the Great Barrier Reef as well as the health of its adjacent catchments and waterways. The Reef Water Quality Protection Plan compliments previous policy that advocated water-quality targets for land-based pollutants discharged to the marine environment (Brodie and others 2001b).

Table 1 Estimates of change in pollutant inputs to the Great Barrier Reef (from Furnas 2003)

Inputs	Pre-1850′s annual pollutant flux estimate	Current annual pollutant flux estimate
Sediment	1–5 million ton	14 million tons/y
Phosphorus	2,400 tons/y	7,000 tons/y
Nitrogen	23,000 tons/y	43,000 tons/y

This article summarises the impacts of key water-quality parameters on tropical marine ecosystems and provides a framework on which a long-term water-quality and ecosystem monitoring program has been developed. The monitoring program is described in detail in a companion article (Haynes and others 2007).

Conceptual Models and Monitoring Programs

Conceptual models are a key component in the development of an integrated monitoring program to assess trends in the ecologic status of a system. They assist in identifying the main environmental stressors or threats, appropriate indicators of ecosystem health, and relations or linkages between the stressors and the indicators. Additionally, conceptual models are an important tool for communicating how complex ecologic systems work, the ecologic and physicochemical interactions between the various components, and which components and linkages might be targeted by specific management actions (Jorgensen 1988; Newton and others 1998; Gross 2003; Downs and others 2005).

In the Great Barrier Reef, conceptual models have been used to underpin process models that describe connections in the paddock-to-reef continuum, *e.g.*, models describing catchments (the SedNet/ANNEX model system, McKergow and others 2005), in risk assessments (Greiner and others 2005), in models describing estuaries and coastal waters (Robson and others 2006) and in models describing reef waters (Wolanski and others 2003, 2004; Wolanski and De'ath 2005; Wooldridge and others 2006). Elsewhere,

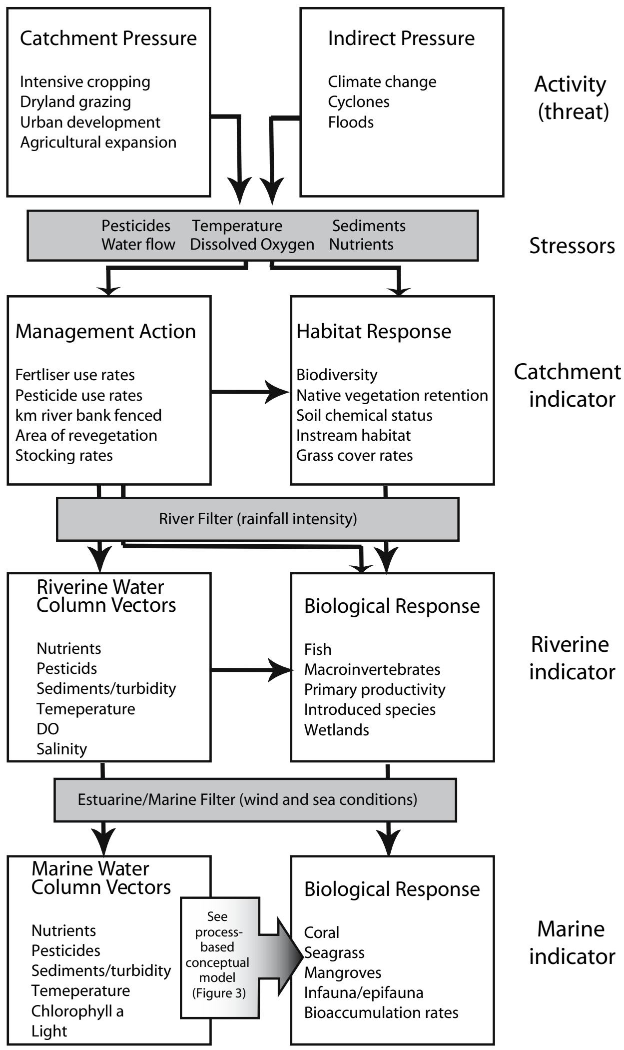

Fig. 2 Great Barrier Reef pressure, Vector, response water-quality conceptual model

other models of land and coral reef interactions have been developed using so-called fuzzy logic (Meesters and others 1998; Ruitenbeek and others 1999), but these have only addressed coral reef impacts and fail to include the catchment drivers of environmental effects.

Development of the Reef Water Quality Protection Plan monitoring program was assisted by three conceptual models that encapsulate the risks posed to reef ecosystems from catchment (agricultural and urban) development:

1. A broad-scale system conceptual model (Fig. 2) shows the relations between contaminant generation in the Great Barrier Reef catchment, transport of these contaminants through the catchment by way of local rivers and their estuaries, and their effects on water quality and ecosystem health in the Great Barrier Reef lagoon. In particular, the model illustrates the conceptual links between dry-land grazing and intensive cropping activity (pressures and threats) and the production and dispersion of key water-quality contaminants (stressors). Also shown are the ecosystem attributes (indicators) that can be used to monitor ecosystem health at the catchment, riverine, and marine scales. This conceptual model also includes reference to longer-term threats to Great Barrier Reef water quality and ecosystem health, such as global climate change, that will potentially confound direct model relationships. The model also recognise that system-specific attributes, such as monsoonal wind direction, rainfall intensity and flood plume residence times, will act as system filters to modify the effects of the stressors (Cloern 2001; Devlin and others 2003). In particular, concentrations of suspended sediments, particulate and dissolved nutrients, and pesticide residues in rivers flowing into the Great Barrier Reef region reach peak values during flood events, which are typically associated with monsoonal rainfall and cyclonic activity (Devlin and others 2003), and the movement of river-discharged pollutants in the marine environment is modified by wind direction and intensity and wave action.
2. A process-based conceptual model (Fig. 3) illustrates the movement and partitioning of contaminants between the water column, marine sediments, and marine biota. The physical and biogeochemic properties of contaminants determine the ways in which they disperse in the environment (Bewers and others 1992). This model has been used to ensure that the appropriate ecosystem compartments were sampled and that information was collected on parameters that could influence the biogeochemical properties of the contaminants.
3. A risk-based conceptual model identifies the regions of the Great Barrier Reef lagoon that are at high risk from contaminants transported from the catchment. In particular, adjacent land use and distance and direction of a reef or other ecosystem from the mouth of the major rivers both have significant influence on the potential risk posed by land runoff (Devlin and others 2003; Greiner and others 2005). This latter model has been most useful in optimising sample collection sites and is fully discussed in the second article in this series (Haynes and others 2007).

Catchment Activity (Pressures and Threats)

The coastal region adjoining the Great Barrier Reef World Heritage Area is divided into 40 wet and dry tropical catchments draining directly into the Great Barrier Reef

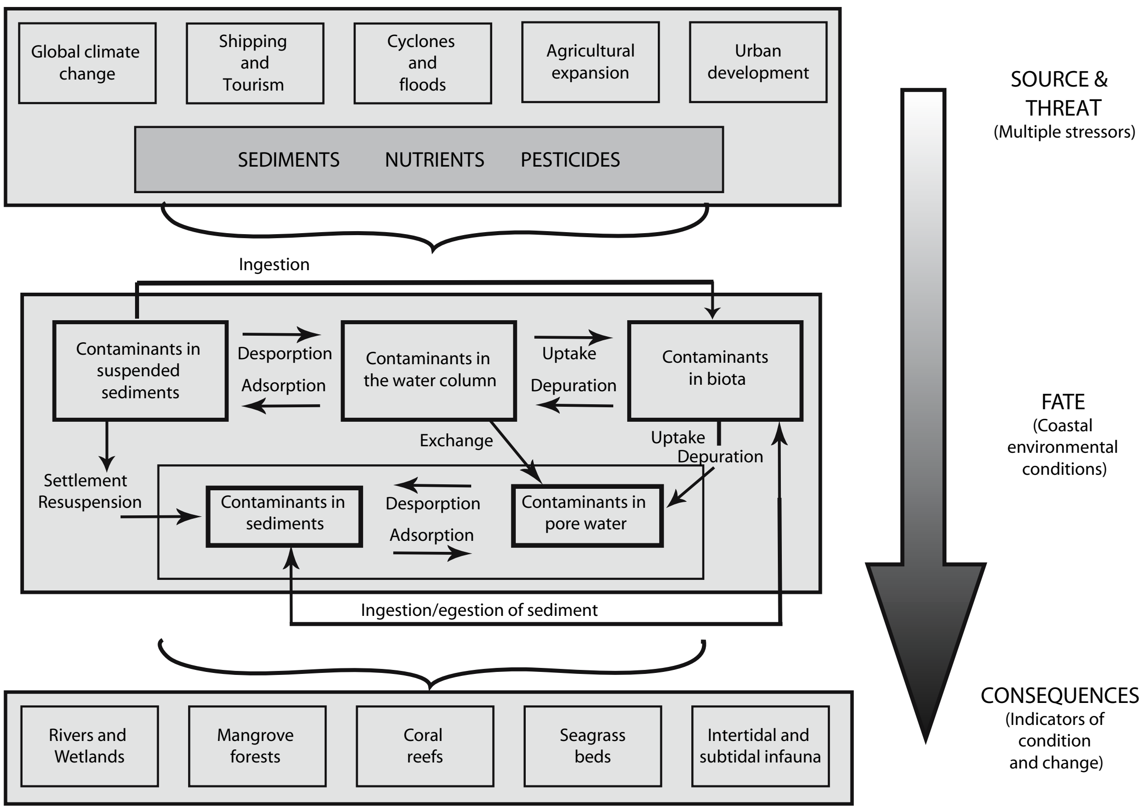

Fig. 3 Great Barrier Reef lagoon process based conceptual model (adapted from Bewers and others 1992)

lagoon (Gilbert and Brodie 2001). Most catchments are small (<10,000 km^2); however, the Burdekin and Fitzroy River catchments (133,000 and 143,000 km^2, respectively) are among the largest in Australia (Fig. 1). Human activity in these catchments is the primary determinant of altered water quality that is ultimately transmitted to the Great Barrier Reef World Heritage Area.

Although the region remains relatively sparsely populated, extensive land clearing has occurred during the last 200 years since European settlement, and approximately 80% of the land area of catchments adjacent to the Great Barrier Reef World Heritage Area now supports some form of agricultural production (Gilbert and Brodie 2001). Grazing of beef cattle is the largest single land use in Great Barrier Reef catchments, and this has resulted in extensive clearance of forests for conversion to pasture (Gilbert and Brodie 2001). Intensive cropping, mainly of sugarcane but with considerable areas of horticulture and cotton and grain crops, is a significant agricultural industry in the catchments between Bundaberg and Port Douglas. Agriculture and urban expansion have resulted in the loss of substantial areas of coastal wetlands in north Queensland, particularly during the last 50 years (Johnston and others 1998; Finlayson and Lukacs 2003). This has significant ramifications for coastal habitat and local water quality, with the loss of nutrient removal and transformation mechanisms, sediment and toxicant retention, flood flow alteration, and disruption of groundwater discharge and recharge (Lukacs 1998).

Catchment-Based Contaminants (Stressors)

The three major classes of water-quality contaminants increased by human activities in Great Barrier Reef catchments are sediments, nutrients, and pesticides. Land clearing and removal of woodlands for the establishment of grazing pasture has greatly increased soil erosion and sediment loss to local watercourses. Sediment loss is exacerbated by chronic overgrazing during drought periods (McIvor and others 1995). Sugarcane cultivation was also a major source of eroded material under conventional cultivation practices. However, recent management improvements in the sugarcane industry, including green cane harvesting and trash blanketing and minimum tillage, have decreased soil losses by approximately 80% (Rayment 2003). Trash and stubble retention in other cropping systems (cotton, bananas) has also decreased erosion rates (Faithful and Finlayson 2005).

Sugarcane cultivation requires substantial use of inorganic fertiliser, particularly nitrogen. It is estimated that only 35% of the fertiliser applied to sugarcane (typically 150–200 kg/ha/y nitrogen fertiliser) is used by the crop in the year of application (Reghenzani and others 1996); the remainder is lost to the environment (to the atmosphere by way of volatilisation and denitrification and to groundwaters and runoff) or stored in the soil, including trash storage (Freeny and others 1994; Bohl and others 2000; Rasiah and Armour 2001). The proportion lost to each compartment depends on climate, weather, soil type, cultivation practices, fertiliser-application practices, and hydrology (McShane and others 1993; Reghenzani and others 1996).

The use of pesticides (herbicides, insecticides, and fungicides) in Great Barrier Reef catchments has increased progressively in areas under crop cultivation (Hamilton and Haydon 1996). There has also been a shift from the use of organochlorine-based compounds such as DDT, dieldrin, and heptachlor as they were progressively restricted and banned for use between 1973 and 1994. Modern use includes triazine, organophosphate, and urea-based pesticides. Organochlorines and modern agricultural pesticides are widely distributed in Queensland catchment soils, irrigation drains, and river sediments and in the nearshore marine environment adjacent to human activity (Haynes and others 2000a 2006; Müller and others 2000; McMahon and others 2005; Mitchell and others 2005; Shaw and Müller 2005).

Contaminant Transport (Vectors and Filters)

Land-based contaminants generated in the catchment from various land uses are transported to waterways by way of surface runoff and subsurface water flows. Most of this transport occurs during high-intensity rainfall events, when the contaminants are released from the landscape in major flow events (Mitchell and others 1997, 2005). The loads of sediment, nutrients, and pesticides discharged from any one Great Barrier Reef river are proportional to rainfall, to the volume of freshwater discharged during the wet season, and to the extent and type of agricultural land in the catchment (Brodie and Mitchell 2005).

Estimates of runoff from Great Barrier Reef catchments show that most of the sediment (approximately 85%) and nutrients (approximately 65% for N and 78% for P) originate from the southern "dry" catchments that are dominated by grazing, such as the Burdekin and Fitzroy Rivers, where the larger volumes of discharge from these rivers are characterised by greater loads of sediments and nutrients per unit volume of discharge. However, wet tropical catchments (*e.g.*, Tully and Johnstone) have the highest sediment and nutrient loss rates per unit of catchment area, reflecting their higher local rainfall and erosion rates (Brodie and Mitchell 2005).

Waters discharged in flooding rivers form plumes that extend out into the nearshore marine environment of the Great Barrier Reef (Brodie and Furnas 1996; Devlin and others 2001). Mapping and coring of sediments in the Great Barrier Reef lagoon shows that most of the eroded sediment transported by these river systems is deposited within 10 km of the coast (Orpin and others 1999; Lambeck and Woolfe 2000; Neil and others 2002; Orpin and others 2004; Pfitzner and others 2004). Under normal conditions (southeasterly trade winds), these flood plumes flow northward from the river mouth for distances of up to 200 km but are usually constrained to within 20 km of the coast. Dissolved materials, including dissolved nutrients, are transported hundreds of kilometers in flood plumes both offshore and more commonly alongshore (Devlin and others 2001; Devlin and Brodie 2005; Rohde and others 2006). Major floodwaters and their associated dissolved nutrients originating from large rivers, such as the Burdekin River, may extend northward for up to 450 km (Wolanski and van Senden 1983; Devlin and Brodie 2005). Nutrient concentrations in these river plumes can be up to 100 times higher than seawater concentrations in nonflood periods (Devlin and others 2001; Devlin and Brodie 2005; Rohde and others 2006). Inshore ecosystems may be exposed to plume waters and their entrained contaminants for periods of days to weeks during the wet season (Devlin and Brodie 2005).

Secondary transport of contaminants, especially particulate matter, occurs in the period after flood plumes dissipate as wind-generated turbulence and currents resuspend inshore sediments and transport them northward along the coast (Orpin and others 1999). Ultimately, most of the fine sediment in inshore waters is trapped in northward-facing bays (*e.g.*, Broad Sound, Bowling Green Bay, Princess Charlotte Bay) (Orpin and others 2004).

Impacts of Contaminants in the Marine Environment (Indicators)

Three of the major ecosystem types that make up the Great Barrier Reef system (mangroves, seagrass, and corals) are affected differently by water-column contaminants. Mangroves are believed to be affected by herbicides, whereas corals and seagrasses are more affected by increases in suspended sediment and nutrient concentrations as well as by herbicide exposure (Bell and Duke 2005; Duke and others 2005; Fabricius 2005; Jones 2005; Negri and others 2005; Waycott and others 2005).

Nutrient Impact Indicators

The waters of the Great Barrier Reef are characterised by high ambient light intensities and water temperatures. As a consequence, available nutrients are rapidly taken up by phytoplankton and converted to organic matter, particularly in interreef regions (Furnas and others 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 two to three times higher in inshore waters of the central and southern Great Barrier Reef compared with areas in the northern Great Barrier Reef (Brodie and others 2007). This is believed to reflect their enhanced nutrient status, which is attributed to terrestrial nutrient discharge from rivers in the central and southern Great Barrier Reef associated with agricultural activities.

Fabricius (2005) and Schaffelke and others (2005) have recently summarised the ways in which increased nutrient concentrations may result in a range of impacts on coral and seagrass communities. Macro-and micro-algal blooms are produced by higher nutrient concentrations, and macroalgae may overgrow coral structures, outcompeting polyps for space and shading coral colonies to critical levels (Hunter and Evans 1995; Stimson and others 2001). Excessive nutrients may also depress coralline algal growth and inhibit reef consolidation (Björk and others 1995). Chronic exposure to increased concentrations of dissolved inorganic nutrients, such as nitrate, can interfere with the relationship between corals and their zoooxanthellae and result in decreased calcification rates (Stambler and others 1994; Marubini and Atkinson 1999; Ferrier-Pages and others 2001). This may weaken the coral skeleton and make coral colonies more susceptible to damage from storm action (Stambler and others 1991; Ferrier-Pages and others 2000). Boring organisms may bioerode coral reef structures at higher rates under increased nutrient conditions, further decreasing overall reef consolidation (Kiene and Hutchings 1994).

Additionally, there is evidence suggesting that coral reproduction and recruitment are highly sensitive to increased nutrient concentrations (Wittenberg and Hunte 1992; Hunte and Wittenberg 1992; Fabricius 2005), with increased concentrations of dissolved organic nutrients inhibiting coral reproductive processes, such as egg size, fertilisation rates, and embryo formation (Ward and Harrison 2000; Koop and others 2001; Cox and Ward 2002). Increased concentrations of particulate organic matter can inhibit all aspects of coral recruitment, including egg fertilization, larval development, larval survival and larval settlement and metamorphosis (Gilmour 1999).

Increased nutrient concentrations can also be deleterious to seagrasses by lowering ambient light levels by way of proliferation of local light-absorbing algae (including water-column phytoplankton, benthic macro algae, or algal epiphytes) and decreasing the photosynthetic capability of seagrass (Walker and others 1999). Increased 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.

Increased concentrations of nutrients sourced from agricultural activities have been linked to an expansion in the range of seagrasses (*e.g.*, *Syringodium isoetifolium*) around Green Island since the 1970s (Udy and others 1999). Also, data collected along the north Queensland coast suggest that the tissue nutrient status of the seagrass *Halophila ovalis* has increased during a 20-year period in concert with increasing fertiliser use by the local agricultural industry and that this seagrass species may be a good bioindicator of local nutrient conditions (Mellors and others 2005).

Sediment Impact Indicators

Evidence exists that high, chronic inputs of terrestrial sediment and organic matter lead to a range of coral and seagrass impacts through shading, smothering, burial, disruption of recruitment, or deleterious community shifts (Dodge and others 1974; Longstaff and Dennison 1999). In contrast, mangroves often respond to increased sediment concentrations through expansion of their range, particularly in areas where river flows and flushing are decreased (Schaffelke and others 2005).

Regardless of whether such sediment loads are natural or the result of human activity, excessive sediment loads can impact corals through smothering when particles settle out (Riegl 1995; Philipp and Fabricius 2003), and by decreasing light availability, coral photosynthesis, and growth (from increased water turbidity) (Rogers 1990; Kleypas 1996; Anthony 1999). Sediments with a higher content of organic matter are more damaging than “clean” sediments in a smothering situation (Weber and others 2006). Sediment impacts on corals can include changes to coral population structure and colony size, altered growth forms, and decreased growth and survival (Rogers 1990; Anthony 2000; Anthony and Fabricius 2000). In particular, low concentrations of sediments and dissolved mucopolysaccharides released by bacteria and other microorganisms can coat corals (Fabricius and Wolanski 2000; Fabricius and others 2003). This creates a metabolic energy drain when the coral removes the aggregate that may decrease reproductive capacity and the organism’s capacity to grow (Stafford-Smith 1993; Riegl and Branch 1995; Telesnicki and Goldberg 1995). Early life–stage corals are at most risk from accumulated sediment through prevention of larval settlement (Hodgson 1990; Gilmour 1999) or burial of the juvenile recruit (Babcock and Davies 1991; Babcock and

Mundy 1996; Fabricius and others 2003). Sedimentation is also suspected to adversely impact abundance of crustose coraline algae and influence the development of algal turfs. Both of these effects will compromise coral recruitment (Birrell and others 2005; Harrington and others 2005).

Increases in suspended sediment concentrations and water-column turbidity cause a decrease in water-column light penetration that can adversely affect seagrass photosynthesis rates (Longstaff and Dennison 1999). Seagrass losses of over 1,000 km^2 were observed in Hervey Bay, southern Queensland in 1992 and again in 1999 during cyclone and storm events (Preen and others 1995; Campbell and McKenzie 2004). Seagrass loss was attributed to river turbidity decreasing the amount of light reaching the plants as well as to physical removal of seagrass by cyclone and storm action (Preen and others 1995; Longstaff and others 1999).

Pesticide Impact Indicators

The herbicides diuron, simazine and, atrazine are commonly found in flood plumes, coastal waters, and sediments in the Great Barrier Reef region (Haynes and others 2000a; McMahon and others 2005; Rohde and others 2005; Shaw and Muller 2005). More than half of the commonly used herbicides such as diuron exert a toxic effect by restricting electron transfer within the photosynthetic chloroplast of the target plant or alga, leading to a decrease in photosynthetic efficiency (Jones 2005). Because most adult corals rely on symbiotic dinoflagellates to provide additional energy requirements for colony functioning, this may result in a loss of fitness in the host coral polyp (Jones and others 2003). Under extreme conditions, high concentrations of the herbicide, or long periods of exposure to it will result in expulsion of the symbiont (bleaching) from the adult coral (Jones and Kerswell 2003; Jones and others 2003).

Laboratory trials have indicated that these types of herbicides are unlikely to affect fertilisation or metamorphosis in corals at the concentrations likely to be present in inshore Great Barrier Reef waters (Negri and others 2005). However, they may depress photosynthetic activity in juvenile and adult coral symbionts (Negri and others 2005). Laboratory experiments have also shown that low concentrations (3 $\mu g\ l^{-1}$) of diuron will inhibit photosynthesis in crustose coralline algae (Harrington and others 2005). Photosynthetic inhibition is increased when coralline algae are exposed to both diuron and fine sediment (Harrington and others 2005). This may compromise coral recruitment because crustose coralline algae are a critical settlement inducer for many coral species (Heyward and Negri 1999).

A limited number of laboratory trials have investigated the toxicity of diuron and other herbicides to tropical seagrass species (Haynes and others 2000b; Ralph 2000). Effective quantum yield as a measure of photosynthetic activity in *Halophila ovalis* and *Zostera capricorni* was found to be significantly depressed by diuron concentrations between 0.1 and 100 $\mu g\ L^{-1}$ after 5 days of laboratory herbicide exposure, whereas effective quantum yield in *Cymodocia serrulata* was only significantly decreased in plants exposed to higher diuron concentrations (10 and 100 $\mu g\ L^{-1}$). *H. ovalis* was similarly affected by the herbicides atrazine and simazine. These results indicate that exposure to herbicide concentrations present in inshore Queensland sediments present a potential risk to seagrass functioning, particularly during flood conditions (Haynes and others 2000a; McMahon and others 2005). Laboratory trials have also indicated the relative sensitivity of some mangrove species to diuron exposure compared with other commonly used herbicides (Bell and Duke 2005; Schaffelke and others 2005).

Confounding Stressors and Impacts

The quantity and subsequent impacts of land sourced sediment, nutrient, and pesticide discharges to tropical marine ecosystems may also be fundamentally influenced and/or confounded by a range of indirect water-quality threats. These indirect threats include global climate change, river floods, cyclonic weather systems, and increased capacity for reef algal growth caused by loss of algal grazers, particularly grazing fish (Hughes 1994). These confounding impacts may all be interlinked (Pandolfi and others 2003; Bellwood and others 2004). The expected primary consequence of global climate change is increased seawater temperatures and changes in ocean chemistry (Hughes and others 2003). Increased seawater temperatures increase the frequency and intensity of coral bleaching as well as the incidence of coral disease (Hoegh-Guldberg 1999; Hughes and others 2003). The recognised biological effects of bleaching are decreased coral growth and calcification, decreased reproductive output, and increased mortality (Goreau and MacFarlane 1990). Increased carbon dioxide concentrations in seawater enhance the dissolution of calcium carbonate. This may decrease calcification rates in coral species and lead to changes in coral community structure, reproduction, and overall functioning in coral reef environments (Kleypas and others 1999). The frequency and intensity of tropical cyclones and the damage they induce is also expected to increase as a consequence of global warming with the long-term elevation of seawater temperatures (Hughes and others 2003). The resultant increase in frequency and intensity of river flooding and freshwater inundation of inshore marine waters will result in increased coral mortality, particularly when this coincides with periods of increased seawater temperatures and coral bleaching (Berkelmans and Oliver 1999). The impacts of these stressors must be quantified in a monitoring program to accurately partition the influence of land-sourced pollutants on the reef systems being monitored.

The Reef Water Quality Protection Plan Monitoring Program

The implementation of a long-term water-quality and ecosystem monitoring program based on the conceptual models previously described is central to assessment of the success of land management strategies initiated under the Reef Water Quality Protection Plan (Anon 2003) to improve reef water quality. This Great Barrier Reef marine-monitoring program is comprised of four complimentary subprograms. River-mouth water quality monitoring is carried out to assesses long-term change in the concentrations and loads of the major land-sourced pollutants (including sediments, nutrients, and pesticides) discharged to the marine environment that have the potential to adversely affect coral reef, mangrove, and seagrass ecosystems. Water-quality monitoring is also carried out in the inshore waters (i.e., within 10 to 15 kms of the coast) of the Great Barrier Reef to assess changes with time in concentrations of similar water-quality indicators. Monitoring of the major marine ecosystem types most at risk from land-based pollutants (*e.g.,* intertidal seagrass beds and inshore coral reefs) is carried out to ensure that any change in their status is identified. Coral and seagrass monitoring sites are associated with the inshore marine water-quality monitoring program to enable correlation with concurrently collected water-quality information. In the fourth subprogram, mud crab (*Scylla serrata*) pollutant concentrations are assessed to monitor the accumulation of specific pesticide and polyaromatic hydrocarbon concentrations in inshore marine biota. Information on weather and sea conditions—including rainfall, seawater temperature and salinity, and river discharge volumes—is also collected to help with interpretation of biological data. In addition, two further subprograms are carried out in the catchments of the Great Barrier Reef. Change in the export of pollutants correlated with land-management change at the property scale are measured through intensive, small-scale monitoring programs, whereas at the subcatchment scale, monitoring of pollutants in event flows allows identification of primary source areas of pollutants and their correlation with different land-management practices. The Reef Water Quality Protection Plan monitoring program is described in detail in a companion article (Haynes and others 2007).

Conclusion

The conceptual models presented here are the first attempt to produce a comprehensive model of catchment to reef pollution and ecological response. This has enabled the construction of numeric models based on these articulated relationships. Quantification of the concepts is now being attempted by way of a number of approaches, including the use of Bayesian Belief Networks (*e.g.*, Thomas and others 2005), fine-scale process models (Robson and others 2006), and empirical process approaches (*e.g.*, Wooldridge and other 2006).

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References

Anonymous (2003) Reef water quality protection plan: for catchments adjacent to the Great Barrier Reef World Heritage Area. Queensland Department of Premier and Cabinet, Brisbane, Australia

Anthony KRN (1999) Coral suspension feeding on fine particulate matter. Journal of Experimental Marine Biology and Ecology 232:85–106

Anthony KRN (2000) Enhanced particle-feeding capacity of corals on turbid reefs (Great Barrier Reef, Australia). Coral Reefs 19:59–67

Anthony KRN, Fabricius KE (2000) Shifting roles of heterotrophy and autotrophy in coral energy budgets at varying turbidity. Journal of Experimental Marine Biology and Ecology 252:221–253

Babcock R, Mundy C (1996) Coral recruitment: Consequences of settlement choice for early growth and survivorship in two scleractinians. Journal of Experimental Marine Biology and Ecology 206:179–201

Babcock R, Davies P (1991) Effects of sedimentation on settlement of *Acropora millepora*. Coral Reefs 9:205–208

Bell AM, Duke NC (2005) Effects of photosystem II inhibiting herbicides on mangroves—preliminary toxicology trials. Marine Pollution Bulletin 51:297–307

Bellwood DR, Hughes TP, Folke C, Nystrom CM (2004) Confronting the coral reef crisis. Nature 429:827–833

Berkelmans R, Oliver J (1999) Large-scale bleaching of corals on the Great Barrier Reef. Coral Reefs 18:55–60

Bewers JM, Blanton JO, Davies AM Gurbutt PA, Hofmann EE, Jamart BM et al. (1992) A conceptual model of contaminant transport in coastal marine ecosystems. Ambio 21:166–169

Birrell CL, McCook LJ, Willis BL (2005) Effects of algal turfs and sediment on coral settlement. Marine Pollution Bulletin 51:408–414

Bjôrk M, Mohammed SM, Bjôrklund M, Semesi A (1995) Coralline algae, important coral-reef builders threatened by pollution. Ambio 24:502–505

Bohl HP, Mitchell DC, Penny RS, Roth CH (2000) Nitrogen losses via subsurface flow from sugar cane on floodplain soils in the Australian wet tropics. *Proceedings of the Australian Society of Sugar Cane Technologists* 22:302–307

Brodie J, Furnas MJ (1996) Cyclones, river flood plumes and natural water quality extremes in the central Great Barrier Reef. In

Hunter HM, Eyles AG Rayment GE (eds) Downstream effects of land use. Queensland Department of Natural Resources, Brisbane, Australia pp 367–374

Brodie J, Christie C, Devlin M, Haynes D, Morris S, Ramsay M et al. (2001a) Catchment management and the Great Barrier Reef. Water Science and Technology 43:203–211

Brodie J, Furnas M, Ghonim S, Haynes D, Mitchell A, Morris S et al. (2001b) Great Barrier Reef Catchment Water Quality Action Plan. Great Barrier Reef Marine Park Authority, Townsville, Queensland, Australia, 116pp

Brodie J, Mitchell A (2005) Nutrients in Australian tropical rivers: changes with agricultural development and implications for receiving environments. Marine and Freshwater Research 56(3):279–302

Brodie J, Fabricius K, De'ath G, Okaji K (2005) Are increased nutrient inputs responsible for more outbreaks of crown-of-thorns starfish? An appraisal of the evidence. Marine Pollution Bulletin 51(1–4):266–278

Brodie J, De'ath G, Devlin M, Furnas M, Wright M (2007) Spatial and temporal patterns of near-surface chlorophyll a in the Great Barrier Reef lagoon. Marine and Freshwater Research 58:1–12

Cambell SJ, McKenzie JJ (2004) Flood related loss and recovery of intertidal seagrass meadows in southern Queensland, Australia. Estuarine, Coastal, and Shelf Science 60:477–490

Cloern JE (2001) Our evolving conceptual model of the coastal eutrophication problem. Marine Ecology Progress Series 210:223–253

Cox EF, Ward S (2002) Impact of elevated ammonium on reproduction in two Hawaiian scleractinian corals with different life history patterns. Marine Pollution Bulletin 44:1230–1235

DeVantier LM, De'ath G, Turak E, Done TJ, Fabricius KE (2006) Species richness and community structure of reef-building corals on the nearshore Great Barrier Reef. Coral Reefs 25:329–340

Devlin M, Waterhouse J, Taylor J, Brodie J (2001) Flood plumes in the Great Barrier Reef: spatial and temporal patterns in composition and distribution. GBRMPA Research Publication No 68, Great Barrier Reef Marine Park Authority, Townsville, Queensland, Australia

Devlin M, Brodie J, Waterhouse A, Mitchell D, Audas D, Haynes D (2003) Exposure of Great Barrier Reef inner-shelf reefs to riverbourne contaminants. In Proceedings of the 2nd National Conference on Aquatic Environments: sustaining our aquatic environments, implimenting solutions. Queensland Department of Natural Resources and Mines, Brisbane, Australia

Devlin M, Brodie J (2005) Terrestrial discharge into the Great Barrier Reef Lagoon: nutrient behaviour in coastal waters. Marine Pollution Bulletin 51:9–22

Dodge RE, Aller RE, Thomson J (1974) Coral growth related to resuspension of bottom sediments. Nature 247:574–576

Downs CA, Woodley CM, Richmond RH, Lanning LL, Owen R (2005) Shifting the paradigm of coral reef health assessment. Marine Pollution Bulletin 51:486–494

Duke NC, Bell AM, Pederson D, Roelfsema CM, Bengston Nash S (2005) Herbicides implicated as the cause of severe mangrove dieback in the Mackay region, NE Australia: consequences for marine plant habitats of the GBR World Heritage Area. Marine Pollution Bulletin 51:308–324

Fabricius KE (2005) Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. Marine Pollution Bulletin 50:125–146

Fabricius KE, Wolanski E (2000) Rapid smothering of coral reef organisms by muddy marine snow. Estuarine, Coastal, and Shelf Science 50:115–120

Fabricius KE, De'ath G (2004) Identifying ecological change and its causes: A case study on coral reefs. Ecological Applications 14:1448–1465

Fabricius KE, Wild C, Wolanski E, Abele D (2003) Effects of transparent exopolymer particles (TEP) and muddy terrigenous sediments on the survival of hard coral recruits. Estuarine, Coastal and Shelf Science 57:613–621

Fabricius K, De'ath G, McCook L, Turak E, Williams DB (2005) Changes in algal, coral and fish assemblages along water quality gradients on the inshore Great Barrier Reef. Marine Pollution Bulletin 51(1–4):384–398

Faithful J, Finlayson W (2005) Water quality assessment for sustainable agriculture in the Wet Tropics—A community-assisted approach. Marine Pollution Bulletin 51:99–112

Ferrier-Pages C, Gattuso JP, Dallot S, Jaubert J (2000) Effect of nutrient enrichment of growth and photosynthesis of the zooxanthellate coral *Stylophora pistillata*. Coral Reefs 19:103–113

Ferrier-Pages C, Schoelzke V, Jaubert J, Muscatine L, Hoegh-Guldberg O (2001) Response of a scleractinian coral, *Stylophora pistillata*, to iron and nitrate enrichment. Journal of Experimental Marine Biology and Ecology 259:249–261

Finlayson CM, Lukacs GP (2003) Status of wetlands in northern Australia. In: Dawson N, Brodie J, (eds.) Proceedings of the 2nd National Conference on Aquatic Environments: Sustaining our aquatic environments—Implementing solutions. Queensland Department of Natural Resources and Mines, Brisbane, Australia

Freeny JR, Denmead OT, Wood AW, Saffigna PG (1994) Ammonium loss following urea addition to sugarcane trash blankets. *Proceedings of the Sugarcane Technologists* 16:114–121

Furnas M (2003) Catchments and corals: terrestrial runoff to the Great Barrier Reef. Australian Institute of Marine Science, Townsville, Queensland, Australia

Furnas MJ, Brodie J (1996) Current status of nutrient levels and other water quality parameters in the Great Barrier Reef. In: Hunter H, Eyles AG, Rayment GE, (eds.) Downstream effects of land use. Queensland Department of Natural Resources, Brisbane, Australia pp 9–23

Furnas M, Mitchell A, Skuza M, Brodie J (2005) In the other 90%: phytoplankton responses to enhanced nutrient availability in the Great Barrier Reef lagoon. Marine Pollution Bulletin 51:253–265

Gilbert M, Brodie J (2001) Population and major land use in the Great Barrier Reef Catchment area: spatial and temporal trends. Great Barrier Reef Marine Park Authority, Townsville, Queensland, Australia. pp 72

Gilmour J (1999) Experimental investigation into the effects of suspended sediment on fertilization, larval survival and settlement in a scleractinian coral. Marine Biology 135:451–462

Goreau TJ, MacFarlane AH (1990) Reduced growth rate of *Montastrea annularis* following the 1987–1988 coral-bleaching event. Coral Reefs 8:211–215

Greiner R, Herr A, Brodie A, Haynes D (2005) A multi-criteria approach to Great Barrier Reef catchment (Queensland, Australia) diffuse source pollution problem. Marine Pollution Bulletin 51:128–137

Gross JE (2003) Developing conceptual models for monitoring programs. Unpublished report. Available at: http://www.science.nature.nps.gov/im/monitor/docs/Conceptual_Modelling.pdf. Accessed: 20th August 2007

Hamilton D, Haydon G (1996) Pesticides and fertilisers in the Queensland sugar industry—Estimates of usage and likely environmental fate. Department of Primary Industries, Brisbane, Australia

Harrington L, Fabricius K, Eaglesham G, Negri A (2005) Synergistic effects of diuron and sedimentation on photosynthesis and survival of crustose coralline algae. Marine Pollution Bulletin 51:415–427

Haynes D, Müller J, Carter S (2000a) Pesticide and herbicide residues in sediments and seagrass from the Great Barrier Reef World Heritage Area and Queensland coast. Marine Pollution Bulletin 41:279–287

Haynes D, Ralph P, Prange J, Dennison W (2000b) The impact of the herbicide diuron on photosynthesis in three species of tropical seagrass. Marine Pollution Bulletin 41:288–293

Haynes D, Brodie J, Christie C, Devlin M, Michalek-Wagner K et al. (2001) Great Barrier Reef water quality: current issues. Great Barrier Reef Marine Park Authority, Townsville, Queensland, Australia

Haynes D, Carter S, Gaus C, Müller J, Dennison W (2005) Organochlorine and heavy metal concentrations in blubber and liver tissue collected from Queensland (Australia) dugong (*Dugong dugon*). Marine Pollution Bulletin 51:361–369

Haynes D, Brodie J, Furnas M, Waterhouse J, Hart B (2007) Assessment of the water quality and ecosystem health of the Great Barrier Reef (Australia), Part II: Long-term monitoring design (in review)

Heyward A, Negri A (1999) Natural inducers for coral larval metamorphosis. Coral Reefs 18:273–279

Hodgson G (1990) Sediment and the settlement of larvae of the reef coral *Pocillopora damicornis.* Coral Reefs 9:41–43

Hoegh-Guldberg O (1999) Climate change, coral bleaching and the future of the world's coral reefs. Marine and Freshwater Research 50:839–866

Hughes TP (1994) Catastrophes, phase shifts, and large-scale degradation of a Carribean coral reef. Science 265:1547–1551

Hughes TP, Baird AH, Bellwood DR, Card M, Connolly SR, Folke C (2003) Climate change, human impacts, and the resilience of coral reefs. Science 301:929–933

Hunte W, Wittenberg M (1992) Effects of eutrophication and sedimentation on juvenile corals. II. Settlement. Marine Biology 114:625–631

Hunter CL, Evans CW (1995) Coral reefs in Kaneohe Bay, Hawaii: two centuries of western influence and two decades of data. Bulletin of Marine Science 57:501–515

Johnson AKL, Ebert SP, Murray AE (1998) Spatial and temporal distribution of wetland and riparian zones and opportunities for their management in catchments adjacent to the Great Barrier Reef Marine Park. In: Haynes D, Kellaway D, Davis K (eds) Protection of wetlands adjacent to the Great Barrier Reef. Great Barrier Reef Marine Park Authority Workshop Series No 24, Great Barrier Reef Marine Park Authority, Townsville, Queensland, Australia pp 82–101

Jones R, Müller J, Haynes D, Schreiber U (2003) The effects of the herbicides diuron and atrazine on corals of the Great Barier Reef. Marine Ecology Progress Series 251:153–167

Jones R, Kerswell A (2003) Phytotoxicity evaluation of photosystem-II (PSII) herbicides in scleractinian coral. Marine Ecology Progress Series 261:149–159

Jones R (2005) The ecotoxicological effects of photosystem II herbicides on corals. Marine Pollution Bulletin 51:495–506

Jorgensen SE (1988) Fundamentals of ecological modelling. Developments in environmental modelling 9. Elsevier

Kiene WE, Hutchings PA (1994) Bioerosion experiments at Lizard Island, Great Barrier Reef. Coral Reefs 13:91–98

Kleypus JA (1996) Coral reef development under naturally turbid conditions: fringing reefs near Broadsound, Australia. Coral Reefs 15:153–167

Kleypas JA, Buddemeier RW, Archer D, Gattuso JP, Langdon C, Opdyke BN (1999) Geochemical consequences of increased atmospheric carbon dioxide on coral reefs. Science 284:118–120

Koop K, Booth D, Broadbent A, Brodie J, Bucher D, Capone D et al. (2001) ENCORE: the effect of nutrient enrichment on coral reefs. Synthesis of results and conclusions. Marine Pollution Bulletin 42:91–120

Lambeck A, Woolfe KJ (2000) Composition and textural variability along the 10m isobath, Great Barrier Reef: evidence for pervasive northward sediment transport. Australian Journal of Earth Sciences 47:327–335

Longstaff BJ, Dennison WC (1999) Seagrass survival during pulsed turbidity events: the effects of light deprivation on the seagrasses *Halodule pinifolia* and *Halophila ovalis*. Aquatic Botany 65:105–121

Lukacs G (1998) Coastal freshwater wetlands of north Queensland—imperatives for their protection. In Haynes D, Kellaway D, Davis K (eds) Protection of wetlands adjacent to the Great Barrier Reef. Great Barrier Reef Marine Park Authority Workshop Series No 24, Great Barrier Reef Marine Park Authority, Townsville, Queensland, Australia pp 105–113

Lukacs P, Webb T, Valentine P, Marsh H (1997) The outstanding universal value of the Great Barrier Reef World Heritage Area. Great Barrier Reef Marine Park Authority, Townsville, Queensland, Australia

Marubini F, Atkinson MJ (1999) Effects of lowered pH and elevated nitrate on coral calcification. Marine Ecology Progress Series 188:117–121

McIvor JG, Williams J, Gardner CJ (1995) Pasture management influences runoff and soil movement in the semi-arid tropics. Australian Journal of Experimental Agriculture 35:55–65

McKergow LA, Prosser IP, Hughes AO, Brodie J (2005) Regional scale nutrient modelling: exports to the Great Barrier Reef World Heritage Area. Marine Pollution Bulletin 51:186–199

McMahon K, Bengtson Nash S, Eaglesham G, Müller J, Duke N, Winderlich S (2005) Herbicide contamination and the potential impacts to seagrass meadows in Hervey Bay, Queensland. Marine Pollution Bulletin 51:325–334

McShane TJ, Reghenzani JR, Proove BG, Moody PW (1993) Nutrient balances and transport from sugarcane land—A preliminary report. In Proceedings of the Australian Sugar Cane Technologists 15th Conference. pp 268–275

Meesters EH, Bak RPM, Westmacott S, Ridgley M, Dollar S (1998) A fuzzy logic model to predict coral reef development under nutrient and sediment stress. Conservation Biology 12:957–965

Mellors J, Waycott M, Marsh H (2005) Variation in biogeochemical parameters across intertidal seagrass meadows in the central Great Barrier Reef region. Marine Pollution Bulletin 51:335–342

Mitchell A, Bramley R, Johnson A (1997) Export of nutrients and suspended sediments during a cyclone-mediated flood event in the Herbert River catchment, Australia. Marine and Freshwater Research 48:79–88

Mitchell C, Brodie J, White I (2005) Sediments, nutrients and pesticide residues in event flow conditions in streams of the Mackay Whitsunday Region, Australia. Marine Pollution Bulletin 51:23–36

Müller J, Duquesne S, Ng J, Shaw G, Krrishnamohan K, Manonmanii K et al. (2000) Pesticides in sediments from Queensland irrigation channels and drains. Marine Pollution Bulletin 41:294–301

Negri A, Vollhardt C, Humphrey C, Heyward A, Jones R, Eaglesham G et al. (2005) Effects of the herbicide diuron on early life stages of coral. Marine Pollution Bulletin 51:370–383

Neil DT, Orpin AR, Ridd PV, Yu B (2002) Sediment yield and impacts from river catchments to the Great Barrier Reef lagoon. Marine and Freshwater Research 53:733–752

Newton J, Mumford T, Dohrmann J, West J, Llanso R, Berry H et al. (1998) A conceptual model for environmental monitoring of a marine system developed for the Puget Sound ambient monitoring program. Puget Sound Research 98:23–33

Orpin AR, Ridd PV, Thomas S, Anthony KRN, Marshall P, Oliver J (2004) Natural turbidity variability and weather forecasts in risk management of anthropogenic sediment discharge near sensitive environments. Marine Pollution Bulletin 49:602–612

Pandolfi JM, Bradbury RH, Sala E, Hughes TP, Bjorndal KA, Cooke RG et al. (2003) Global trajectories of the long-term decline of coral reef ecosystems. Science 301:955–958

Pfitzner J, Brunskill G, Zagorskis I (2004) ^{137}Cs and excess ^{210}Pb deposition patterns in estuarine and marine sediment in the central region of the Great Barrier reef Lagoon, north-eastern Australia. Journal of Environmental Radioactivity 76:81–102

Philipp E, Fabricius KE (2003) Photophysiological stress in scleractinian corals in response to short-term sedimentation. Journal of Experimental Marine Biology and Ecology 287:57–78

Preen AR, Lee Long WJ, Coles RG (1995) Flood and cyclone related loss, and partial recovery, of more than 1000 km^2 of seagrass in Hervey Bay, Queensland, Australia. Aquatic Botany 52:3–17

Ralph PJ (2000) Herbicide toxicity of *Halophila ovalis* assessed by chlorophyll a fluorescence. Aquatic Botany 66:141–152

Rasiah V, Armour JD (2001) Nitrate accumulation under cropping in the Ferrosols of Far North Queensland wet tropics. Australian Journal of Soil Research 39:329–341

Rayment G (2003) Water quality in sugar catchments of Queensland. Water Science and Technology 48:35–47

Reghenzani JR, Armour JD, Prove BG, Moody PW, McShane T (1996) Nitrogen balances for sugarcane plant and first ratoon crops in the wet tropics. In: Wilson JR, Hogarth DM, Campbell JA, Garside AL, (Eds.). Sugarcane research towards efficient and sustainable production. CSIRO Division of Tropical Crops and Pasture, Brisbane. pp 275–277

Riegl B (1995) Effects of sand deposition on sceractinian and alcyonacean corals. Marine Biology 121:517–526

Riegl B, Branch GM (1995) Effects of sediment on the energy budgets of four scleractinian (Bourne 1900) and five alcyonacean (Lamouroux 1816) corals. Journal of Experimental Marine Biology and Ecology 186:259–275

Robson BJ, Webster IT, Rosebrook U (2006) Biogeochemical modelling and nitrogen budgets for the Fitzroy Estuary and Keppel Bay. Technical Report No. 40, Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management, Brisbane, Australia. 53 pp

Rodhe K, Masters B, Noble R, Brodie J, Faithful J, Carroll C et al. (2005) Fresh and marine water quality in the Mackay Whitsunday Region, 2004/2005. Mackay Whitsunday Natural Resource Management Group, Mackay, Australia

Rogers CS (1990) Responses of coral reefs and reef organisms to sedimentation. Marine Ecology Progress Series 62:185–202

Ruitenbeek J, Ridgley M, Dollar S, Huber R (1999) Optimization of economic policies and investment projects using a fuzzy logic based cost-effectiveness model of coral reef quality: empirical results for Montego Bay, Jamaica. Coral Reefs 18:381–392

Schaffelke B, Mellors J, Duke N (2005) Water quality in the Great Barrier Reef: responses of mangroves, seagrass and macroalgal communities. Marine Pollution Bulletin 51:279–298

Shaw M, Müller J (2005) Preliminary evaluation of the occurrence of herbicides and PAHs in the wet tropics region of the Great Barrier Reef, Australia, using passive samplers. Marine Pollution Bulletin 51:876–881

Stafford-Smith MG (1993) Sediment-rejection efficiency of 22 species of Australian scleractinian corals. Marine Biology 115:229–243

Stambler N, Popper N, Dubinsky Z, Stimson J (1991) Effect of nutrient enrichment and water motion on the coral *Pocillopora damicornis.* Pacific Science 45:299–307

Stambler N, Cox EF, Vago R (1994) Effects of ammonium enrichment on respiration, zooxanthellar densities and pigment concentrations in two species of Hawaiian corals. Pacific Science 48:284–290

Stimson J, Larned ST, Conklin E (2001) Effects of herbivory, nutrient levels, and introduced algae on the distribution and abundance of the invasive macroalga *Dictyosphaeria cavernosa* in Kaneohe Bay, Hawaii. Coral Reefs 19:343–357

Telesnicki GJ, Goldberg WM (1995) Effects of turbidity on the photosynthesis and respiration of two South Florida reef coral species. Bulletin of Marine Science 57:527–539

Thomas C, Hart B, Nicholson A, Grace M, Brodie J, Pollino C (2005) Development of criteria for simplifying ecological risk models. In: Zerger A, Argernt RM, (eds.) MODSIM 2005 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand pp 772–778

Touchette BW, Burkholder JM (2000) Review of nitrogen and phosphorus metabolism in seagrasses. Journal of Marine Biology and Ecology 250:133–167

Udy JW, Dennison WC, Lee Long W, McKenzie LJ (1999) Responses of seagrass to nutrients in the Great Barrier Reef, Australia. Marine Ecological Progress Series 185:257–271

van Woesik R, Tomascik T, Blake S (1999) Coral assemblages and physico-chemical characteristics of the Whitsunday Islands: evidence of recent community changes. Marine and Freshwater Research 50:427–440

Walker D, Dennison W, Edgar G (1999) Status of Australian seagrass research and knowledge. In: Butler A, Jernakoff P (eds.) Seagrass in Australia. Strategic review and development of an R&D plan. CSIRO, Canberra Australia pp 1–24

Ward S, Harrison P (2000) Changes in gametogenesis and fecundity of acroporid corals that were exposed to elevated nitrogen and phosphorus during the ENCORE experiment. Journal Experimental Marine Biology and Ecology 246:179–221

Waycott M, Longstaff B Mellors J (2005) Seagrass population dynamics and water quality in the Great Barrier Reef: a review and future research directions. Marine Pollution Bulletin 51:335–342

Weber M, Lott C, Fabricius K (2006) Sedimentation stress in a scleractinian coral exposed to terrestrial and marine sediments with contrasting physical, organic and geochemical properties. Journal of Experimental Marine Biology and Ecology 336:18–32

Wittenberg M, Hunte W (1992) Effects of eutrophication and sedimentation on juvenile corals: I. Abundance, mortality, and community structure. Marine Biology 112:131–138

Wolanski E, van Senden D (1983) Mixing of Burdekin River floodwaters in the Great Barrier Reef. Australian Journal of Marine and Freshwater Research 34:49–63

Wolanski E, De'ath G (2005) Predicting the impact of present and future human land-use on the Great Barrier Reef. Estuarine, Coastal and Shelf Science 64:504–508

Wolanski E, Richmond RH, McCook L, Sweatman H (2003) Mud, marine snow and coral reefs. American Scientist 91:44–51

Wolanski E, Richmond RH, McCook L (2004) A model of the effects of land-based, human activities on the health of coral reefs in the Great Barrier Reef and in Fouha Bay, Guam, Micronesia. Journal of Marine Systems 46:133–144

Wooldridge S, Brodie J, Furnas M (2006) Exposure of inner-shelf reefs to nutrient enriched runoff entering the Great Barrier Reef Lagoon: Post-European changes and the design of water quality targets. Marine Pollution Bulletin 52:1467–1479