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Synthesis of evidence to support the Scientific Consensus Statement on Water Quality in the Great Barrier Reef

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This document was prepared by an independent panel of scientists with expertise in Great Barrier Reef Water Quality.
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Background

A consensus statement of the current understanding of Great Barrier Reef (GBR) water quality science was prepared to underpin the future direction of the Reef Water Quality Protection Plan (Reef Plan) actions and to guide future investment in Reef Plan activities.

Terms of Reference

The Terms of Reference for the statement, prepared by the Reef Water Quality Partnership (RWQP) Support Team and Reef Plan Secretariat, and reviewed by the RWQP Scientific Advisory Panel, are provided below.

Purpose

To review the *Summary Statement of the Reef Science Panel regarding water quality in and adjacent to the Great Barrier Reef*, in a contemporary context. This statement, which was produced by technical experts in 2002, supported the development of the Reef Plan. Given that it was nearing the halfway mark of the 10-year plan, it was considered timely to review and, where appropriate, update the statement to support the reinvigoration of Reef Plan and guide future investment in Reef Plan priority activities.

Tasks

Review the 2002 statement and update it by:

1. Reviewing scientific evidence for:

- a decline in the quality of water that discharges from the catchments into the Great Barrier Reef
- a decline in the quality of water in GBR catchment waterways leading to reduced instream ecosystem health
- the presence, nature and extent of land-derived contaminants in Reef waters
- causal relationships between water quality change and ecosystem health
- the effectiveness of current or proposed management intervention in solving the problem and the social and economic impediments to uptake.

2. Evaluating current research, and advising on capabilities, gaps and priority research needs, to:

- assess water quality impacts
- quantify acceptable levels of pollution
- locate and quantify the sources of pollution
- reduce pollution from key sources
- assess the effectiveness of actions to reduce pollution.

3. Discussing the implications of confounding influences, including climate change.

The wording of the above Terms of Reference has been slightly modified by the Taskforce, in consultation with the Reef Plan Secretariat.

The taskforce

A taskforce has been convened to prepare the consensus statement and includes the contributors listed in the table below.

Contributor	Title	Organisation	Expertise
Jon Brodie (Lead author)	Principal Research Officer, Water Quality	Australian Centre for Tropical Freshwater Research	Water quality and agricultural science – catchment to reef
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Professor Ove Hoegh-Guldberg	Director, Centre for Marine Studies	University of Queensland	Coral reef ecology and climate change
Dr Heather Hunter	Principal Scientist, Natural Resource Sciences	Department of Natural Resource and Water	Biogeochemistry of land and water systems
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Dr Ian Webster	Research Scientist, Catchment and Aquatic Systems	CSIRO Land and Water	Catchment and marine hydrodynamics and biogeochemistry
Additional contributors			
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Apologies have been received from the following individuals that were approached to participate:

Tim Wrigley (Canegrowers – cane management practices)

Brigid Nelson (DPI&F – grazing management practices)

Miles Furnas (AIMS – marine water quality and oceanography)

Malcolm McCulloch (ANU – marine water quality and climate change).

Definitions

The following terms are defined for the purposes of this discussion paper:

Contaminant – any material that can be detected in water at above 'natural' concentrations.

Pollutant – when a contaminant is at concentrations known to cause environmental harm.

Introduction

The establishment of the Reef Water Quality Protection Plan (Reef Plan – Anon, 2003) by the Australian and Queensland governments was supported by a body of evidence showing a decline in water quality on the GBR. Efforts to review this evidence included Williams (2002), Williams et al. (2002) and the Great Barrier Reef Protection Interdepartmental Committee Science Panel (2003). The latter document was a comprehensive review of the evidence available at the time, prepared by a taskforce of experts led by Dr Jo Baker.

As the Reef Plan approached its five-year (half-way) mark there was recognition of the need to improve the effectiveness of its delivery, particularly through improved partnership arrangements and a clear focus on land management actions. In November 2007, the Labor party released an election policy document proposing funding of $200 million over five years for a Reef Rescue program 'to tackle climate change and improve water quality in the Great Barrier Reef'. This package includes substantial funding ($146 million) for a Water Quality Grants Scheme, and supporting monitoring, reporting and research programs, with additional funding to build partnerships.

This package will constitute Commonwealth Government investment over the next five years for addressing GBR water quality improvement targets. There is a need to focus investment in GBR water quality in a way that demonstrates a tangible return on investment for government agencies, regional National Resource Management (NRM) bodies and industry groups over the life of the Reef Rescue policy.

Since 2003, there have been significant advances in the knowledge to support implementation of the Reef Plan. It is timely to synthesise this knowledge and reach consensus on current understanding of the system to support the reinvigoration of Reef Plan and guide future investment in Reef Plan priority activities. This discussion paper provides a synthesis of current knowledge against a set of Terms of Reference defined by the Reef Water Quality Partnership Scientific Advisory Panel and the Reef Plan Secretariat. It reviews the *Summary Statement of the Reef Science Panel regarding water quality in and adjacent to the Great Barrier Reef* in a contemporary context and, where appropriate, updates the statement.

Part A

Review the 2003 statement and update it by reviewing available scientific evidence

1. Review scientific evidence for a decline in the quality of water that discharges from the catchments into the GBR

Conclusion: Water discharged from rivers to the GBR continues to be of poor water quality in many locations.

The quality of waters entering the GBR from its river systems and groundwater is highly variable both spatially and temporally across the region. Natural catchment characteristics (e.g. geology, climate) and anthropogenic activities (e.g. land use, land and water management) both strongly influence water quality, including the concentrations and loads of land-derived materials transported from the catchment to the GBR lagoon. Excessive levels of suspended sediment and nutrients (nitrogen and phosphorus) are of concern, as well as the presence of pesticide residues or other substances that do not occur naturally in the environment. These pose a risk to the health of aquatic ecosystems both within the catchment and in the GBR.

Evidence suggests that concentrations and loads of suspended sediment and nutrients have increased substantially with catchment development, although the magnitude of the increases compared with natural conditions is not precisely known. Contemporary land uses differ in their export rates of these contaminants, and there are marked cross-regional differences, particularly between the Wet and Dry Tropics. Emerging results from long-term monitoring indicates increasing trends in nitrogen concentrations in two river systems. The widespread presence of certain herbicide residues in both surface waters and groundwater is further evidence of a decline in water quality.

1.a. Lines of evidence

1.a.i. Pesticide residues, particularly herbicides, are present in surface and groundwater in many locations in the catchments.

These substances do not occur naturally in the environment.

1.a.ii. Concentrations of nitrate and nitrite are elevated in groundwater in areas under intensive agriculture.

A portion of this groundwater is believed to enter the coastal waters.

1.a.iii. River loads of nutrients, sediments and pesticides are higher than in pre-European times.

Inferred from changes in land use and estimated through monitoring and modelling, although with significant uncertainty (in models and monitoring). Long-term datasets in the Tully River show upward trends in concentrations of particulate nitrogen and nitrate from 1987 to 2001.

1.a.iv. Concentrations of contaminants in waterways are related to specific forms of land use.

Monitoring and modelling identify the main sources of nutrients, sediments and pesticides, and show strong regional differences. Evidence includes:

- Nitrogen – a strong relationship exists between the areas of nitrogen-fertilised land use in a catchment and the mean nitrate concentration during high flow conditions, implicating fertiliser residues as the source of nitrate. Elevated stream concentrations of nitrate indicate fertiliser application above plant requirements in sugarcane and bananas.
- Phosphorus – elevated concentrations of dissolved inorganic phosphorus are also related to fertiliser application above plant requirements in intensive cropping and to locally specific soil characteristics.
- Sediment – most sediment originates from grazing lands of the dry and sub-tropics. The influence of land use on sediment loads is now well known at a regional scale but more work is required to identify sources at finer scales, due to variability associated with hillslope, streambank and gully erosion within individual catchments.
- Pesticides – concentrations in waterways are highest in areas of intensive agricultural activity including sugarcane and cotton.

1.a.v. The priority source areas of contaminants are now relatively well known for GBR catchments.

Analysis of data on fertiliser use, loss potential and transport has ranked fertilised agricultural areas of the coastal Wet Tropics and Mackay Whitsunday as the hot-spot areas for nutrients (mainly nitrogen) that pose the greatest risk to GBR reefs.

In the Dry Tropics, high suspended sediment concentrations in streams are associated with rangeland grazing and locally specific catchment characteristics, whereas sediment fluxes are relatively low from cropping land uses due to improvements in management practices over the last 20 years.

In the Wet Tropics, sediment fluxes are comparatively lower due to high vegetation cover maintained throughout the year from high and year-round rainfall and different land management practices from Dry Tropics regions within industries such as beef grazing.

Urban development sites can be local high impact sources of suspended sediment.

Of the herbicide residues most commonly found in surface waters in the GBR region, diuron, atrazine, ametryn, hexazinone derive largely from areas of sugarcane cultivation, while tebuthiuron is derived from rangeland beef grazing areas.

1.b. The evidence base

1.b.i. Pesticide residues, particularly herbicides, are present in surface and groundwater in many locations.

The presence of pesticide residues, especially herbicides, is widespread in waterbodies of the GBR region, including streams, wetlands, estuaries, coastal and reefal waters (e.g. Hunter *et al.,* 2001; Packett *et al.,* 2005; Rohde *et al.,* 2006a, 2008; Faithful *et al.,* 2007; Lewis *et al.,* 2007a; 2007b). Residues commonly detected include atrazine, diuron, ametryn, hexazinone and tebuthiuron. Although most of the concentrations are very low, these substances would not have been present at all before agricultural development of the catchments. The leaking of these chemicals from cane paddocks has been confirmed by paddock scale studies throughout the GBR catchment, including Bundaberg (Stork *et al.,* 2008) and the lower Burdekin (Ham, 2006; 2007). Atrazine residues have been found in the groundwater of many regions including the lower Burdekin (Bauld, 1994), Mackay (Baskeran *et al.,* 2002), Bundaberg (Bauld, 1994) and Bowen (Baskeran *et al.,* 2001). Where this water is used for drinking water supplies, the detection of atrazine means that the water fails to meet Australian and New Zealand Environment Conservation Council (ANZECC) requirements for drinking water.

1.b.ii. Concentrations of nitrate and nitrite are elevated in groundwater in areas under intensive agriculture.

High concentrations of nitrogen have been found in groundwaters of many regions, and these have been linked to fertiliser sources (Weier, 1999; Thorburn *et al.,* 2003a). The final fate of the elevated nitrate concentrations found in groundwater is still uncertain (e.g. in the Burdekin delta refer to Thayalakumaran *et al.,* 2008). Drainage of nitrate below the root zone in sugarcane in the Johnstone catchment has been shown to produce a nitrate 'bulge' below the surface (Rasiah and Armour, 2001; Rasiah *et al.,* 2003a) and it has also been shown that this nitrate is likely to move laterally in subsoil to adjacent streams and rivers (Rasiah *et al.,* 2003b). However, a high degree of uncertainty exists in the role of groundwater transported contaminants (especially nitrate) in material transport from paddocks to coastal waters.

1.b.iii. River loads of nutrients, sediments and pesticides are higher than in pre-European times.

Evidence of changes in river concentrations of contaminants over recent decades is only available for a few rivers. The most complete long-term monitoring data set is from the Tully River (Mitchell *et al.,* 2001; 2006) where particulate nitrogen concentrations increased by 100% and DIN concentrations by 16% between 1987 and 2000. This occurred during a period of increasing fertiliser use in the catchment, although a direct cause-effect association has not been established. Further, an increase in ammonia and phosphorus in the Daintree River over the period 1994–2000 was measured by Cox *et al.* (2005).

It is to difficult to pick up short- or medium-term trends in water quality at large scales due to climate variability and inherent difficulties in logistics associated with monitoring at the right spatial and temporal scales. See also discussion in Section 5.

Changes in loads and concentrations of suspended sediment and the various forms of nitrogen and phosphorus since European settlement have been estimated using models such as SedNet and ANNEX (Brodie *et al.,* 2003; Cogle *et al.,* 2006) and other models (e.g. Furnas, 2003). The models have incorporated water quality data collected from sites with extensive agricultural and urban land uses and compared with data from areas with little or no development (Brodie and Mitchell, 2005). The SedNet and ANNEX model group has been widely used at the catchment and sub-catchment scale for the entire GBR catchment area and has also been repeated and developed for regional catchments (e.g. Brodie *et al.,* 2003; Cogle *et al.,* 2006; Armour *et al.,* 2007a; Kinsey-Henderson and Sherman, 2007; Dougall *et al.,* 2006a) to predict sediment and nutrient generation, transport and delivery to the GBR lagoon; and at small subcatchment scales to determine sources and sinks of sediment at a scale suitable for grazing land management (Kinsey-Henderson *et al.,* 2005; Bartley *et al.,* 2007a; 2007b; 2007c).

In some cases, estimates have been supported by comparison with monitoring results (Fentie *et al.,* 2005; Armour *et al.,* 2007a; Mitchell *et al.,* 2007a; Sherman *et al.,* 2007). Results from such modelling studies indicate that in many rivers, suspended sediment loads (and hence mean concentrations) may have increased by a factor of 5–10 since European settlement, and loads of total nitrogen and total phosphorus, by factors of 2–5 and 2–10, respectively. These models also indicate that nitrate loads in these rivers may have increased twenty-fold over the same period (Armour *et al.,* 2007a). However, it is important to note the very high levels of uncertainty that are unavoidably associated with these types of estimates. Consequently, use of a different modelling approach may produce a contrasting set of estimates, depending on model assumptions, spatial resolution, and availability of data to feed into the models. This is highlighted by results for the Johnstone catchment, where a catchment model and a purpose-designed monitoring data set were used (Hunter and Walton, 2008) which suggested considerably lower increases in suspended sediment and nutrient loads since European settlement than those reported above (e.g. an increase in suspended sediment loads by a factor of 1.4 and nitrate loads by a factor of 6).

Steps in the transport pathway have now been better quantified; for example, studies on bedload storage have shown that sand-sized sediment may take decades to be transported to the river (Bartley *et al.,* 2007a). Estimates of overbank flow in the Tully catchment have shown that 43–50% of the sediment load and 35–46% of the nutrient load is from the river channel of the floodplain (Wallace *et al.,* in press; Karim *et al.,* 2008) and the dynamics of dissolved organic nitrogen are now also being considered (Wallace *et al.,* in press; Wallace *et al.,* 2007) and reported (Hunter and Walton, 2008).

1.b.iv. Concentrations of contaminants in waterways are related to specific forms of land use.

The sources of contaminants are now relatively well known for the GBR catchments. Current knowledge is based largely on information derived from modelling (e.g. using SedNet), with some of the model results supported by monitoring data. Large, detailed catchment-specific studies, such as the monitoring/modelling of the Johnstone catchment (Hunter and Walton, 2008) remain the exception, but results from monitoring programs now underway should enable similar detailed modelling to be carried out in the future for several other catchments.

Nitrogen

On average, about 50% of the total nitrogen loads transported annually in catchment waterways is associated with the suspended sediment fraction (Bramley and Roth, 2002; O'Reagain *et al.,* 2005; Bainbridge *et al.,* 2007; Faithful *et al.,* 2007; Hunter and Walton, 2008; Rhode *et al.,* 2008), which is associated predominantly with soil erosion processes. The remainder is present in various dissolved forms. Most dissolved inorganic nitrogen (DIN, primarily nitrate) in streams that drain cropping areas is considered to come from fertiliser residues (Rohde *et al.,* 2006a; Faithful *et al.,* 2005, 2007; Hunter and Walton, 2008) with 90% of the DIN attributed to this source in the Tully/Murray Region (Mitchell *et al.,* 2006; Armour *et al.,* 2007a). A strong relationship exists between the area of fertilised land use in a catchment and the mean nitrate concentration in high flow conditions proving that the source of nitrate is fertiliser residues (e.g. Mitchell *et al.,* 2006; Pearson and Stork, 2007). This is shown in Figure 1 (Mitchell *et al.,* 2006). However, it is worth noting that results from monitoring and modelling in the Wet Tropics (Johnstone catchment) have shown areas of non-sewered residential development to have the highest nitrate export rates of all land uses, on a unit area basis (Hunter and Walton, 2008). This may be locally important within the catchment, even if of lesser significance for the catchment as a whole, due to the relatively small proportion of the total catchment occupied by this land use. Associations between land use or

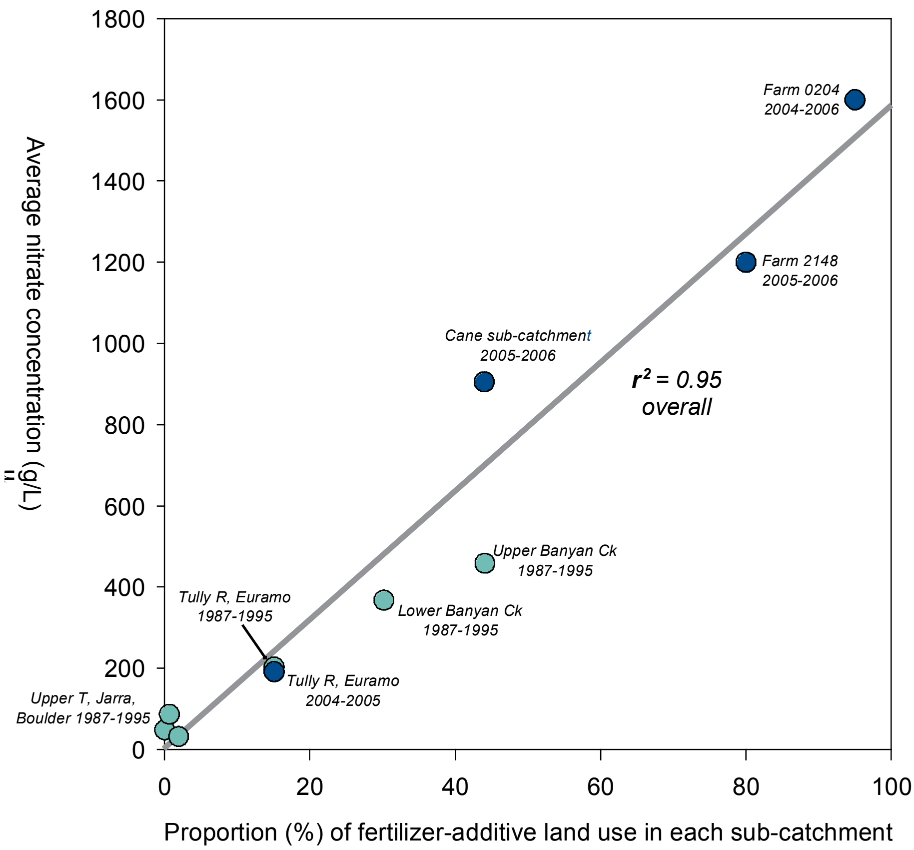

Figure 1. Relationship between fertiliser-additive land use and average (mean) nitrate concentration. Sourced from Mitchell *et al.,* 2006. Green symbols are AIMS-BSES data from wet-season. Blue symbols represent wet-season data from Faithful *et al.,* 2007 (Cane sub-catchment) and Faithful *et al.,* 2006 (Farm 2148 – 80% bananas; Farm 0204 – 95% sugarcane; Tully River, Euramo).

land management and concentrations of other forms of nitrogen are less clear. The strong influence of climatic variability on annual loads of nitrogen (and other constituents) exported, highlights the potential challenges faced in detecting, with confidence, any future reduction in loads associated with the adoption of improved land management practices.

In the Tully catchment, where sugarcane production makes up only 13% of the catchment land use, 76% of the dissolved inorganic nitrogen discharged from the Tully River comes from sugar fertiliser losses, while about 85% is generated from sugar and bananas combined (Armour *et al.,* 2007a). Similarly, in the Johnstone catchment, sugarcane and bananas account for 75% of nitrate exported from the catchment (Hunter and Walton, 2008).

Increases in nitrogen concentrations in the Tully and South Johnston Rivers have also been associated with sugarcane production (Mitchell *et al.,* 2001; 2006; Hunter and Walton, 2008). Large amounts (up to 1000 kg/ha) of nitrogen have also been found in subsoils in the Bundaberg (Keating *et al.,* 1996), Innisfail (Rasiah *et al.,* 2003a) and Babinda (Meier et al. 2006) regions. High concentrations of nitrogen (N) have been found in groundwaters of many regions, and these have been linked to fertiliser sources (Thorburn *et al.,* 2003a). Nitrogen fertiliser management practices in sugarcane crops are consistent with these results on the presence of nitrogen in sugarcane areas. Rates of nitrogen fertiliser applications increased dramatically since the mid-1970s, and substantially more nitrogen fertiliser has been applied to sugarcane crops than removed from the cropped lands in either harvested cane or trash that was burnt. The difference between the nitrogen fertiliser applied and that removed is called the 'N surplus', which is an indicator of potential losses of nitrogen to the environment. Across the whole sugarcane industry, nitrogen surpluses have been in the order of

1 kg N/t cane since the early 1980s (Thorburn *et al.,* 2003b). Thus, for a crop yielding 80 t/ha, N surpluses are likely to be in the order of 80 kg/ha. Expressed at a regional scale, in a region producing 7 Mt of sugarcane per year (e.g. the Wet Tropics), there could be around 7000 t of surplus nitrogen annually. Reductions in nitrogen fertiliser use has occurred in some regions over the past five to ten years, but yields have also declined and as a result nitrogen surpluses are still close to 70 kg/ha (Thorburn *et al.,* 2007). Thus, the evidence of high stream concentrations of nitrogen in areas of sugarcane production described above is not unexpected.

While not studied as extensively, the situation is similar in some important horticultural crops. Nitrogen surplus is in the order of 200 kg/ha for bananas (Weier, 1994; Moody and Aitken, 1996; Prove *et al.,* 1997), although this has been reduced in recent years due to better fertiliser management regimes for bananas (Armour *et al.,* 2006, 2007b), and 100 kg/ha for capsicums (Moody and Aitken, 1996). Not surprisingly, large amounts (~200 kg/ha) of N have been found in subsoils following small crops in the Bundaberg region (Weier and Haines, 1998).

Phosphorus

Typically, most of the total phosphorus load in catchment waterways is associated with the suspended sediment fraction (and thus soil erosion processes), with <20% occurring in dissolved forms (e.g. Bainbridge *et al.,* 2007; Faithful *et al.,* 2007; Hunter and Walton, 2008). However, there are exceptions (e.g. the Mackay region), where relatively high concentrations and loads of dissolved phosphorus may occur, probably related to locally-specific soil characteristics (Bloesch and Rayment, 2006; Rhode *et al.,* 2008). The downstream fate of phosphorus sorbed onto suspended sediment is dependent on environmental conditions (e.g. pH, salinity, dissolved oxygen concentrations) as well as the geochemical properties of the sediment are still poorly understood. In certain situations, the phosphorus may be de-sorbed and released into the water column, as reported by McCulloch *et al.,* (2003a) for anoxic sediment offshore from the Johnstone catchment.

Sediments

In the Dry Tropics, high suspended sediment concentrations in streams derive from rangeland grazing and urban development sites (Bainbridge *et al.,* 2006a; 2006b; Rohde *et al.,* 2006b) whereas sediment fluxes are relatively low from cropping land uses (especially sugarcane cultivation). This is due to improvements in management practices over the last 20 years (e.g. minimum tillage and trash blanketing in cane) (Rayment, 2003; Bainbridge *et al.,* 2006b; Rohde *et al.,* 2006a; Faithful *et al.,* 2007). In the Wet Tropics (Johnstone catchment), sediment fluxes from grazing areas are low due to high vegetation cover maintained throughout the year, with sediment export rates similar to those from areas of native rainforest. By contrast, fluxes from cropping areas (sugarcane and bananas) in this catchment are around three to four times higher than those from areas of native rainforest (Hunter and Walton, 2008). Urban development sites can also be local high impact sources of suspended sediment.

Field studies in the Burdekin region (Virginia Park Station, Meadowvale Station and the Bowen catchment) have shown that river sediment and particulate nutrient concentrations in grazed areas are two to five times those in environmentally comparable non-grazed areas (Townsville Field Training Area managed by the Defence Department) (Post *et al.,* 2006a, 2006b). It is probable that hillslope and gully erosion are both major sources in the Dry Tropics, with bank erosion generally a smaller source of eroded sediment (Bartley *et al.,* 2007c). Roth (2004) and Hawdon *et al.,* (2008) have demonstrated evidence of changed hillslope hydrology in grazed rangelands that resulted in increased runoff. Further work showed that patches bare of vegetation are particularly prone to erosion, resulting in high hillslope sediment yields (Bartley *et al.,* 2007b, Bastin *et al.,* 2008). Improved monitoring techniques are now available to measure landscape leakiness and patchiness with respect to runoff and sediment (Abbott and Corfield, 2006).

There is reasonable understanding of spatial variation in the contribution of sediments and nutrients at the whole of GBR scale (McKergow *et al.,* 2005a; 2005b), which indicates that spatially targeted remediation will achieve greater reductions than a blanket approach (Wilkinson, 2008). However, considerable uncertainty still exists in the relative source contributions within individual river catchments;

for example, different SedNet runs in the Fitzroy basin have had a 30% range (uncertainty) in the predicted contribution of hillslope erosion (Wilkinson, 2008). In addition, there is limited knowledge on the relative importance of gully erosion compared with hillslope erosion in rangeland grazing, the primary causes of gully erosion in the landscape and the most effective remedial management practices to stabilise new and existing gullies. Broad assumptions are currently made in the sediment transport models on gully extent and behaviour leading to significant uncertainty in modelled predictions in some locations (Bartley *et al.,* 2007b; Herr and Kuhnert, 2007).

Sediment particle sizes influence delivery rates and system lags in delivery (i.e., different rates of delivery for sand versus silt versus clay). Lags vary from short (a few days) for clay to much longer timeframes (years) for silt and decadal timeframes for sand (Bartley *et al.,* 2007b; Bainbridge *et al.,* 2007). Different particle sizes are important components of different ecosystems; for example, sand is an important element of riverbed environments and beaches, while clay provides substratum for mangrove communities.

Pesticides

The herbicide residues most commonly found in surface waters in the GBR region (diuron, atrazine, ametryn, hexazinone) derive largely from areas of sugarcane cultivation (Rohde *et al.,* 2006a; Faithful *et al.,* 2007; Lewis *et al.,* 2007a) and for atrazine from cropping relatively specific to the Fitzroy (Packett *et al.,* 2005). At a local scale, diuron residues may also be associated with its use as an anti-foulant on boats (e.g. in marinas). Residues of tebuthiuron are associated primarily with the use of this product (Graslan) in grazing lands for woody weed control (Bainbridge *et al.,* 2007).

The capacity to predict contaminant loads through combined monitoring and modelling approaches is discussed further in Section 5.

Other

Other sources of contaminants that may be of concern to water quality in the GBR include disturbance of coastal areas and generation of acid sulphate soils (ASS) (Powell and Martens, 2005; http://www.nrw.qld.gov.au/land/ass/index.html). In recognition of these potential issues, the NRW has recently completed distribution mapping of ASS in Queensland.

1.b.v. The priority source areas of contaminants are now relatively well known for GBR catchments.

Several initiatives have attempted to identify the priority source areas of contaminants in GBR catchments; examples are described below. Further discussion of priority areas for management intervention is included in Section 5 (Part A).

Analysis of data on fertiliser use, loss potential and transport in the Nutrient Management Zones project (Brodie, 2007) has ranked fertilised agricultural areas of the coastal Wet Tropics and Mackay Whitsunday as the hot-spot areas for nutrients (mainly nitrogen) that pose the greatest risk to GBR reefs.

In the Dry Tropics, high suspended sediment concentrations in streams derive from rangeland grazing, locally specific catchment characteristics and urban development sites, whereas sediment fluxes are relatively low from cropping land uses due to improvements in management practices over the last 20 years (refer also to Section 5 of Part A). Projects have also identified catchment hot-spots for sediment delivery (erosion). For example, a modelling study on the Burdekin ranked the east Burdekin, Bowen River and NW Burdekin sub-catchments as areas of highest delivery (Brodie *et al.,* 2003; Fentie *et al.,* 2006; Kinsey-Henderson *et al.,* 2007). This analysis has been confirmed to some extent by monitoring studies that have identified very high concentrations of suspended sediment from the Burdekin sub-catchments Bowen River, Dry River and Camel Creek (Bainbridge *et al.,* 2007). In the Fitzroy catchment, modelled estimates suggest a significant proportion of the fine sediment delivered by the river to the estuary and coastal marine environment is derived from the basaltic soils of the western catchment (Douglas *et al.,* 2005; Smith *et al.,* 2006).

1.c. Key uncertainties related to decline in water quality and sources of pollutants

The following points summarise the key uncertainties associated with knowledge related to the decline in water quality and the sources of contaminants:

- Due to time lags in system response and relatively short-term monitoring information, estimates of contaminant loads generated by model predictions are subject to large uncertainties. Refinement of model approaches that predict contaminant loads by incorporating finer temporal resolution, characterisation of hydrological processes, nutrient speciation and better techniques for quantifying uncertainty is required.
- There is a need to review and integrate land-based modelling of sediment sources in the dry tropical catchments. In particular, the relative importance of gully erosion compared with hillslope erosion, the primary cause of gully erosion in the landscape and the most effective remedial management practices to stabilise new and existing gullies requires further work. Broad assumptions are currently made in the sediment transport models on gully extent and behaviour leading to significant uncertainty in modelled predictions in some locations.
- Identify major drivers, both natural (soils and geology, elevation and rainfall intensity and duration) and/or anthropogenic (land management such as stocking rates, fencing and spelling and resultant ground cover), of suspended sediment concentrations from different dry tropical sub-catchments (e.g. Burdekin and Fitzroy Rivers). Developing load models using available data has potential to identify the effect of climate and land management on loads.
- Knowledge of the residence times of different particle size fractions of suspended sediments transported through catchments and the implications and timescales for sediment delivery to the GBR lagoon.
- A high degree of uncertainty exists in the role of groundwater transported contaminants (especially nitrate) from paddock to coastal waters.

2. Review scientific evidence for the presence, nature and extent of land-derived contaminants in GBR waters

Conclusion: Land derived contaminants, including suspended sediments, nutrients and pesticides, are present in the GBR at concentrations likely to cause environmental harm.

Advances in monitoring and modelling techniques in recent years have enabled greater understanding of the presence, nature and extent of land-derived contaminants in GBR waters. Satellite imagery technology has enabled observation of the extent of flood plumes to distances substantially further than was previously understood. Recent efforts to collate long-term water quality data have identified some trends in water quality with strong regional differences and it is now clear that the presence of pesticides in GBR waters is widespread.

Coral cores have been demonstrated as a useful indicator of changes in the delivery of contaminants to the GBR and records show strong correlation of increases in contaminants with introduction of cattle and intensive fertiliser use.

2.a. Lines of evidence

2.a.i. Contaminants are dispersed widely within the GBR.

Remote sensing demonstrates the transport of river plume derived dissolved matter across and along the GBR lagoon, through the reef matrix and out to the Coral Sea. Particulate matter is dispersed less widely and tends to be trapped and deposited inshore.

2.a.ii. Pesticides are present in the GBR.

Pesticide residues, especially herbicides, are detected in many GBR waters. Pesticides at biologically active concentrations have been found up to 60 km offshore in the wet season and in low but detectable concentrations in the dry season.

2.a.iii. Contaminants may have long residency times in the GBR lagoon.

Most sediment is trapped near the coast and hence has decadal residence times in the GBR lagoon. Dissolved nutrients are dispersed more rapidly and may be trapped in the lagoon by biological uptake and persist in this particulate form for years; most pesticide residues have short residence times (at most a few years) due to their chemical breakdown.

2.a.iv. Large river discharge events (‘floods’) in the wet season are the major delivery mechanism of land-derived contaminants to the GBR.

In GBR waters, concentrations of dissolved inorganic nitrogen (nitrate, ammonium), suspended sediment and dissolved inorganic phosphorus are many times higher in flood plumes than in non-flood waters.

2.a.v. Correlations exist between river-discharged material and GBR lagoon water quality.

Phytoplankton biomass and pesticide concentrations in the GBR lagoon are directly correlated with river nutrient and pesticide loads, respectively. In inshore waters, long-term mean chlorophyll concentrations are high to the south compared with north of Port Douglas, coinciding with more intense land use south of Port Douglas. Offshore chlorophyll concentrations are similar south and north of Port Douglas, suggesting that the pattern is not due to latitudinal differences. Limited evidence exists for a relationship between regional turbidity and river suspended sediment discharge.

2.a.vi. Temporal changes are observed in contaminants in GBR waters.

Evidence of temporal change in contaminants in GBR waters is limited due to the small number of long-term monitoring programs; however, some examples include:

- Evidence for increasing concentrations of suspended sediments, dissolved organic nitrogen and dissolved organic phosphorus in Cairns lagoonal waters between 1989 and 2005 (the only long-term water quality monitoring program in the GBR lagoon).
- At Low Isles, water clarity (measured by Secchi disc transparency) is now half the value it was in 1928. However, the validity of this comparison is reduced as only two data sets are used for this assessment with little data produced between 1928 and the early 1990s.
- Coral cores record large increases in the delivery of suspended sediment and nutrients to the GBR, following the introduction of cattle and fertiliser to the catchments since the 1860s.

2.b. The evidence base

2.b.i. Contaminants are dispersed widely within the GBR.

The large increase in the availability of new satellite remote sensing platforms (e.g. MODIS, MERIS, ASTER, SPOT-5, QUICKBIRD, IKONOS, SEAWIFS) added to existing platforms (LANDSAT, AVHRR) allows daily tracking of flood plume dispersal in the GBR lagoon. The use of such images, combined with traditional concurrent surface vessel sampling and image analysis for parameters such as suspended sediments and chlorophyll a (A. Dekker, *pers comm.*) allows to quantify the spatial extent of exposure of GBR reefs and other ecosystems (Brodie *et al.,* 2006; Rohde *et al.,* 2006a; Brodie *et al.,* 2007a).

Figure 2 shows how remote sensing images can be used to support evidence of material transport in flood events. Of particular note in Figure 2a, is the presence in 2007 of an algal bloom and the presence of coloured dissolved organic matter (CDOM) derived from Burdekin and Wet Tropics river runoff dispersing completely across the mid and outer shelf reefs of the GBR between Townsville and Port Douglas and well into the Coral Sea (Brodie *et al.,* 2007a). Figure 2b shows the high sedimentation area near the mouth of the Burdekin River in 2005 where most of the suspended sediment drops out. This area, and the plume generally, is affected by wind over a 48-hour period. Figure 2c shows a plume extending offshore and to the north associated with Fitzroy River discharge in a large event in 2008; the movement of the body of discoloured water initially northwards and then to the south requires further explanation. Figure 2d shows the extensive algal bloom off nutrient-rich Mackay Whitsunday Rivers in 2005.

It is believed that only a small proportion (perhaps 5%) of the suspended sediment load of major rivers is transported large distances in the marine environment during major discharge events (evident from satellite images and flood plume monitoring). Limited knowledge exists on the specific origin in catchments of this small, but high risk, component and how geology, soil type and land management practices interact to produce this presumably fine-grained, washload (non-settling) suspended sediment. Areas of catchments producing this component of the suspended sediment load will be of high management priority. Further discussion of the correlation between river discharge water quality and GBR lagoon water quality is included in Section 2 in Part A.

Marine water quality monitoring is undertaken as part of the Reef Plan Marine Monitoring Program established in 2004 and led by the Great Barrier Reef Marine Park Authority (GBRMPA). Monitoring at inshore sites includes: collection of water column nutrients and suspended sediment concentration data around inshore reefs during the wet and dry seasons; deployment of automated long-term water quality loggers at several regional locations; sampling of pesticides in the water column at >10 inshore reef and island sites; collection of chlorophyll a samples in the water column at more than 50 sites from Cape York to the Burnett Mary regions; and monitoring of seawater temperature using continuous loggers at 28 sites (Prange *et al.,* 2007). Some of these tasks are assisted by community groups and tourism operators. A flood plume monitoring program was also initiated in 2007 to measure water quality conditions in flood plumes in as many regions as possible. Remote sensing techniques to measure chlorophyll, turbidity, colour dissolved organic matter and temperature are also being developed under the program.

Models have been developed to estimate the exposure of Great Barrier Reef inner-shelf reefs to terrestrial runoff using ratings of volume and frequency of discharge from major rivers, the predominant distribution of river plumes in GBR waters, loads of riverine contaminants, and distance of reefs to river mouths (Devlin *et al.,* 2003; Maughan *et al.,* 2008). Coastal and island areas at high risk of exposure to terrestrial runoff were identified adjacent to the Wet Tropics region, from Tully to north of Cairns, and in the Whitsunday region. This model has a number of limitations; for example, it assumes single, average river discharge events and does not deal with temporal dynamics; and it only assessed coral reefs as exposed ecosystems. The model is currently the only available marine exposure analysis that covers the entire GBR and is a useful representation of the spatial extent of the coastal areas that are likely to be regularly exposed to land runoff. However, the model did not consider the consequences of this exposure – for example to coral reefs – which should be part of a complete risk assessment. Research findings that could contribute to a future risk assessment are included in Section 3.

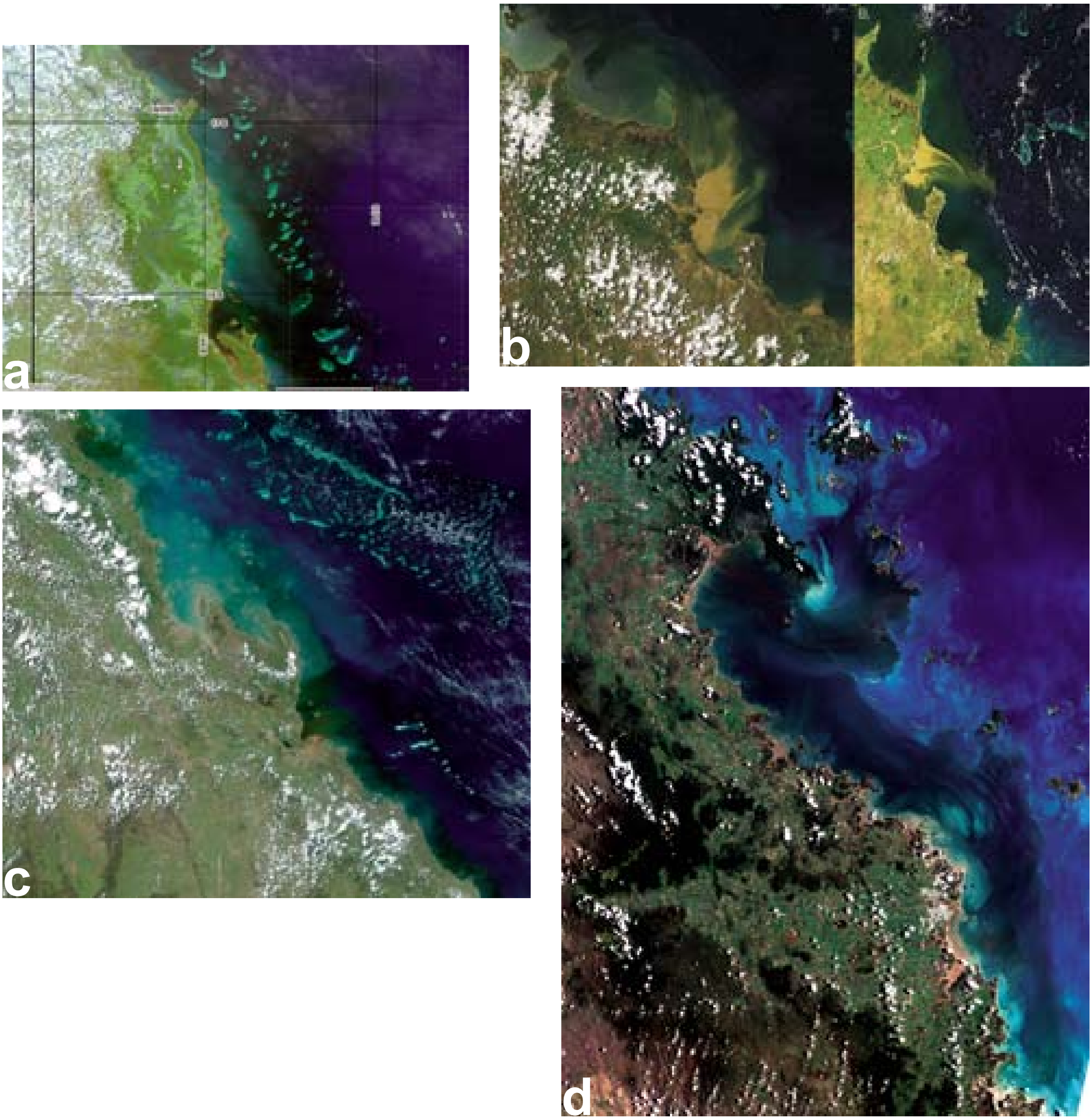

Figure 2. Satellite images of the GBR coast in flood conditions in a) Burdekin and Wet Tropics rivers in 2007 (MODIS image, 13 February 2007: CSIRO); b) Burdekin River in 2005 (MODIS image, 28 and 29 January 2005: CSIRO); c) Fitzroy River in 2008 (MODIS image, 22 February 2008: ACTFR); d) Mackay Whitsunday Rivers in 2005 (Landsat (7) image, 2005: NRW).

2.b.ii. Pesticides are present in the GBR.

As most of the pesticides of concern to marine ecosystems mix conservatively during flood plumes, the concentration in marine waters is closely related to the concentration discharged from the river (Rhode *et al.,* 2006a). Pesticides have recently been recognised as a greater potential threat to GBR ecosystems (mangroves, wetland plant communities, seagrass, coral reefs, phytoplankton communities) than was realised before 2003. Pesticide residues, especially herbicides, are ubiquitous in many GBR region waterbodies including streams, wetlands, estuaries, coastal and reefal waters (e.g. Packett *et al.,* 2005; Rohde *et al.,* 2006a; Faithful *et al.,* 2007; Lewis *et al.,* 2007a). In marine waters, residues at biologically active concentrations have been found up to 60 km offshore (Rohde *et al.,* 2006a) in the wet season and in low but detectable concentrations in the dry season (Shaw and Muller, 2005; Prange *et al.,* 2007).

2.b.iii. Contaminants may have long residency times in the GBR lagoon.

The GBR Lagoon is a system that receives contaminant inputs, moves these around, stores some of it by burying it or incorporating it into living matter, transforms some of the material and ultimately exports the remainder. Our understanding and ability to model transport processes including currents and mixing which are responsible for transporting contaminants is relatively well understood (Webster *et al.,* 2008a). Hydrodynamic models have been developed on the scale of the GBR Lagoon to predict water movement (Legrand *et al.,* 2006; Lambrechts *et al.,* 2008) and investigate the fate of flood plumes (King *et al.,* 2002) and to examine exchange times through the year (Luick *et al.,* 2007). Most sediment is trapped near the coast (Orpin *et al.,* 2004; Devlin and Brodie, 2005) and hence has decadal residence times in the GBR lagoon. Dissolved nutrients are dispersed more rapidly and may be trapped in the lagoon by biological uptake and persist in this particulate form for years (Furnas *et al.,* 2005). Most pesticide residues have short residence times (at most a few years) due to their chemical breakdown (Haynes *et al.,* 2000).

Smaller-scale hydrodynamic models have been used to estimate current transport and mixing of contaminants in Keppel Bay (Herzfeld *et al.,* 2006). Cross-shelf mixing, which is important to move contaminants from the coast out to mid-shelf reefs, has been measured indirectly using radium isotopes (Hancock *et al.,* 2006) and salinity (Wang *et al.,* 2007).

Hydrodynamic modelling of the GBR Lagoon has recently been reviewed in a study of the adequacy of existing receiving water models for the GBR (Webster *et al.,* 2008a). It was concluded that while hydrodynamic modelling is in a moderately advanced stage, the applications of fine-sediment and biogeochemical models are much more limited. These latter models are more complex and much more difficult to calibrate and verify than hydrodynamic models. Process studies are needed to support their development as well as data collection strategies that can be used for calibration and validation. Studies and analyses designed to address these issues are required to understand both the acute and chronic impacts of contaminants on the GBR Lagoon and how reducing catchment loads might provide benefits to the biogeochemical and ecological function of the GBR.

2.b.iv. Large river discharge events (‘floods’) are the major delivery mechanism of land-derived contaminants to the GBR.

The highest concentrations of land-based contaminants are found in GBR waters during flood plume events. Concentrations of dissolved inorganic nitrogen (nitrate and ammonium), suspended sediment, dissolved inorganic phosphorus are found at levels many times those in non-flood conditions, including upwelling offshore waters (Devlin *et al.,* 2001; Furnas, 2003; Devlin and Brodie, 2005; Rohde *et al.,* 2006a, 2008; Packett, 2007) and many times the concentrations that would have occurred in these river plumes before catchment development. Pesticide residues, especially herbicides, are almost ubiquitous in GBR estuaries, coastal and reefal waters (e.g. Packett *et al.,* 2005; Rohde *et al.,* 2006a; 2008; Faithful *et al.,* 2007; Lewis *et al.,* 2007a). In marine waters, residues at biologically active concentrations have been found up to 60 km offshore (Rohde *et al.,* 2006a; 2008) in the wet season flood plume conditions.

Most of the sediment discharged from rivers, especially the coarser fraction, is deposited and trapped on the shelf close to the river mouth. This has been clearly shown for the Fitzroy River (Bostock *et al.,* 2007; Ryan *et al.,* 2007) and the Burdekin River (Orpin *et al.,* 2004). Subsequently to deposition, sediment is resuspended by tidal and wind driven currents and carried northward by the long shore current and eventually trapped in northward facing bays (Lambeck and Woolfe, 2000). However, a small proportion (13%) of riverine sediment output is delivered across the shelf to the Coral Sea (Queensland Trough) (Francis *et al.,* 2007).

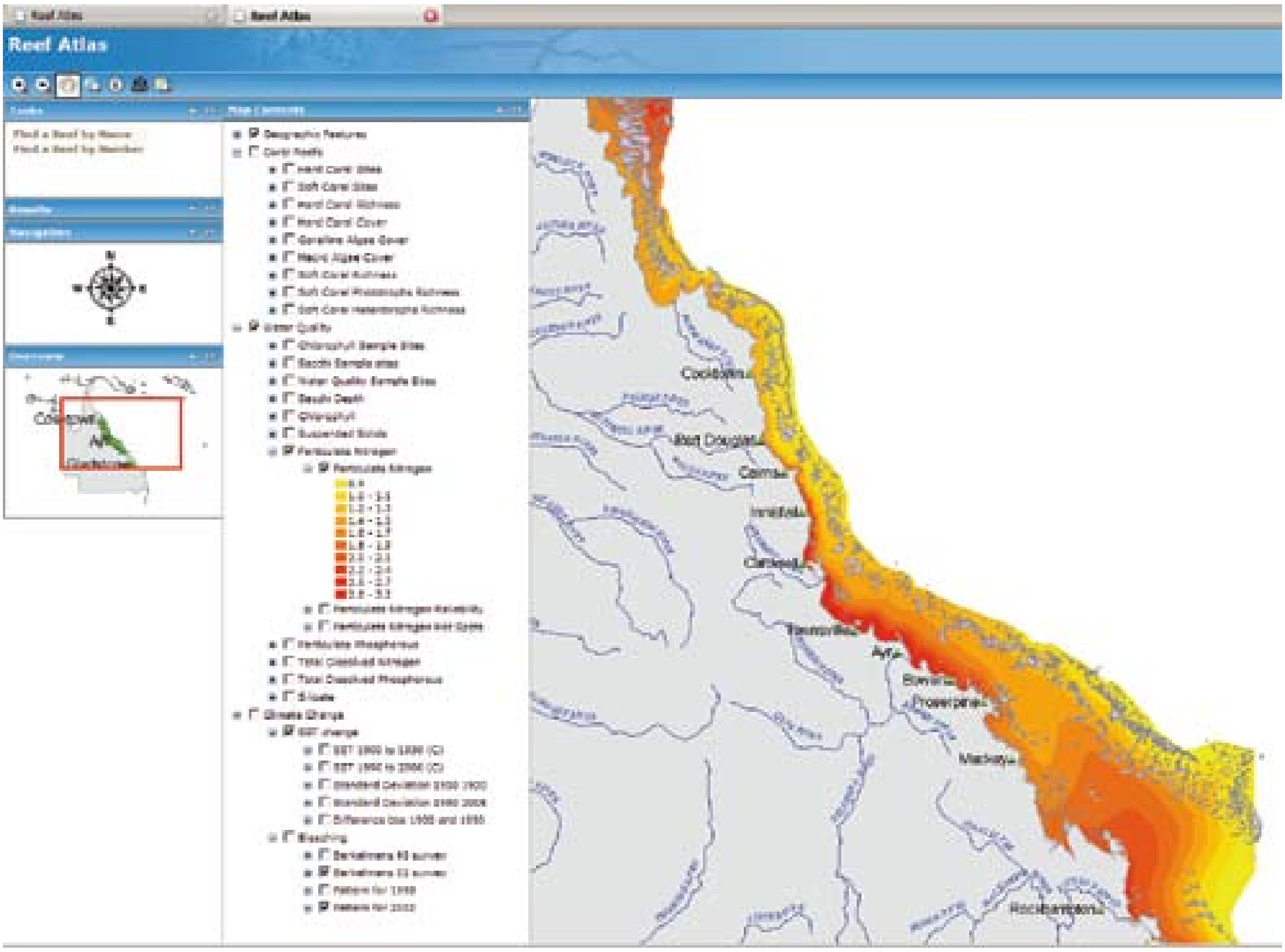

Figure 3. Map of the spatial distribution of particulate nitrogen in the GBR (De'ath and Fabricius, 2008).

2.b.v. Correlations exist between river discharged material and GBR lagoon water quality.

Nutrient loads can be related to chlorophyll concentrations in marine waters. Results from chlorophyll a monitoring in the GBR lagoon show that chlorophyll a is currently (1991–2006) low (mean 0.2 µg/L) in Cape York inshore waters and higher (0.3–0.7 µg/L) in central and southern GBR inshore waters (Brodie *et al.,* 2007b). The assumption is that inshore central and southern waters have increased in chlorophyll concentrations due to enhanced nutrient inputs from a position similar to Cape York waters more than 100 years ago. Offshore concentrations of chlorophyll also vary from south to north, but insufficient evidence exists to indicate that this is directly related to terrestrial influence over external factors such as upwelling, currents and tidal mixing.

Water quality data from the GBR lagoon have been spatially analysed and integrated into a series of maps (De'ath, 2005; De'ath and Fabricius, 2008), which are being made available through the Marine and Tropical Science Research Facility (MTSRF) Risk Resilience and Response Atlas. The maps show the spatial distribution of mean concentrations of all major water quality parameters, indicating distinct areas of long-term elevated concentrations of particular parameters (Figure 3 shows particulate nitrogen distributions, and Figure 4 shows spatial distribution of water quality variables across the six NRM regions).

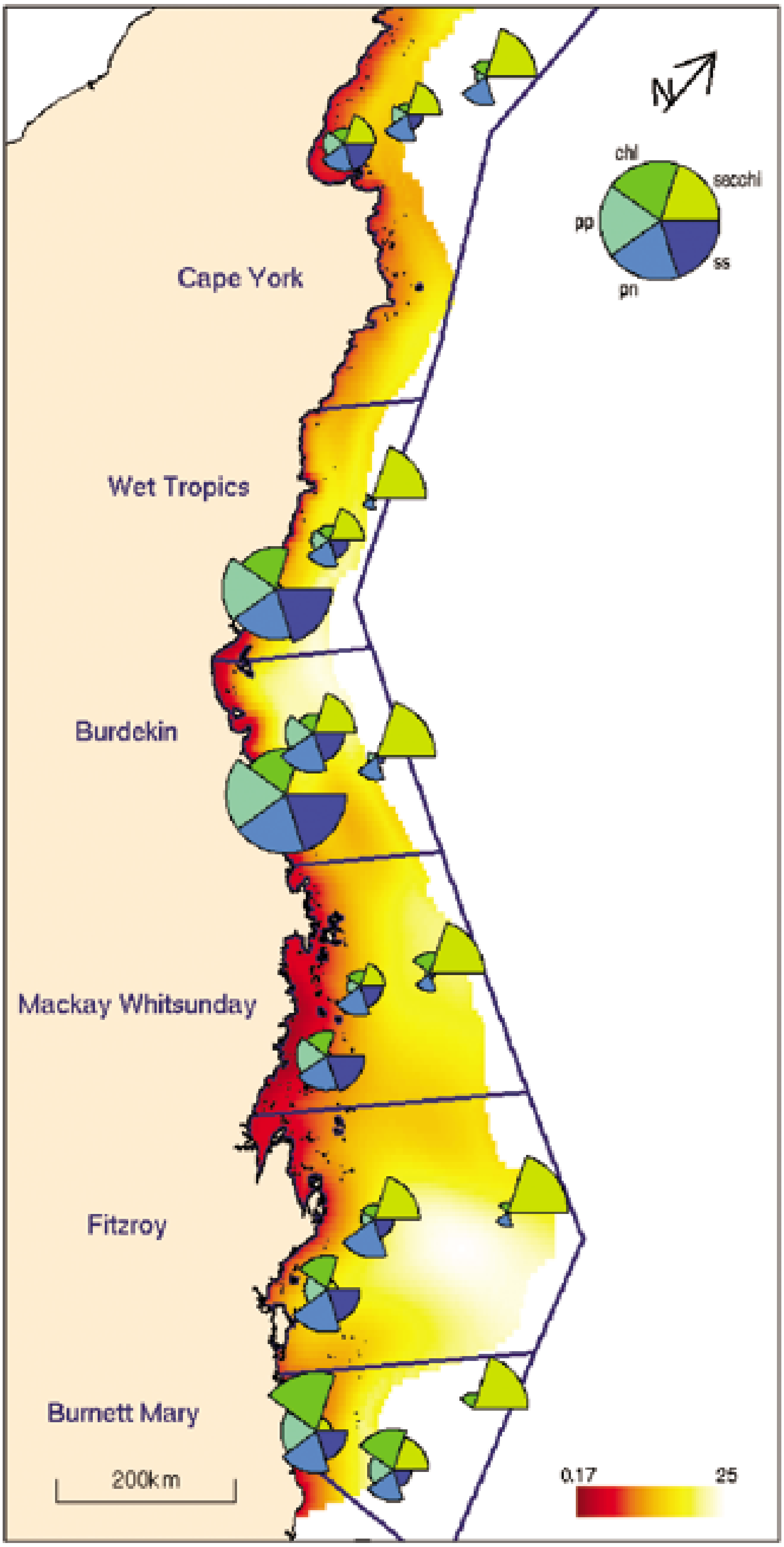

Figure 4. Map of the spatial distribution of water quality variables across the six NRM regions, for coastal (0–0.1 relative distance across), inshore (0.1–0.4 relative distance across), and offshore waters (0.4–1.0 relative distance across) (from De'ath and Fabricius, 2008). The colour ramp represents Secchi disk depth, the pie charts the mean values for each of the 18 NRM × cross-shelf regions of: chl = chlorophyll, Secchi = Secchi disk depth, ss = suspended solids, pn = particulate nitrogen, and pp = particulate phosphorus. Of note are the high concentrations of ss, pn and pp in the Burdekin and Wet Tropics regions, and the high chlorophyll values in the Burnett Mary region and the low values in the coastal regions of Cape York.

The fate of nutrients following the cessation of flood plumes is not clear-cut. High DIN concentrations in plumes are associated with elevated phytoplankton concentrations (Wooldridge *et al.,* 2006; Devlin and Brodie, 2005). What is less well understood, is how the discharge of nutrients might cause a chronic impact on inshore reefs. Dissolved nutrients will be carried and mixed by currents, but some will fuel the growth of sessile organisms such as micro- and macroalgae and so be retained by the system. Nutrients associated with particles will follow dynamics of settling, resuspension, burial, and diagenesis processes that might ultimately release these nutrients in forms suitable for plant growth. Measurements in Keppel Bay suggest that ~1/3 of the input particulate nitrogen and phosphorus is buried in sediments, presumably in refractory form (Radke *et al.,* 2006). Further, the biogeochemical modelling work in Keppel Bay (Robson *et al.,* 2006a) suggested a significant missing source of bioavailable nitrogen was necessary in Keppel Bay in order to close the budget of this nutrient. Laboratory experiments on sediment cores collected from the bay suggest that the source may have been benthic nitrification (Radke *et al.,* 2006). For phosphorus, river inputs appear to be retained close to the coast in the central GBR and phosphorus inputs due to upwelling events are a greater contribution to shelf phosphorus budgets than local river inputs over an average year (Monbet *et al.,* 2007).

Recent research by Wallace *et al.,* (2007) has also raised questions regarding the fate of the dissolved organic nitrogen (DON) fraction of the nitrogen load from agriculturally developed catchments of the GBR catchment area. DON was previously considered to be relatively refractory and non-bioavailable on a very limited theoretical basis. However, DON is a large component of the nitrogen load in many rivers and the degree of its bioavailability will be a critical factor in assessing the risk to both fresh and marine ecosystems from nitrogen driven eutrophication. In addition, the bioavailability of particulate nitrogen and phosphorus needs to be further investigated in the GBR catchments and lagoon.

Fine sediments introduced to the GBR lagoon by flood events undergo cycles of settling and resuspension by the winds and tides and can be dispersed far from the river mouth. Larcombe and Woolfe (1999) argue that chronic turbidity at coral reefs due to suspension of fine sediments by tides and winds will not be significantly affected by changes in sediment inputs due to catchment management since the sediments pool in the lagoon is large. Measurements in Keppel Bay (Radke *et al.,* 2006) suggest that there is a relationship between turbidity and river discharge of sediment suspended associated with flood events. In the mouth of the Fitzroy Estuary, where suspended sediment concentrations show a strong tidal cycle, these concentrations are higher in the period following riverine inputs than later in the year when riverine inputs have ceased for six months. It would appear that freshly introduced sediments are more readily suspendable. Later, much of this suspendable sediment moves into zones where it is less readily suspended, such as in northern facing bays or in the tidal creeks. Fine-sediment transport is very difficult to model effectively. The question as to whether increased suspended sediment loads from increased erosion from agricultural and urban development in major rivers lead to increased regional turbidity generated by resuspension in inshore areas of the GBR lagoon (with depths generally less than 10 m) is also being examined in a current Marine and Tropical Sciences Research Facility (MTSRF) research program. Initial results from the Tully and Burdekin regions suggest there is a period of increased turbidity for several months following each flood plume event (Wolanski *et al.,* 2008).

Pesticide concentrations in plume waters are directly correlated to pesticide concentrations in river discharge as the main process affecting plume concentrations is dilution. This notion is best supported by the information on mixing curves investigated in the Mackay Whitsunday region (Rohde *et al.,* 2006a).

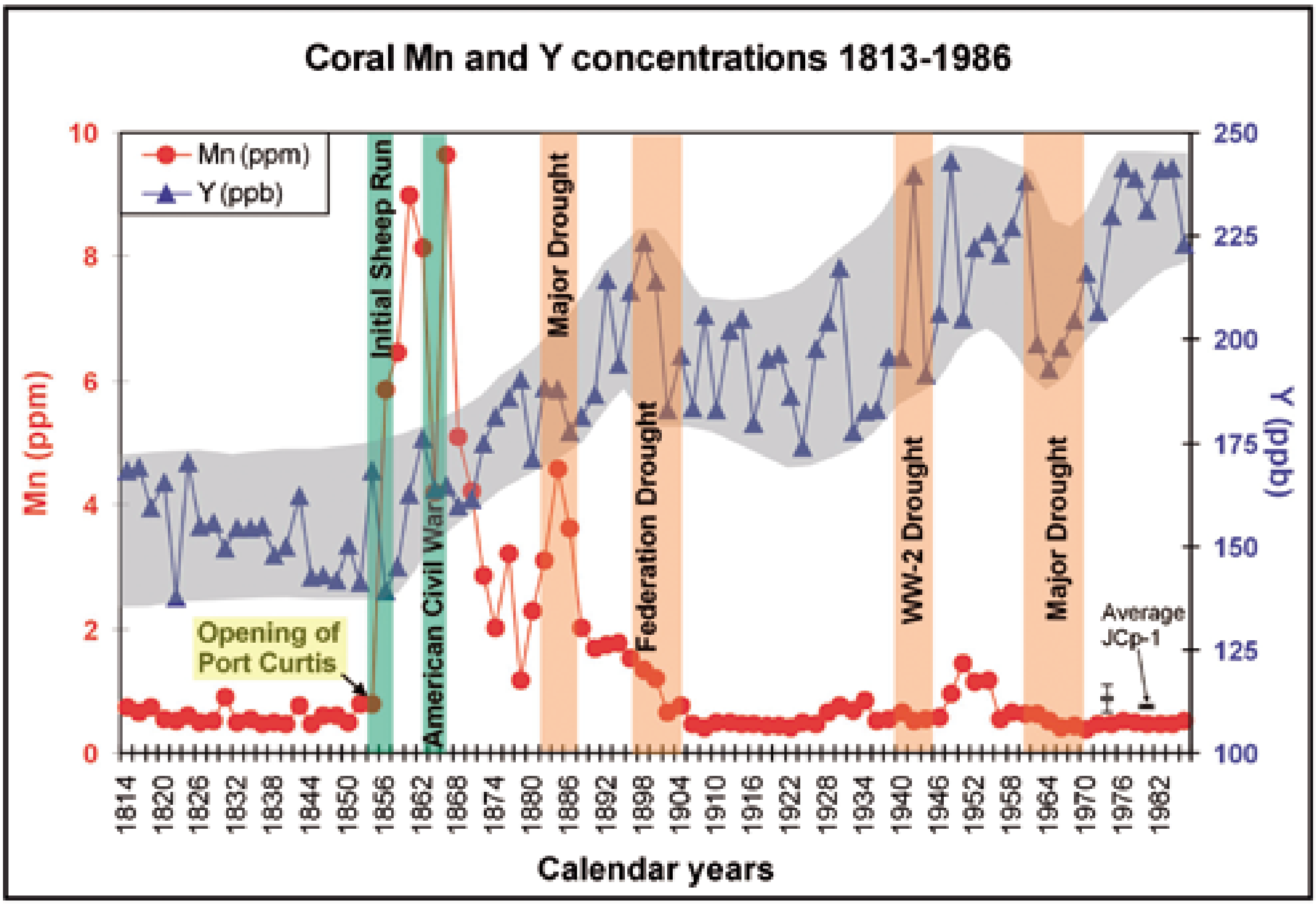

Figure 5. Mn and Y concentrations in the coral core from 1813–1986. Yttrium concentration, like Ba, is interpreted to be an erosion indicator, steadily increasing after 1860–70. Manganese defines a different history. Elevated Mn concentrations coincide with major land settlement in the Burdekin catchment. The initial Mn spike in 1855–1856 is related to the establishment of the first sheep run in the southern Burdekin catchment. The peak Mn concentration coincides with the end of the American Civil War and the climax of rapid expansion of the sheep industry in the Burdekin catchment. The second major Mn peak in 1883–1884 coincides with, and may thus be related to, the expansion of the cattle industry or the beginning of the sugarcane industry on the lower Burdekin catchment. The return of Mn concentrations to pre-1850 levels coincides with the Federation Drought, which devastated sheep and cattle numbers throughout the catchment. An increase in Mn after World War II may be related to the further development of the cattle industry. Reproducibility of Mn by our method is shown for the (slightly heterogeneous) G.S.J. coral standard JCp-1. Also shown for comparison, are average and standard deviation of Mn in a mid-Holocene coral recovered from Nelly Bay, Magnetic Island. Source: Lewis *et al.,* (2007b).

2.b.vi. Temporal changes are observed in contaminants in GBR waters.

Increasing concentrations of suspended sediment (TSS), dissolved organic nitrogen (DON) and dissolved organic phosphorus (DOP) are evident in the only long-term repeated sampling program in the GBR lagoon for nutrients – the Cairns transect of Miles Furnas (AIMS). Concentrations of TSS increased from 1.6 to 3.7 mg/L, DOP from 1.1 to 16 µg/L and DON from 68 to 91 µg/L in the period 1989 to 2005 (Furnas *et al.,* 2005). At Low Isles, Secchi disc transparency has almost halved from 11 in 1928 (during a 1-year study by the British Museum field expedition), to 6 m during current measurements (Wolanski *et al.,* 2004).

The use of coral cores to show the presence of a 'terrestrial signal' in the GBR, and hence changes in the delivery of materials from the land to the GBR with catchment development, are now well established. For example, the ratio of barium to calcium in corals offshore from the Burdekin River indicated a five- to ten-fold increase in suspended sediment loads following European settlement of the Burdekin catchment. This has been interpreted as indicating a large increase in erosion and delivery of suspended sediment to the mouth of the Burdekin River, where the barium adsorbed onto the sediment desorbs and is taken up by the coral. The barium replaces calcium in the coral structure, resulting in an altered ratio of Ba/Ca indicative of a land-based influence (McCulloch *et al.,* 2003b; Lewis *et al.,* 2007b). Other metals including yttrium and manganese, which are used as indicators of erosion and land settlement, also show changed concentration in coral cores after 1860 (Lewis *et al.,* 2007b). Figure 5 shows an example of results from Magnetic Island in the Burdekin region.

Additional proxies in coral cores of past water quality conditions are currently being developed (Alibert *et al.,* 2003; Wyndham *et al.,* 2004; Sinclair, 2005; Marion *et al.,* 2005). Changes in the amount of water discharged due to vegetation change/loss and soil compaction in catchments have also been investigated using coral cores, and some dispute currently exists over the interpretation of this record (McCulloch, 2006; Lough, 2007).

Increases in nitrogen delivery, up to four-fold, have also been demonstrated from coral cores off Mackay associated with increasing fertiliser use for sugarcane cultivation in the Mackay region (Jupiter *et al.,* 2007; Marion, 2007).

2.c. Key uncertainties related to presence, nature and extent

The following points summarise the key uncertainties associated with knowledge related to the presence, nature and extent of land-derived contaminants in the GBR:

- Our conceptual and quantitative understanding of the transport and fate of nutrients and sediments is highly imperfect, particularly during non-flood times.
- Hydrodynamic models of the GBR Lagoon are moderately advanced, but models of the transport and fate of fine sediments and biogeochemical models are much more limited. Process studies as well as data collection strategies that can be used for calibration and validation are needed to support their development. Current models need to link end of river to specific reef locations.
- Satellite images and flood plume monitoring suggest that some suspended sediment is transported over large distances in the marine environment during major discharge events. However, knowledge is limited of the specific origin of this presumably fine-grained, washload (non-settling) suspended sediment, and how geology, soil type and land management practices interact to produce it.
- While all terrigenous sediments and pesticides are land-derived, some of the dissolved nutrients are sourced from deepwater upwelling and from nitrogen fixing blue-green algae. Improved nutrient budgets are needed to quantify the relative contributions of all sources.
- Processes beyond gauging stations are poorly understood (i.e. what is entering the coastal/estuarine interface and material transformation in estuaries).
- It is unclear whether increased suspended sediment loads due to increased erosion from agricultural and urban development in major rivers leads to increased regional turbidity from resuspension in inshore areas of the GBR lagoon.
- Improved availability of high frequency, low cost data through the application of innovative monitoring techniques such as remote sensing will enable more comprehensive assessment of the presence and extent of contaminants in the GBR.

3. Review scientific evidence for causal relationships between water quality change and ecosystem health

Conclusion: There is strengthened evidence of the causal relationship between water quality and coastal and marine ecosystem health.

Our understanding of the effects of land-sourced contaminants on GBR species and ecosystems has been expanded enormously in the period since 2003. However, the size of the system and its temporal variability means that 'representative' monitoring and measurement of conditions in the water column and of ecosystem condition is difficult. The impacts of water quality on corals have been demonstrated through laboratory and field studies and data synthesis and integration has enabled the development of trigger values/thresholds of corals to water quality parameters. Knowledge related to the impacts of water quality on seagrasses has been synthesised. Efforts to understand the synergistic effects of multiple stressors on corals and seagrasses have commenced. However, the complexity of the relationship between nutrient enrichment, coral reef decline, macroalgal proliferation, grazing fish abundance (and other grazers) still prevents there being a clear consensus view on these relationships.

3.a. Lines of evidence

3.a.i. Seagrass.

There is evidence of decline in seagrass health with increasing concentrations of herbicides. The effects of nutrient enrichment, turbidity, increased temperature and synergistic effects are still poorly understood, especially for sub-tidal and deep-water seagrass beds.

3.a.ii. Coral reefs.

The impacts of water quality on corals has been demonstrated through both field studies and laboratory experiments. Field studies have shown that:

- Macroalgae increase and coral richness declines with increasing turbidity and chlorophyll in the GBR (Lat 12–24° S).
- Links between nutrient enrichment and crown-of-thorns starfish population outbreaks are now well supported. Both the GBR and other reefs off high islands exposed to terrestrial nutrient enrichment, and northern Pacific systems exposed to non-anthropogenic nutrients show increased propensities for outbreaks of crown-of-thorns starfish.
- Coral reef development diminishes along a water quality gradient in the Whitsunday Islands. Changes include the decline in the depth limit for coral growth from 25 m to 5 m water depth and a three-fold decline in the density of young corals, while the density of coral-boring macro-bioeroders increases five-fold and macroalgal cover increases six-fold along this water quality gradient.
- Coral cores from reefs off Mackay show that increasing exposure to nitrogen from the Pioneer River is correlated with poor reef condition and high macroalgal cover.
- Inshore reefs off the Wet Tropics have lower coral and octocoral diversity than would be expected from their latitudinal location.

Laboratory studies have shown that:

- Stress and mortality in corals exposed to sedimentation increases with increasing organic content of the sediment.
- Coral calcification decreases with elevated phosphate concentrations.
- The presence of muddy marine snow (aggregates of planktonic organic matter and fine sediment) increases sedimentation stress and mortality in coral recruits.
- Many pesticides found in the GBR exert detrimental effects on zooxanthellae photosynthesis and coral reproduction at trace concentrations.
- There are negative synergistic effects between herbicides and sediments on crustose coralline algae that are essential for successful coral recruitment.

3.a.iii. Mangroves.

There is conflicting evidence concerning the cause of mangrove dieback in the Mackay region. Early research attributed an association with diuron, but affected mangroves have recovered despite diuron levels remaining high at some sites. This suggests that the complexities of cause and effect relationships for such diebacks are yet to be fully resolved.

3.b. The evidence base

3.b.i. Seagrass.

The distribution and growth of seagrasses is dependent on a variety of factors such as temperature, salinity, nutrient availability, substratum characteristics, and underwater light availability (turbidity). Terrigenous runoff, physical disturbance, low light and low nutrients, respectively, are the main drivers of each of the four seagrass habitat types found in Queensland and changes to any or all of these factors may cause seagrass decline (Waycott *et al.,* 2005).

The most common cause of seagrass loss is the reduction of light availability due to chronic increases in dissolved nutrients which leads to proliferation of algae, thereby reducing the amount of light reaching the seagrass (e.g. phytoplankton, macroalgae or algal epiphytes on seagrass leaves and stems), or chronic and pulsed increases in suspended sediments and particles leading to increased turbidity (Schaffelke *et al.,* 2005). In addition, changes of sediment characteristics may also play a critical role in seagrasses loss (Mellors *et al.,* 2005).

Herbicides (principally diuron) have been found in coastal and intertidal seagrasses adjacent to catchments with high agricultural use at levels shown to adversely affect seagrass productivity (McMahon *et al.,* 2005; Haynes *et al.,* 2000). For example, diuron toxicity trials on three tropical seagrass species (Halophila ovalis, Cymodocea serrulata and Zostera capricorni) using Pulse-Amplitude-Modulated (PAM) fluorometry indicated that environmentally relevant levels of diuron (0.1–1.0 µg/l) exhibited some degree of toxicity to one or more of the tested seagrass species (Haynes *et al.,* 2000). These are comparable with diuron concentrations detected in several GBR regions (Prange *et al.,* 2007). Seagrasses are known to accumulate heavy metals, but appear to be moderately resistant to the direct effects of metals. However, the fauna associated with seagrass meadows is considered to be highly sensitive to metal exposure (Ward, 1989).

The effects of nutrients on GBR seagrass health have proved more complex to understand but it is now clear that the effects are different to those shown for temperate seagrass and the threat from increased nutrients may be less in tropical cases (Mellors *et al.,* 2005; Schaffelke *et al.,* 2005; Waycott *et al.,* 2005). To date, no major decline in seagrass abundance in the GBR region has been recorded or attributed directly to increased nutrient availability, though localised declines have occurred in the Whitsunday and Hervey Bay areas. In both cases, light deprivation was implicated, by (i) algal overgrowth caused by nutrient enrichment from sewage effluent (Campbell and McKenzie, 2001) and (ii) smothering by settling particles and high suspended particle load from flood plumes (Campbell and McKenzie, 2004; Preen *et al.,* 1995; Longstaff and Dennison, 1999).

The presence of high or low concentrations of nutrients in the environment is one of the stressors on seagrass survival. Field research to date in the GBR suggests that nutrients do not have a negative effect on seagrass growth and distribution, as reported in temperate regions (Mellors *et al.,* 2005). On the contrary, Udy et al. (1999) observed an increase in seagrass cover at Green Island between 1936 and 1994, and attributed this increase to a net increase in the total nutrient pool available over 50 years of gradual build-up of nutrients in the Cairns region. Recent data on seagrass tissue nutrient content (*Halophila ovalis*) collated by Mellors (2003) and Mellors *et al.,* (2005) in Cleveland Bay shows an increase in tissue nutrients over a 25-year period, which circumstantially reflects increases in fertiliser usage in the adjacent Burdekin catchment.

Direct effects of higher nutrient availability on seagrass have been observed in laboratory experiments. Moderate levels of nitrate additions (3.5 to 7.0 µM) promoted the decline of the temperate seagrass species *Zostera marina* (Burkholder *et al.,* 1992; Short *et al.,* 1995). Increased levels of ammonia (1.85–5.41 µM) and phosphate (0.22–0.50 µM) lead to a reduction in shoot density and biomass of Z. *marina* (Short *et al.,* 1995). The concentrations measured in water samples taken in flood plumes have consistently recorded elevated dissolved inorganic nitrogen concentrations of 0.6 to 10 µM and phosphate levels of 0.13 to 1.98 µM (Brodie and Mitchell, 1992; Steven *et al.,* 1996; Brodie and Furnas, 1996; Devlin *et al.,* 2001). These nutrient levels have remained high in the inshore lagoon for periods of several days to weeks. Approximate ranges for (non-flood) inshore water nutrient concentrations have been measured between non-detectable and 2 µM for dissolved inorganic nitrogen (predominantly ammonia) and non-detectable and 0.2 µM for phosphate (Furnas *et al.,* 1995; Brodie and Furnas 1996; Devlin *et al.,* 1997).

Other studies have shown that in the GBR seagrass growth is limited by nitrogen (Udy *et al.,* 1999; Mellors, 2003). Both studies assessed the response of seagrass to enhanced nutrient levels and saw a response to both nitrogen and phosphorus, but nitrogen was the primary limiting element. Thus, at present, seagrasses have the capacity to absorb additional nutrients enhancing their growth and it would appear that the current nutrient loadings in the GBR have not yet reached critical levels for seagrasses. However, the limits of the ability of seagrasses to continue to absorb nutrients is not known and additional experiments on interactions between sedimentation, nutrients, light and temperature as other important drivers of plant growth are required. In addition, nutrient analyses have been conducted primarily on the smaller more ephemeral species. Larger more persistent species may be more sensitive to additional nutrients in this region and this should be assessed (CRC Reef Consortium, 2005).

The Reef Plan Marine Monitoring Program includes a seagrass monitoring component, which involves monitoring of intertidal seagrass meadows at 14 sites along the GBR coast for percent cover, species composition, reproductive health (through seedbank monitoring) and seagrass tissue nutrient status. Seagrass surveys are undertaken at the end of winter in October and following the wet season in April. Additional information is also collected on sediment pesticide and absorbed nutrient concentrations within seagrass meadows and seagrass tissue nutrients (Prange *et al.,* 2007). This task is assisted by the community-based Seagrass-Watch program (www.seagrasswatch.org).

3.b.ii. Corals.

Corals and water quality – field studies.

Strong links between coral reef health and water quality conditions have been shown at local scales (reviewed in Fabricius, 2005), at regional scales (van Woesik *et al.,* 1999, Fabricius *et al.,* 2005), and recently at a GBR-wide scale (De'ath and Fabricius, 2008). The effects of corals have been most frequently studied and effects of water quality on coral reproduction have been reported repeatedly. However, abundances of a range of other reef associated organisms have also been shown to change along water quality gradients. Figure 6 summarises the results of a review of existing reef studies from around the world to identify the main effects of nutrient and sediment related parameters on key coral reef organism groups. The data suggests that nutrient enrichment can lead to macroalgal dominance if light levels are sufficient, but lead to a dominance by heterotrophic filter feeders if light becomes a limiting factor for macroalgae (Johannes *et al.,* 1983; Birkeland, 1988). It also shows that crustose coralline algae, which are essential settlement substratum for coral larvae, are negatively related to sedimentation (Fabricius and De'ath, 2001), as later confirmed by laboratory experiments (Harrington *et al.,* 2005).

Studies where the predicted ecological effects of poor water quality (elevated delivery and/or concentrations of suspended sediment, nutrients or pesticides) have been borne out in the field in the GBR include:

- Deepest depth of coral growth reduced from 25 m to 5 m depth, the number of young corals decreased three-fold, the density of coral-boring macro-bioeroders increased five-fold and macroalgal cover increased six-fold along a water quality gradient in the Whitsundays (Cooper and Fabricius, 2007, Fabricius *et al.,* 2008, Cooper *et al.,* 2008).
- Poor reef condition correlated with poor water quality conditions in Wet Tropics inshore reefs compared with reefs in similar physical locations near Cape York, but which have good water quality (Fabricius *et al.,* 2005).
- A sag in coral biodiversity in the region between Townsville and Cooktown correlated with poor water quality conditions in this area (Devantier *et al.,* 2006).
- Links between nutrient enrichment and crown of thorns starfish population outbreaks are now well supported in both anthropogenically enriched systems such as the GBR (Brodie *et al.,* 2005) and naturally enriched systems such as the northern Pacific (Houk *et al.,* 2007).
- Reduced coral reef development in a water quality gradient through the Whitsunday Island group (van Woesik *et al.,* 1999).
- A raft of physiological changes in corals have been documented along a water quality gradient in the Whitsunday Island group (Cooper and Fabricius, 2007). These sub-lethal changes are now being developed into a bioindicator system to investigate changes in the water quality conditions and ecological status of inshore coral reefs.
- The species composition of foraminifera (the ration between large, symbiont bearing and small, heterotrophic foraminifera) is being developed into a bioindicator system for the GBR. The Foraminifera in Reef Assessment and Monitoring Index metric, previously developed for coral reefs in the Caribbean, shows a relationship with water quality conditions along the Whitsunday water quality gradient (Uthicke *et al.,* 2006; Uthicke and Nobes, 2007).
- The delivery of nitrogen from the Pioneer River to coastal reefs in the Mackay area as shown through coral core records is correlated with poor reef condition in areas of higher nitrogen delivery and a high proportion of macroalgal cover (Jupiter *et al.,* 2007).

	Dissolved inorg. nutr	POM*	Light reduction	Sedimentation
Crutose coraline algae	↓			⬇
Bioeroders	↑	⬆		↓
Macroalgae	⬆	↑	⬇	↓
Heterotrophic filter feeders		⬆	⬆	↓
Coral diseases	↑			↑
Coral predators		⬆		

* including phytoplankton

Figure 6. Effects of the four main parameters of terrestrial runoff on organisms that interact with corals. High abundances crustose coralline algae as settlement substrata promote coral populations, whereas high abundances of the other groups are assumed to negatively affect coral populations. The arrows indicate the relative strength and direction of the response (arrows pointing up or down = increasing or decreasing, thick arrow = strong, medium = moderate, thin = weak effect); empty cells indicate that insufficient data are available. From Fabricius (2005).

While pollution effects on coral reefs at local scales are well understood, links at regional scales between increasing sediment and nutrient loads in rivers, and the broadscale degradation of coral reefs, have been more difficult to demonstrate (Fabricius and De'ath, 2004). This is due to a lack of large-scale historic data and the confounding effects of other disturbances such as bleaching, cyclones, fishing pressure and outbreaks of the coral eating COTS, and is further complicated by the naturally high variability in monsoonal river flood events. In addition, the relationship between macroalgal proliferation, nutrient enrichment and the abundances of grazers (fishes and invertebrates) is complex and far from understood, and subject to scientific debate (McCook, 1999; McCook *et al.,* 2001; Bellwood *et al.,* 2006; Hughes *et al.,* 2005; Littler *et al.,* 2006). The full extent of organism responses are poorly understood, as each of the numerous inshore species has its own tolerance limit at every life stage, and interactions between the organisms add to the complexity.

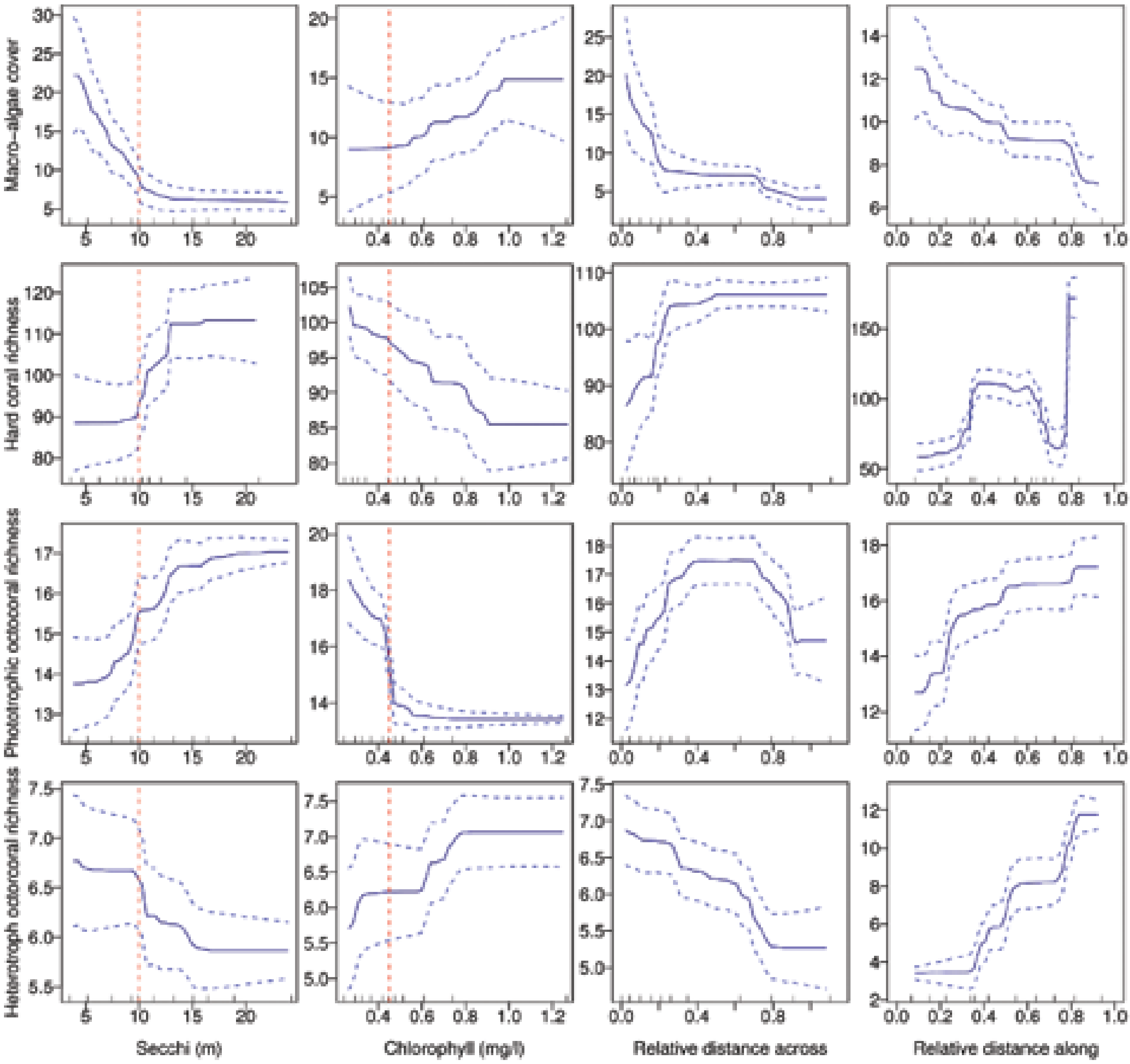

Figure 7. Relationship of macroalgal cover, and the taxonomic richness of hard corals, phototrophic and heterotrophic octocorals (soft corals and sea fans with and without zooxanthellae, respectively), along gradients in water clarity (measured as Secchi disk depth) and chlorophyll, while also controlling for relative distance across and along the shelf (from De'ath and Fabricius 2008). Substantial increases in macroalgal cover and losses in coral biodiversity are being observed at <10 m Secchi disk depth, and >0.45 µg L-1 chlorophyll. The red lines show the proposed water quality guideline values (10 m Secchi disk depth, and 0.45 µg L-1 chlorophyll).

However, recently relationships between data sets of water quality, and macroalgal cover and the richness of hard corals and phototrophic and heterotrophic octocorals, were investigated at a GBR-wide scale (De'ath and Fabricius, 2008). The study showed that the four biotic indicators chosen are significantly related to GBR water quality. Macroalgae increased and hard coral richness and the richness of phototrophic octocorals declined with increasing turbidity and chlorophyll, after cross-shelf and long-shore effects were statistically removed (Figure 7). Heterotrophic octocorals slightly benefited from high turbidity. Mean annual values of >10 m Secchi depth and <0.45 g L-1 chlorophyll were associated with low macroalgal cover and high richness of phototrophic octocorals and hard corals. The study suggested these values to be useful water quality guideline values. These guidelines are presently exceeded on 650 of the 2800 gazetted reefs of the GBR. The models showed that compliance with these guideline values (e.g. minimising agricultural runoff would likely reduce macroalgal cover by ~50% and increase hard coral and octocoral richness by 40% and 70%, respectively, on these 650 reefs). GBRMPA is in the process of refining the existing water quality guidelines that have previously been developed for three GBR regions (Moss *et al.,* 2005; De'ath and Fabricius, 2008; GBRMPA, 2008).

This synthesised information could support the completion of a comprehensive risk assessment for the ecosystems of the GBR that should include consideration of the relative risk of different contaminants to GBR ecosystems. Currently, the risk modelling (such as Maughan *et al.,* 2008; Wolanski and De'ath, 2005) assumes that all contaminants of concern are of equal risk, which is clearly not the case. This lack of knowledge prevents prioritisation of management options for each of the individual contaminants in the catchments, or at a cross-regional scale. To conduct a meaningful prioritisation, knowledge of the degree of deviation from some assumed 'natural' condition and elevation above trigger values/thresholds, and potential consequences of such enrichment need to be understood. Currently, contaminant management is prioritised based on deviation from assumed 'natural' only.

In terms of ongoing monitoring of coral reef health, the Reef Plan Marine Monitoring Program includes an inshore reef monitoring component. Annual underwater photographic surveys are undertaken along transects established at 35 inshore reef sites. These surveys are an effective way of monitoring benthic cover and reef community demographics. Coral settlement rates are also measured after the annual coral spawning (using settlement plates) in the Wet Tropics, Burdekin, Mackay-Whitsunday and Fitzroy regions. Adult corals can tolerate poorer levels of water quality than new coral recruits, thus one of the ways in which water quality is likely to impact reef communities is through an effect on coral reproduction and recruitment (Prange *et al.,* 2007).

Corals and water quality – laboratory studies.

A number of ecotoxicology-style experiments exist to investigate the effects of various contaminants on selected target organism groups. Such studies include the investigation of nutrients on corals (Koop *et al.,* 2001) and of sedimentation stress on corals (Philipp and Fabricius, 2003). Herbicides found in GBR waters have biological effects on coral zooxanthellae at concentrations below 1 µg/L (e.g. Jones and Kerswell, 2003; Jones *et al.,* 2003; Jones, 2005; Negri *et al.,* 2005; Markley *et al.,* 2007; Cantin *et al.,* 2007). The long-term effect on ecosystem performance of the continuous presence of such residues is not known, but evidence is emerging that some pesticides not only affect the photosynthesis of the endosymbionts but also coral reproduction (Jones, 2005; Negri *et al.,* 2005; Markley *et al.,* 2007; Cantin *et al.,* 2007). Lastly, first evidence is emerging that the existence of synergistic effects may have to be carefully considered in estimates of tolerance thresholds (and hence water quality targets). For example, sedimentation effects on crustose coralline algae are significantly worsened when trace concentrations of herbicides occur in the sediments (Harrington *et al.,* 2005). Other studies have demonstrated that sedimentation effects on corals worsen with increasing organic enrichment of the sediments (Weber *et al.,* 2006), and with enrichment with marine snow (Fabricius *et al.,* 2003; Wolanski *et al.,* 2003).

Though considerable knowledge has been gained from single species exposure experiments in the laboratory, it is important to relate such laboratory studies to field settings and ecosystem responses. Detailed surveys at relatively fine taxonomic resolution, when cautiously interpreted in the context of available biophysical environmental data and biological knowledge of key species, can provide important information on the health and status of inshore coral reefs (Fabricius *et al.,* 2005; Devantier *et al.,* 2006), and laboratory experiments may then be used to investigate causal relationships between water quality and the patterns observed in the field.

Recently, several conceptual models have been developed to articulate known relationships to better underpin monitoring programs and form the basis for numerical modelling (Prange, 2007; Webster *et al.,* 2008a; Haynes *et al.,* 2007; Fabricius, 2007).

3.b.iii. Mangroves.

The responses of marine plants (mangroves, seagrass and macroalgae) to changes in water quality in the GBR is reviewed in Schaffelke et al. (2005). The limited information of these responses limits the ability to make conclusions about responses across community types; however, there are clear indications that declining water quality negatively affects GBR macrophytes. In addition, loss or disturbance of habitat-building macrophytes such as mangroves and seagrasses has serious downstream effects for coastal water quality due to their capacity to assimilate nutrients and to consolidate sediments.

Mangrove responses to nutrients are complex, with examples of both enhanced growth and associated dieback found in locations outside of the GBR (e.g. Laegdsgaard and Morton, 1998; Environmental Protection Agency [EPA], 1998). As with the nuisance algae, nutrients enhance growth of mangrove plants. This has been demonstrated in nutrient enrichment experiments, which also showed that nitrogen and phosphorus were growth-limiting differently at lower and higher intertidal positions (Boto and Wellington, 1984). Nutrients derived from sewage discharge can be beneficial for growth and productivity of mangroves (Clough *et al.,* 1983). However, under high nutrient demand other chemicals, such as herbicides, may be taken up at greater rates along with extra nutrients (Duke *et al.,* 2003a). This synergistic effect of increased nutrients has resulted in the increased phytotoxicity of specific herbicides (Hatzios and Penner, 1982). High nutrient levels may also alter faunal communities that might affect the vulnerable trophic links between mangrove trees and fauna (Robertson *et al.,* 1992).

Increased sediment loads in runoff from catchments affect mangrove distributions within estuaries as well as water quality (Duke *et al.,* 2003b). In recent decades, there have been unprecedented gains in mangrove areas at the mouths of at least four GBR river estuaries, Trinity Inlet (Duke and Wolanski, 2001), Johnstone River (Russell and Hales, 1994), Pioneer River (Duke and Wolanski, 2001) and Fitzroy River (Duke *et al.,* 2003b). Although these rivers occupy a broad range of climatic and geographic conditions, they each have characteristic and significant new mangrove stands. At the mouth of the Fitzroy River, the area of mangroves had been relatively constant for a century but increased rapidly after the 1970s. The increases were correlated with concurrent human activities including increased clearing of vegetation in the catchment, which increased sediment loads in runoff, and the construction of a major river barrage, which reduced river flows and flushing.

An unusual species-specific dieback of Avicennia marina has been observed in the Mackay region since the mid-1990s (Duke and Bell, 2005; Duke *et al.,* 2005). By 2002, it was estimated that 97% of the A. marina trees in the Pioneer River estuary were affected by moderate to severe dieback (Duke *et al.,* 2003a). Laboratory studies have shown that mangroves are sensitive to the root application of atrazine, diuron and ametryn (Photosystem II inhibiting herbicides) and Avicennia marina is more sensitive than other mangroves tested (Bell and Duke, 2005). Although the Mackay dieback was associated with the levels of diuron and other herbicides present in mangrove sediments and pore water, and in stream/drain waters flowing into mangrove areas (Duke and Bell, 2005), two recent surveys of mangrove communities in the Pioneer River estuary have shown an overall improvement in the health of A. marina although herbicide levels in sediments and pore water have remained high at some sites (Wake, 2008).

The dieback has also been attributed to sedimentation (Kirkwood and Dowling, 2002).

These findings indicate that the causes of such diebacks require further investigation and the complexities of cause and effect relationships are yet to be fully resolved.

3.c. Key uncertainties related to causal relationships between water quality and ecosystem health

The following points summarise the key uncertainties associated with knowledge related to the causal relationships between water quality change and ecosystem health.

- While a limited number of models exist that attempt to link marine ecosystem health to end of catchment loads, further development is required as a matter of urgency to assess the influence of catchment management actions on GBR health in a comprehensive way.
- Synergistic effects of contaminants and external influences on GBR ecosystems.
- Definition of acceptable/desired thresholds for key indicators (i.e. coral, seagrass and biodiversity).
- Drivers of seagrass change and health, in particular the influence of declining water quality, especially nutrients and turbidity.
- The specific impacts of pesticides (particularly herbicides) on the GBR ecosystems. Presently there is a lack of toxicity data for organisms specific to the GBR. Much of the current research has been focused particularly on corals with comparatively little data on mangroves, seagrass and micro-organisms. In addition, the synergistic effects of mixtures of pesticides are relatively unknown, as well as the effects of long-term exposure.
- Understanding the response of estuarine systems to floods and the role of the coastal floodplain.
- Knowledge of the response of the GBR ecosystem to different events in different areas, and the ability to recover. Understanding the implications of combined scale and frequency of disturbance to GBR ecosystems.
- The relative risks to GBR ecosystems of individual terrestrial-sourced contaminants.
- The complexity of the relationship between nutrient enrichment, coral reef decline, macroalgal proliferation and abundances of grazing fishes (and other grazers) still prevents there being a clear consensus view on this specific relationship.

4. Review existing scientific evidence for a decline in the quality of water in GBR catchment waterways leading to reduced instream ecosystem health

Conclusion: The health of freshwater ecosystems is impaired by agricultural land use, hydrological change, riparian degradation and weed infestation.

Waterways of the GBR catchment include streams that drain forested uplands and the cultivated tablelands of the Wet Tropics, intermittent dry-land streams, lowland rivers and estuaries, and the lagoons and swamps of the floodplains. In the Wet Tropics, most systems are perennial, but in the Dry Tropics, streams and wetlands may be intermittent, and even large rivers may contract to isolated waterholes in the dry season.

Our understanding of the ecosystem health of GBR waterways has been greatly enhanced by recent reports on Wet Tropics streams (e.g. Arthington and Pearson, 2007) and floodplain waterways (Pearson *et al.,* 2005), and on the riverine waterholes and floodplains of the dry tropics (e.g. Perna and Burrows, 2005). The GBR catchments support high biodiversity and many endemic species of freshwater fish (Pusey *et al.,* 2004), some of the highest diversity of freshwater invertebrates in the world (Pearson *et al.,* 1986; Vinson and Hawkins, 2003; Pearson, 2005), and many species of aquatic plants (Mackay *et al.,* 2007).

While the diversity of information on catchment freshwater health is increasing, much work is unpublished. Recent reviews on within-catchment water quality and ecosystem health have focused on the Wet Tropics (e.g. Pearson and Stork, 2007; Connolly *et al.,* 2007a, 2007b; Pusey *et al.,* 2007; Faithful *et al.,* 2006); there has been less work on the Dry Tropics, highlighting an important information gap, although reports on the Burdekin and the Fitzroy systems are advancing our understanding of those systems.

4.a. Lines of evidence

4.a.i. Priority factors affecting instream ecosystem health are riparian vegetation condition, aquatic and riparian weed prevalence, vegetation removal and habitat loss.

These factors have been shown to be more important factors reducing instream ecosystem health than water quality per se.

4.a.ii. Concentrations of nutrients in fresh waters in many catchments are proportional to the area of land under agriculture.

Elevated nutrient inputs from agricultural sources are known to contribute to enhanced weed growth, vegetation change and associated changes in instream community structure.

4.a.iii. Agricultural development has led to substantial damage to riparian and wetland health in many catchments.

These influences have negative consequential effects on water quality and hence detrimental effects on instream biota.

4.a.iv. Concentrations of pesticides in waterways are highest in areas of intensive agricultural activity.

The implications of elevated pesticide concentrations for community structure in freshwater ecosystems are potentially severe but our knowledge is incomplete.

4.a.v. The condition of riverine waterholes in the Dry Tropics is largely determined by cattle access.

Cattle contaminate and disturb the waterholes causing deoxygenation from excretia, increased turbidity, and consequent loss of biodiversity.

4.a.vi. The condition and biodiversity of floodplain waterways are adversely affected by irrigation inputs and drainage.

Sediments, nutrients from fertilisers and organic material have been shown to lead to oxygen depletion, enhanced weed growth, turbidity and hence biodiversity loss.

4.b. The evidence base

4.b.i. Priority factors affecting instream ecosystem health are riparian vegetation condition, aquatic and riparian weed prevalence, vegetation removal and habitat loss.

As described in Section 1, water quality conditions in the GBR catchments in runoff events are reasonably well documented; water quality in the catchments through the non-event periods is much less well documented. It is this ambient or chronic water quality that is of greatest importance to the ecology of the rivers and wetlands, as opposed to the short-term events that appear to drive water quality in coastal waters. The relative importance of ambient inputs to coastal ecosystem processes is also not known.

However, the most serious factors affecting health in Wet Tropics streams and wetlands are changes to habitats, including invasion by exotic weeds and loss of riparian vegetation, which can cause major changes to waterway morphology, habitat complexity, food availability, gas exchange with the atmosphere and, therefore, biodiversity. Organic effluents have been shown to cause fish kills and a major decrease in biodiversity as a result of oxygen depletion; and deposition of fine sediments derived from agriculture and other sources reduce biodiversity in streams.

The multitude of human impacts that might affect catchment and GBR health is summarised in Figure 8. The most important of these potential impacts is land clearing (Pearson and Stork, 2007).

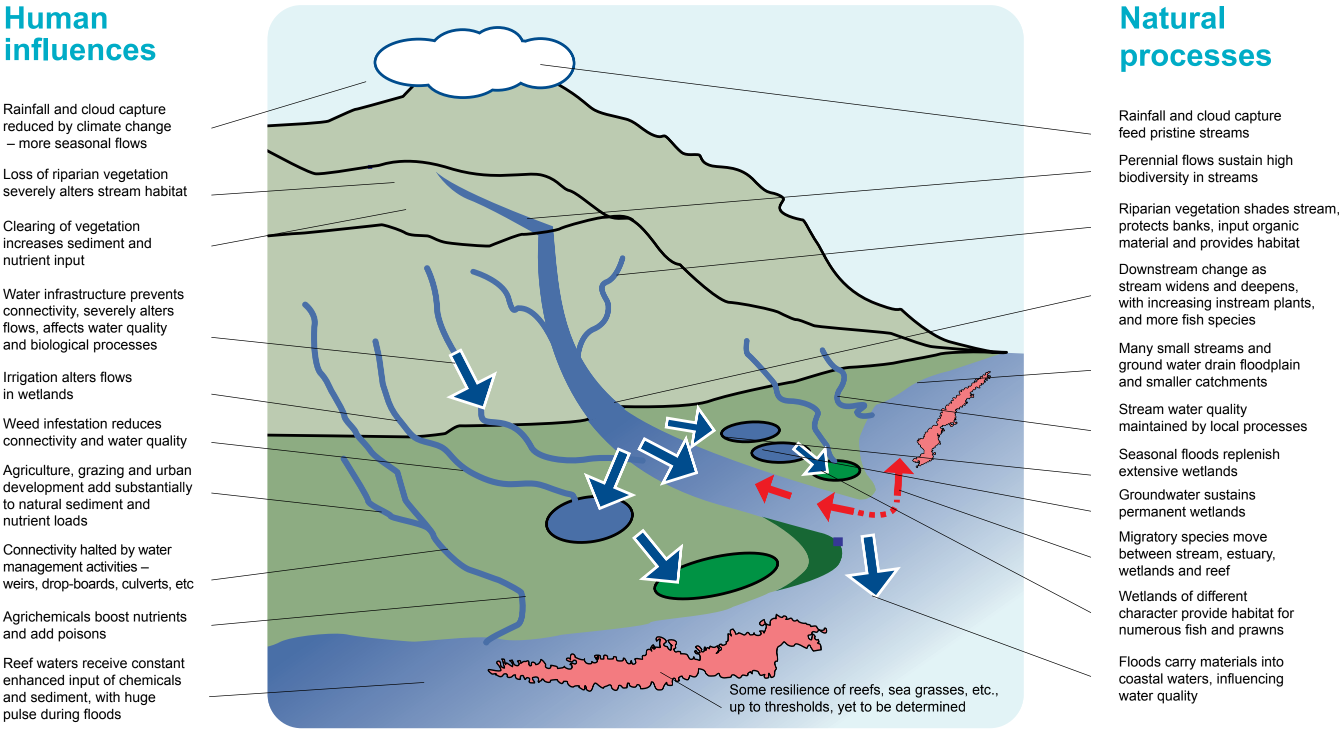

Figure 8. Outline of processes from catchment to reef (adapted from Pearson and Stork, 2007).

However, in the Wet Tropics, there is little available land left to clear, so the issue is more one of management of cleared land. Changing land use is a growing concern because, as climate changes and as the economics of particular crops changes, new land uses may bring problems that have not yet been experienced. Even the change in sugarcane harvesting, from the old method of burning first to remove trash, to the current approach of green cane harvesting, had unpredicted impacts. Leaving the trash on the land had the major benefits of retaining organic material, removing smoke impacts and protecting the soil against erosion, but the interaction of rainfall with trash can produce organic pollution in streams, leading to fish kills. Fine-scale land and water management can alleviate such problems.

Long-term turbidity in the water is often caused by loss of riparian vegetation or cattle access, such as occurs in the Burdekin River Dam (Lake Dalrymple) and in the river downstream, and may have a long-term detrimental effect on normal processes. Moreover, if that suspended material settles to the substrate it can have major effects on benthic habitats and organisms, by clogging substrate interstices and microhabitats, and smothering plants and small animals (e.g. Connolly and Pearson, 2007).

Organic inputs to aquatic systems, such as effluents from sewage works or dairies, typically cause oxygen depletion through bacterial respiration of organic materials, with subsequent loss of hypoxia-intolerant species of invertebrates and fish. In the Wet Tropics, sugar mill effluents were once the main source of problems (Pearson and Penridge, 1987), but there has been substantial effort to remove or clean up discharges to waterways.

Disturbance of riverbanks also occurs by access of feral animals, including pigs that can severely disturb the sediments and benthic fauna of shallow wetlands, and also several species of fish, for example Tilapia (Webb, 2006).

In the Wet Tropics, of major concern are tilapia (*Oreochromis mossambicus*) and other related cichlid fishes of African origin that, it is feared, might displace native species (Burrows, 2004). Currently it appears that introduced fishes do especially well in disturbed habitats, but are not yet implicated in displacement of natives in more pristine systems (Webb, 2003).

The dynamics of oxygen (and, incidentally, pH) in catchment waterways are complex and dependent on a range of natural and human-influenced variables (Pearson *et al.,* 2003). Natural oxygen status can best be achieved by maintaining riparian zones, curtailing weed growth; by preventing the input of nutrients and by removing blockages to flow. While the tropical Australian invertebrate and fish fauna appear extremely resilient to low dissolved oxygen status (Pearson *et al.,* 2003; Connolly *et al.,* 2004), their tolerance thresholds can be breached, as evidenced by the occasional fish kills that occur in floodplain waterways. Prolonged high sediment levels reduce diversity and abundance of stream biota such as fishes (Hortle and Pearson, 1990).

4.b.ii. Concentrations of nutrients in fresh waters in many catchments are proportional to the area of land under agriculture.

The concentrations of dissolved nutrients in stream water correlates with the proportion of agricultural land use in the catchments (e.g. Dillon and Kirchner, 1975; Smart *et al.,* 1985; Jordan *et al.,* 1997). Although streams are well flushed in Wet Tropics waterways, nutrient supplements from fertilisers are reflected by algal productivity and consequent changes in the fauna. In many disturbed streams the effects of increased nutrients are exacerbated because the clearing of riparian vegetation increases light levels and encourages vigorous growth of invasive weeds and the instream growth of algae and larger plants.

For example, water hyacinth (Eichornia crassipes) and salvinia (Salvinia molesta) are two plants introduced for their ornamental values, but which have become major weeds in the GBR catchment waterways. They infest lagoons and slow-flowing waterways, eventually covering the whole water body in a thick mat that blocks out light and prevents gas exchange, rendering the waterway hypoxic and uninhabitable for native plants, fish and other animals. This growth is accelerated by increased nutrient input. In the Wet Tropics, the major weed problem is para grass (Brachiaria mutica), which grows in profusion wherever there is sufficient light and appropriate substrate. Its growth is enhanced by nutrients in the water. It now infests most minor drainage channels, small streams and river banks. It is a severe impediment to normal drainage, and has substantial effects on the morphology of waterways (Bunn *et al.,* 1998).

Pearson and Penridge (1987) found high abundances of macroinvertebrates below the outfall of a sugar mill in the Wet Tropics. They associated the increase in macroinvertebrate production with high levels of nutrients and organic matter in mill effluent. In experiments using artificial stream channels on the bank of a first order rainforest stream Pearson and Connolly (2000) were able to increase macroinvertebrate abundance by 75%.

Aquatic macroinvertebrates offer a time-integrated sample of environmental conditions over their lifetime (weeks to years) and consequently have been regularly used as indicators of water quality and ecosystem health (Rosenberg and Resh, 1993). They are numerous and ubiquitous, occurring in nearly all water bodies and are easily sampled using cheap, readily available equipment, making them ideal for this purpose. The aquatic macroinvertebrates are typically diverse, with different species having specific requirements for biophysical conditions. As a consequence, their distributions follow natural gradients in environmental conditions and they have been shown to respond to changes in water quality and physical parameters associated with anthropogenic disturbance (Connolly and Pearson, 2004). For example, they have been demonstrated to be sensitive to changes in water chemistry, including dissolved oxygen concentration (e.g. Connolly *et al.,* 2004), pH (e.g. Rutt *et al.,* 1990), salinity (e.g. Metzeling, 1993) and to be vulnerable to toxic contaminants such as insecticides (e.g. Liess, 1994; Shultz and Liess, 1995). They have also been shown to respond to organic pollution (e.g. Pearson and Penridge, 1987) and nutrient enrichment (e.g. Økelsrud and Pearson, 2007; Pearson and Connolly, 2000). The clearing of riparian vegetation and increases in sedimentation have also been shown to be detrimental to macroinvertebrate assemblages (e.g. Ryan, 1991; Connolly and Pearson, 2007; Harrison *et al.,* 2008).

4.b.iii. Agricultural development has led to substantial damage to riparian and wetland health in many catchments.

Various estimates of loss of freshwater wetlands in developed catchments along the GBR coast range between 70–90% (EPA, 1999) while the condition of the remaining 10–30% range from moderate to no value as fisheries resources (Veitch and Sawynok, 2005). The most significant reason for the reduction in the value of remaining wetlands to fisheries is changed catchment hydrology resulting in loss of connectivity, habitat modification, poor water quality and poor habitat quality. Wetland loss affects species whose lifecycle includes a marine phase (Veitch and Sawynok, 2005).

Floodplain lagoons are affected by inputs of nutrients (from fertilisers) that promote aquatic plant growth, and consequent nocturnal oxygen depletion and loss of biodiversity. Floodplain lagoons are also affected by inputs of organic materials (e.g. cane field wastes) that promote bacterial production and further oxygen depletion.

The loss of riparian vegetation in the GBR catchments is documented throughout Queensland in the Statewide Landcover and Trees Study (SLATS) (e.g. Queensland Department of Natural Resources and Water [QNRW], 2007), and at a local or regional scale through specific, mostly short-term, assessments. Natural riparian (riverbank) vegetation in GBR catchment typically includes forest trees, shrubs and, with sufficient light penetration, some grasses and herbs. Where drainage is poor, species that are tolerant of waterlogging may dominate. The benefits of riparian vegetation to normal ecosystem function are well documented (e.g. Pusey and Arthington, 2003). They include: habitat and habitat corridors for terrestrial animals and plants; habitat for semi-aquatic animals; shade; filtration mechanisms; organic inputs; bank stability; instream habitat via roots and snags and basking sites for reptiles. In the past, farmers were often encouraged to clear land right up to the river banks. It is now acknowledged that this policy was ill-conceived as the lost amenity values greatly outweighed the value of the land exposed. Despite broad acceptance of this assessment, restoration of riparian zones is only occurring very slowly.

As part of the Queensland Wetlands Programme established in 2003 under the Reef Plan, Queensland's wetlands have been mapped digitally by building on existing information, including water body mapping derived from satellite imagery, regional ecosystem mapping and a springs database (EPA, 2005). Wetlands have been classified according to a range of criteria, including the type of ecological system (riverine, estuarine etc), their degree of water permanency, and salinity. The result is a consistent wetland map at a scale of 1:100 000, with finer detail in some parts of Queensland (mainly coastal regions) where appropriate mapping data exists. A wetland inventory is also being developed to describe the listing and storage of wetland information from a range of sources including tenure, climate, population, land use and field data.

4.b.iv. Concentrations of pesticides in waterways are highest in areas of intensive agricultural activity.

Some monitoring of pesticide concentrations has been done in the Wet Tropics that shows that the concentrations of pesticides in waterways are highest in areas of intensive agricultural activity (e.g. Bainbridge *et al.,* 2006a) but there is very little information on the impacts of pesticides on native biota (exceptions include Kevan and Pearson, 1993). Clearly, our understanding of the fate and impacts of pesticides is a major knowledge gap that needs addressing.

Weeds such as paragrass, which become a nuisance to farmers as a result of accelerated growth through increased nutrient availability, are often managed by mechanical or chemical means. This results in direct pesticide application to waterways. The implications of these applications for instream or downstream ecosystem health have not been adequately investigated.

4.b.v. The condition of riverine waterholes in the dry tropics is largely determined by cattle access.

The condition of riverine waterholes reflects their local surroundings. In the dry tropics, the condition of riverine waterholes is largely determined by the availability of access to cattle, which contaminate and greatly disturb remnant and refugial ecosystems, causing, among other things, deoxygenation and consequent loss of biodiversity (Burrows, 2003).

4.b.vi. The condition and biodiversity of floodplain waterways are adversely affected by irrigation inputs and drainage.

Condition and biodiversity of floodplain waterholes are affected by irrigation inputs and drainage, particularly sediments, nutrients from fertilisers and organic material, which lead to oxygen depletion and biodiversity loss (Burrows and Butler, 2007).

4.c. Key uncertainties related to reduced instream health

The following points summarise the key uncertainties associated with knowledge related to decline in the quality of water in GBR catchment waterways leading to reduced instream ecosystem health.

- Understanding of the fate and impacts of pesticides in freshwater ecosystems.
- Quantitative assessment of the different requirements for catchment management for improved instream health.
- The greatest influence on streams and wetlands is caused by the ambient concentrations in the non-flood periods. The short, sharp flush of material in the flood periods have little influence on streams and wetlands, but produce the bulk of materials reaching the GBR; it is the regular supply of nutrients that occurs through the year on which weed growth (for example) is dependent. Those weeds are detrimental to instream health, smothering natural habitats, exacerbating hypoxic conditions and creating barriers to dispersal, but may provide an excellent filter, reducing contaminants being delivered to the GBR. This hiatus needs to be explicitly assessed and quantified. It is possible, for example, that these beneficial effects of weeds are short-lived, as they are over-run by wet season floods.

5. Review scientific evidence for the effectiveness of current or proposed management intervention in solving the problem

Conclusion: Current management interventions are not effectively solving the problem.

Knowledge related to the effectiveness of management interventions has moved forward in the last five years but there are still significant gaps that hinder the capacity to identify the priorities for investment and provide confidence in their likely water quality outcomes. The Water Quality Improvement Plans (WQIPs) in the GBR have provided a substantial driver to improve the availability and accessibility of this information, and in defining which practices are most appropriate in certain locations for the most efficient biophysical, social and economic outcomes.

Despite regional collaborative efforts between industry, research, government and the regional NRM bodies to develop Best Management Practices (BMP) for the major industries (sugarcane, grazing and horticulture) within the GBR catchments, there is still a lack of quantitative evidence linking these BMPs with water quality benefits to downstream waterbodies. The linkage between the adoption of BMPs and resultant improvements in water quality in a quantitative sense is unknown, and an understanding of the timeframes that changes in water quality are detected at different scales (i.e. paddock to sub-catchment monitoring).

There has been a small body of relevant social and economic research undertaken to inform the management of the GBR; evaluations of the existing social and economic research already undertaken in the GBR relating to water quality have indicated that the research is relatively limited. In addition, much of the research and development has often not been well integrated with physical research and development, or does not provide a comprehensive understanding of the social and economic issues across the GBR.

5.a. Lines of evidence

5.a.i. Priority contaminants for intervention are known for Water Quality Improvement Plan areas.

There is improved regional understanding of management practices associated with the presence of contaminants in waterways, including knowledge of variability in risks across and within catchments and industries. However, prioritisation between the regions and between industries at a GBR-wide scale is lacking.

5.a.ii. A range of measures for managing sediment, nutrient and pesticide loss are available for implementation across industries and across regions in the GBR catchments.

Agricultural industry land management systems such as Grazing Land Management and fertiliser efficiency techniques are established.

5.a.iii. Quantification of water quality outcomes of management practices is inadequate.

Management systems believed to be effective (based on limited information) are known for the sugarcane and grazing industries and some of these incorporate potential 'win-win' benefits (e.g. '6 Easy Steps' nutrient management system in sugarcane), although to variable degrees across regions and industries; less information is available for many of the regions' diverse horticultural industries.

5.a.iv. There are many social and economic impediments to the implementation of management interventions.

There are multiple economic and social impediments to the implementation of changes of management practices aimed at reducing contaminant loads to the GBR. While 'win-win' scenarios exist for some management interventions such as the '6 Easy Steps' nutrient management system in sugarcane, many practices involve net costs to producers, particularly in the shorter term. Economic and social impediments to practice change vary between regions, complicating the design of policies to achieve practice change.

5.a.v. Knowledge of the effectiveness of restoration techniques is insufficient to guide investment.

The effectiveness of riparian vegetation and wetlands as potential filters of sediments, nutrients and pesticides is known for some cropping locations, but is limited for grazing areas. The system understanding that is required to prioritise investment into riparian and wetland rehabilitation, taking into account social and economic factors, is extremely limited. Potential lags in system responses to management interventions are beginning to be quantified.

5.a.vi. Targets have been set at regional scales based on best available science but GBR-wide targets are lacking.

Targets for management actions, end of catchment loads and resource condition have been set through the GBR Water Quality Improvement Plans. The targets are thus far more robust than previously set but still require modification in the light of new information. However, no targets have been set at the GBR scale that would allow trade-offs in management actions across the GBR region to be considered.

5.a.vii. The capacity to measure effectiveness of management interventions has improved.

Several major monitoring and modelling partnerships have been established to measure water quality condition in the

GBR catchments, including the Short Term Modelling Project led by NRW and the Reef Plan catchment and marine monitoring programs. Integration of these programs at the GBR paddock – to catchment to reef scales – is lacking.

5.b. The evidence base

5.b.i. Priority contaminants for intervention are known for WQIP areas.

Substantial variability exists in the biophysical, social and economic characteristics across the GBR catchments which influences the suitability and application of management priorities. A priority for recent research has been identification of the primary sources of terrestrial contaminant runoff to the GBR through more detailed regional assessments to target management interventions; the outcomes of these assessments is addressed in Section 1a. The most recent information has largely been generated through the WQIP process undertaken for 17 of the 35 major river catchments in the GBR region. For example, in most of the Burdekin and Fitzroy catchments where grazing is the predominant land use, sediment is identified as the contaminant of greatest concern (Burdekin WQIP – Mitchell *et al.,* 2007a; Fitzroy – Johnston, 2006), while in the Tully catchment within the Wet Tropics, where intensive sugarcane and banana cropping is dominant, nitrogen and pesticides are the key concern (Tully WQIP – Kroon, 2008). Nutrients and pesticides are also of greatest concern in the lower Burdekin catchments (Mitchell *et al.,* 2007a) and Mackay Whitsunday region (Drewry *et al.,* 2008) where land use is dominated by intensive cropping, predominantly sugarcane. The Burnett-Baffle catchments incorporate a range of land uses including intensive cropping and grazing; the WQIP process has identified sediments, nutrients and pesticides as important contaminants. The Black Ross WQIP is dominated by urban land uses where nutrients, pesticides, sediments and heavy metals are of concern.

Improved management techniques in intensive wet tropic areas have already reduced sediment generation through practices such as minimum tillage and green cane trash blanketing (Prove *et al.,* 1997; Rayment, 2003), although there remain relatively minor sediment issues in horticultural crops such as bananas. Substantial issues still exist for sediment management in grazing lands.

The focus for sediment control and reduction of erosion associated with rangeland grazing is in the Burdekin and Fitzroy catchments, and to a lesser extent catchments in the Cape York and Burnett regions and upper parts of the Wet Tropics catchments (Joo *et al.,* 2005; Brodie *et al.,* 2003; Furnas, 2003; Cogle *et al.,* 2006). Hillslope, streambank and gully erosion dominate sediment delivery processes, although further studies are required to demonstrate predominant erosion mechanisms in the catchments. Particulate nutrients are also sourced from soil erosion in grazing lands and can therefore be managed through soil erosion control.

Dissolved inorganic nutrients are largely associated with fertiliser application in intensive cropping industries. For the GBR region as a whole, management of these nutrient losses is essentially about reducing fertiliser losses from sugarcane and to a lesser extent, horticulture (but noting that horticulture may be of major importance in some catchments).

Herbicides are mostly derived from sugarcane applications (Rohde *et al.,* 2006a) with some contributions from cropping in the Fitzroy catchment (Packett *et al.,* 2005), and woody weed control in grazing lands.

5.b.ii. A range of measures for managing sediment, nutrient and pesticide loss are available for implementation across industries and across regions in the GBR catchments.

The principles for effective management of sediment, nutrient and pesticide generation are well known and these are incorporated into management practices being implemented across the GBR catchments. However, large uncertainties exist regarding their profitability and short- and long-term impacts of implementation upon industries. Examples of methods designed and currently applied for targeting specific problems are provided below.

There are several schemes available for managing fertiliser application in the intensive cropping industries and these have been examined on a regional basis for each WQIP (e.g. Roebeling and Webster, 2007; Thorburn *et al.,* 2008). Examples include '6 Easy Steps' (Shroeder *et al.,* 2005) where cane farmers are encouraged to follow a series of steps that tailor the fertiliser application rate to the plant and soil requirements, and has benefits for productivity such as reduced fertiliser application. Thorburn et al. (2003b) developed the N-Replacement system and this system has been trialled in several sugar areas within the GBR catchments (Thorburn *et al.,* 2007; Webster *et al.,* 2008b). Field trials have been positive, suggesting the assumptions behind the system are often valid. The main assumption is that soil nitrogen stores can buffer the difference between the amount of nitrogen needed by the crop and the amount of nitrogen fertiliser applied. For example, if the yield of the coming crop was larger than that of the previous crop, additional nitrogen requirements would be supplied from soil nitrogen stores. Conversely, these nitrogen stores would be 'topped up' when a small crop followed a large one. This assumption means the concept of a 'target yield', as used in programs such as '6 Easy Steps', is no longer necessary in determining fertiliser rates. Target yields are generally related to possible production, not actual production, and so can be a significant driver of high fertiliser application rates (relative to actual production) and high fertiliser and high fertiliser surpluses (Beaudoin *et al.,* 2005). The success of the N-Replacement system is a potential saving in nitrogen fertiliser applications of up to 40%, and a reduction in the overall nitrogen surplus across the whole sugarcane industry of up to 60%. The N-Replacement research is currently in the 'proof-of-concept' phase and plans are underway for developing the concept into a practical management system.

However, in contrast to recent developments for sugarcane, little consideration has been given so far to similarly update fertiliser and other management practices for most of the region's horticultural industries. A review of fertility management in horticulture and associated environmental issues (Hunter and Eldershaw, 1993) provides information and priorities for improving fertiliser and pesticide management in these industries across Queensland, including the GBR region. This review should be updated and its recommendations implemented so that up-to-date information is available on optimal fertiliser and pesticide management practices for horticultural industries in the region.

In addition, the information needs to be provided for each industry and should take into account cross-regional differences (e.g. in production systems and climate).

Sediment control in the grazing industry is guided by the industry-led initiative, Grazing Land Management, or 'GLM'. This initiative has developed regionally-specific best management practices (BMPs). As with practices for fertiliser management, each region has also conducted an assessment of management practices suitable for reducing sediment runoff in priority catchments; for example, BMPs for grazing in the Burdekin are assessed and prioritised in Coughlin *et al.,* (2007). Sediment control in these areas requires increased vegetation cover, as well as improved pasture condition and soil health to retain water, sediments and nutrients on the land (Nelder, 2006; Gordon, 2007). In principle, this means applying the appropriate utilisation rates of vegetation through better management of stocking rate (particularly in regard to rainfall variability), wet season spelling to improve pasture condition, forage budgeting to ensure cover levels are adequate from year to year and preventing selective overgrazing of preferred areas in the landscape (Chilcott *et al.,* 2003; Gordon and Nelson, 2007). However, recent unpublished work by Bartley *et al.,* (2007c) suggests that the majority of the sediments flowing into the creeks and rivers come from streambank and gully erosion which will sometimes need engineering solutions such as contour banks or ripping (as opposed to retaining walls or sediment traps) and fencing riparian and gullied areas to provide reduced grazing pressure, rather than changes in grazing land management. Current practices largely address hillslope erosion and further work is required on management and restoration techniques for gully erosion.

There are also other means of addressing sediment runoff in grazing lands. Maintaining soil health, for example through reduced stocking pressure, is also identified as an important contribution to improving soil infiltration, and therefore reducing surface water runoff and sediment loss (Dawes-Gromadzki, 2005). The importance of off-stream watering as a means of reducing cattle impact on waterholes and lagoons has also been demonstrated by Burrows (2003). However, there has been little work on managing grazing in riparian areas (with the exception of fencing) and direct management is unlikely to be financially viable in extensive grazing areas. Ongoing research (field experiments and modelling) is required regarding the influence of variable groundcover levels and patterns for major landscapes within each region, and improved understanding of the impact of significant flood events on sediment loads and defining the threshold of various management practices in these events, is necessary to identify the best sediment management practices for water quality outcomes.

Herbicide management is focused on better and more effective delivery techniques which reduce losses and integrated pest management programs focused on reducing use. Current practices include zonal application and the use of hooded sprayers, and the replacement of residual herbicides such as diuron by other less residual herbicides such as glyphosate.

There are some examples of incidental interventions that have had benefit to water quality outcomes, such as green cane trash blanketing, which while introduced to improve harvesting and organic carbon content of soils, had the incidental benefit of reducing soil erosion. A second example is evident with fertiliser application rates – in the last 10 years, at a time of reducing cane prices, fertiliser prices have risen, while fertiliser application rates have reduced.

5.b.iii. Quantification of water quality outcomes of management practices is inadequate.

While water quality outcomes are expected from the implementation of the management practices outlined above, there is limited evidence of measured water quality outcomes from particular practices in particular locations.

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. This noise in the signal is due to system variability, natural occurrence of sediments and nutrients in the system and limitations of the capacity to monitor and model material transport and fate. A good example of demonstrated time lags in system response to management changes is recorded in the Tully catchment. The Tully catchment is the least variable river in the GBR catchments, and yet very large changes in fertiliser use (increases) took 14 years to be manifest as increasing nitrogen levels in the lower Tully River to a statistically robust trend (Mitchell *et al.,* 2001, 2006). 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. These issues are also discussed in Section 1.

The response of the system to these land management changes is significantly influenced by system dynamics, depending on the contaminant and catchment systems. The major influences are summarised below (Waterhouse *et al.,* in press).

- Sediment control mechanisms and targets in large catchments such as the Burdekin are likely to encounter long lag times in the system, depending on the soil and flow characteristics, and the time for riparian vegetation to grow. However, fine sediments such as clays, which present the highest risk to GBR ecosystems, experience the least system lags in transport. In addition, the variability in the systems in terms of hydrology (decadal events) and climate mean that responses in the system are likely to be in decadal time scales (Lewis *et al.,* 2007b; Bartley *et al.,* 2007a).
- Fertiliser management in intensively cropped areas such as the Wet Tropics and the Mackay Whitsunday Region will also experience significant lag times in system response because of the sugar crop cycles (six to seven years) and storage in soil and groundwater stores. Responses are likely to be multiple years (i.e. five to ten years). Lags in groundwater transport and sub-surface transport (Rasiah *et al.,* in prep; Rasiah *et al.,* 2007; Armour *et al.,* 2006) and floodplain trapping (Wallace *et al.,* in press; Karim *et al.,* 2008; McJannet, 2007) also have a significant influence on the system.
- Herbicide management is expected to be characterised by limited time lags because most of the herbicides of concern have half-lives of less than

one year (e.g. 50 days). Significant reductions in loads are expected to be evident within two years of practice change involving reductions in use and loss. Changes in the presence of herbicides due to improved practices are also easier to identify in the system as they are not present naturally, generating a clearer signal related to practice change.

While vegetation management through maintenance or rehabilitation of vegetated areas is considered to be a beneficial practice for water quality outcomes, direct measurements of long-term outcomes are difficult to find. However, vegetation management in Queensland is probably one of the few examples of documented evidence of the effectiveness of a management action in Queensland through introduction of the Vegetation Management Act 1999. The legislation restricted the amount of tree clearing that could be undertaken on freehold and leasehold land. Figures from the Statewide Landcover and Trees Study (SLATS) showed the statewide average annual rate for clearing of woody vegetation in 2004–05 was 351 000 hectares. This is 27% lower than in 2003–04 (482 000 ha) and 54% lower than the peak measured clearing rate in 1999–2000 (758 000 ha). Reductions in clearing of more environmentally significant remnant woody vegetation are even greater – 35%, down from 267 000 ha in 2003–04 to 172 000 ha in 2004–05 (QNRW, 2007). These figures demonstrate the effectiveness of the introduction of the legislation and in the short term, assumptions are made about the outcomes in terms of water quality and biodiversity values.

5.b.iv. There are many social and economic impediments to the implementation of management interventions.

Similarly to the variability in the physical impacts on loads from practice change across and within industries of the GBR, there is significant evidence of variability in the economic and social characteristics of regions across the GBR, between sectors, and often within sectors within regions. This variation applies to both industries contributing to loads with the catchments such as grazing, sugar and horticulture (Marsden Jacob Associates, 2008a; Greiner *et al.,* 2003) and industries that are largely within receiving environments such as tourism and recreational fishing (Access Economics, 2007; Campbell and Murphy, 2005; Marsden Jacob Associates, 2008b). This variability in social and economic makeup further complicates the measurement of the effectiveness of proposed management interventions. While the understanding of cost effectiveness of alternative management interventions is still relatively rudimentary, it is generally better understood in grazing and sugar environments (Rolfe *et al.,* 2007, Donaghy *et al.,* 2007, Roebeling, 2006; Roebeling *et al.,* 2004, 2007; Alam *et al.,* 2006). For example, Roebeling *et al.,* (2007) analysed the water quality efficacy and the economic dynamics of management practices in the Tully-Murray catchment.

Based on the proposition that regional (i.e. private and social) benefits are maximised where marginal private costs equal marginal social benefits, the studies showed that the cost-structure around BMPs is such that a certain level of improvement in water quality can be made at no cost (e.g. for sugar – a 25% to 40% gain depending on adoption of new fertiliser practices) but beyond that point, costs for water quality improvement rise sharply. It showed that the current BMPs do not yet balance both production and environmental goals. In addition, the spatial arrangement of industries in the catchment was not optimal for improved water quality outcomes. Subsidies, incentives and/or regulations will be needed to provide the business case for industries to develop and implement improved management practice settings and to guide spatial change in this, and many other GBR catchment locations.

There are significant barriers to the adoption of practices that could materially reduce loads into GBR catchments. These barriers are economic such as the private cost of changing practices and social such as attitudes towards particular practices, skills required and attitudes towards risk (Cary *et al.,* 2001; Preston *et al.,* 2007; Donaghy *et al.,* 2007). These constraints are often not well understood. Because of the multiple types of constraints to change and the variability of the constraints between managers, a number of regulatory, suasive and economic tools are being used to address water quality in the GBR, with the use of market-based instruments providing significant opportunities as they specifically integrate bio-physical and economic information (revealed by managers) of the benefit, costs and cost-effectiveness of alternative management interventions (Marsden Jacob Associates, 2008a).

There has been a small body of relevant social and economic research undertaken to inform planning and management of water quality in the GBR (e.g. Windle and Rolfe, 2006; Hug and Larson, 2006; Larson and Stone-Jovicich, 2008; Larson, in press), although many of the studies have been regionally specific including socio and economic assessments completed to support water quality planning in the Tully Murray catchments (Bohnet *et al.,* 2007; Larson, 2006, 2007), Burdekin region (Greiner *et al.,* 2003; Greiner and Hall, 2006; Greiner *et al.,* 2006), Mackay Whitsunday (Strahan, 2007) and Fitzroy (Preston *et al.,* 2007). These studies have highlighted the substantial variability in the socioeconomic characteristics of the GBR catchment that ultimately influence the choice of management interventions for water quality outcomes. Integrating targeted social and economic analysis and research into the implementation of the Reef Plan should provide significant improvements in the understanding of the cost effectiveness of alternative management interventions (including variability) and the impediments to change over time.

The Reef Plan Marine Monitoring Program includes a socio-economic component. This involves reporting on: market values of GBR industries and their inputs to regional economies; patterns of human use of the GBR particularly non-commercial recreational activities, tourism and commercial fishing; and community and visitor perceptions of, and satisfaction with, GBR health (Prange *et al.,* 2007).

A suitable indicator for assessing the performance of management interventions is the adoption rates of various practices and tracking extension efforts by region and industry. At this stage, limited effort has been made to benchmark these indicators (with some exceptions at a regional scale). This is a critical information need to inform the evaluation of Reef Rescue Plan investments.

5.b.v. Knowledge of the effectiveness of restoration techniques is insufficient to guide investment.

Rehabilitation of riparian zones and wetlands and management in extensive grazing lands is considered a priority activity for improving water quality, particularly focused on the function of these areas as filters of sediment, nutrients and pesticides. Rehabilitation is not an economic option for vast areas in the rangelands – these riparian areas still need to be managed under grazing (Coughlin *et al.,* 2007). Large areas of riparian forest have been cleared over the last 30 years in the Burdekin (Lymburner and Dowe, 2006) and over the last 50 years in the Fitzroy (Lymburner, 2001).

From a management perspective, resources for rehabilitation are best directed to those parts of the catchment where they can have greatest effect, recognizing that the functions and capabilities of riparian and wetland areas may differ depending on their position in the landscape (Hunter and Hairsine, 2002). For example, where hillslopes drain directly into streams without the presence of a floodplain, the riparian zone will act to reduce sediment loads and associated contaminants carried by overland flow. In smaller, frequently ephemeral, streams the emphasis is on filtering of overland flow. In larger streams riparian vegetation has a major role in stabilising stream banks. Similarly, remedial management should target riparian areas where shallow groundwater discharge of nitrate occurs, most likely in small to medium sized streams (Hunter *et al.,* 2006). Careful management may be required to ensure these areas retain this capability and do not become contaminant sources; for example, as shown for phosphorus in constructed wetlands in the Burdekin region (Hunter and Hairsine, 2002).

In general, scientific knowledge of these riparian and wetland buffering functions in cropping situations or in wetter more intensive environments is relatively well developed and the principles have now been incorporated into software that enables assessment of alternative management scenarios and identification of optimal locations for rehabilitation. For example, the Riparian Nitrogen Model (RNM) (Rassam *et al.,* 2008) enables users to identify sub-catchments and stream reaches where rehabilitation is likely to have greatest effect in reducing downstream nitrate concentrations, and it can also indicate the optimal buffer width required. The RNM has been successfully applied in the Tully catchment. A Riparian Particulate Model (RPM) has similarly been developed (Newham *et al.,* 2005). It is also clear that in Wet Tropics catchments that it is best to have a mixture of grass and trees to trap overland flow of fine particulate matter rather than just trees (McKergow *et al.,* 2004a, 2004b).

The lack of locally-relevant data sets is a significant limitation to reducing the uncertainty of these model outputs. At a systems level, there is currently only a limited capability to optimise prioritisation of sites for rehabilitation, not only from a biophysical perspective but also taking into account social and economic factors.

Despite the very considerable efforts made in riparian rehabilitation, both in the GBR region and elsewhere, there have been very few attempts to quantify the benefits of these investments in terms of improved water quality downstream. Long-term monitoring studies are needed at a sufficiently large (e.g. sub-catchment) scale to demonstrate that such benefits can be achieved following rehabilitation. However, some local examples of monitoring effectiveness of wetland systems do exist, for example in the Burdekin catchment (Burrows and Butler, 2007) and the Tully catchment (McJannet, 2007). Recent research by McJannet and others (unpublished) in the Tully catchment indicates that further investigation is required to substantiate preliminary data showing the filter function that wetland systems provide in a wet tropical floodplain environment.

5.b.vi. Targets have been set at regional scales based on best available science but GBR- wide targets are lacking.

In the last three years, targets have been set for management actions and resource condition to support water quality management in the Douglas, Tully-Murray, Burdekin, Black-Ross, Mackay Whitsunday, Fitzroy and Burnett-Baffle catchments, mostly through the WQIP process. A consistent approach, reflected in Figure 9, has been adopted across the regions and significant advances have been made in the rigour of the target setting process than earlier efforts (e.g. Brodie *et al.,* 2001).

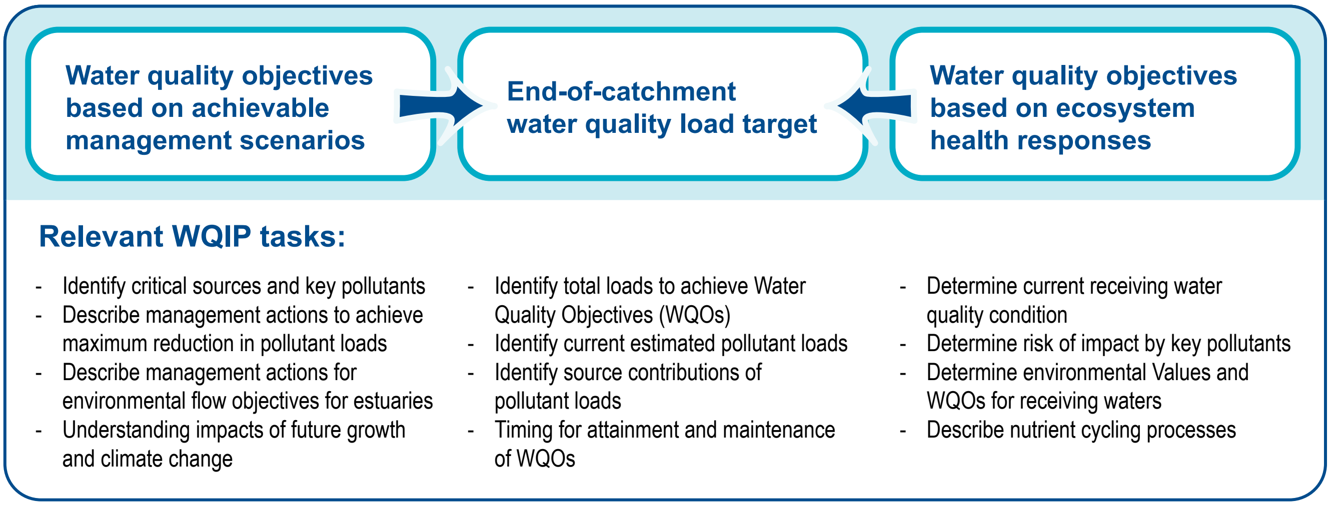

Figure 9: Water quality target setting within the GBR and relevant tasks within the WQIPs.

However, as a result of the limitations in monitoring and modelling capacity referred to in sections 1 and 3, water quality targets are at present largely driven by an understanding of what is achievable water quality change within current land use systems and practices. The environmental tradeoffs in this decision have not yet received much attention because of the low confidence in our understanding of what is actually being discharged from catchments and how this relates to requirements to sustain healthy GBR ecosystems. The implications for ecosystems of not meeting targets, and the lag time to change practices and realise water quality benefits for the target adopted, have high levels of uncertainty.

This is most apparent in the marine environment, where relationships between water quality parameters and the resilience of GBR ecosystems is still emerging (refer to Section 3). The establishment of the GBRMPA Water Quality Guidelines (GBRMPA, 2008) and the supporting science documentation (De'ath and Fabricius, 2008) provide a substantial advancement towards setting marine water quality targets; however, considerable work is required to define and measure desired water quality outcomes in the relatively short policy timeframes.

5.b.vii. The capacity to measure effectiveness of management interventions has improved.

Catchment and marine water quality monitoring programs have commenced in priority catchments of the GBR as part of the Reef Plan arrangements. Catchment and end of catchment load water quality monitoring is led by QNRW in collaboration with regional Natural Resource Management (NRM) bodies in 31 locations with a focus on sampling in major runoff events, when these exports predominantly occur (Hunter and Walton, 2008). A number of monitoring programs are undertaken at regional levels to support NRM planning and Water Quality Improvement Plans, with comprehensive programs established in the Burdekin (e.g. Bainbridge *et al.,* 2007), Mackay Whitsunday (e.g. Rohde *et al.,* 2008) and Fitzroy (e.g. Packett *et al.,* 2005) catchments for event monitoring. Many of these programs encourage community participation. The ecological risks associated with pesticide use in GBR catchments are currently being assessed and a monitoring program developed for high risk waterways by QNRW. Marine water quality monitoring is undertaken as part of the Reef Plan Marine Monitoring Program led by the GBRMPA (Prange *et al.,* 2007) described in Sections 2 and 3. A comprehensive overview of the location and extent of water quality monitoring currently undertaken in the GBR catchments is provided in QNRW (2008a).

Estimates of the loads of contaminants discharged to the GBR that are not captured in existing monitoring programs due to inadequacy of sampling sites and methods have been made in a number of catchments. In the Tully catchment Wallace *et al.,* (in press) showed that a large proportion of the total load of suspended sediment and nitrogen was present in waters in overbank flow on the floodplain and this was not included in load calculation made at Euramo (the lowest gauging station) in the river channel. Similarly it is clear that much of the nitrate lost from sugarcane fertiliser in the lower Burdekin reaches the GBR via small stream discharge and possibly groundwater discharge and is thus not included in loads measured at Home Hill in the Burdekin River (Brodie and Bainbridge, 2008). Similar 'missing' loads are obvious in Mackay-Whitsunday region through small stream discharge (Rohde *et al.,* 2008) and are likely in other regions. 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.

SedNet modelling predicts that high levels of suspended sediment trapping will occur in dams such as the Burdekin Falls Dam (Fentie *et al.,* 2006) and the Paradise Dam (Henry and Marsh, 2006). This has significant implications for management of different parts of the catchment when considering overall sediment delivery; for example, management could be targeted in catchments areas below the dam wall. However, recent studies using monitoring data suggest that trapping in the Burdekin Falls Dam is lower than modelled (average 60% instead of the modelled 80%) (Lewis *et al.,* 2008) and therefore careful consideration is required regarding location of management efforts.

Much of the modelling performed to date has provided information on annual-average conditions based on long-term datasets and this type of modelling will continue to have its place (e.g. for assessing likely impacts of alternative planning/management options). However, the priority now is to develop more dynamic water quality models to analyse the large monitoring datasets being developed for several major catchments of the GBR (Bartley *et al.,* 2007b). The aims of such monitoring programs are to identify the sources of contaminants and to detect changes in contaminant concentrations and loads with time, in response to changes in land-management practices. Teasing out from the dataset the effects of changed land management is challenging particularly in large complex catchments, where many factors, including climate change, co-determine water quality (Grayson, 2007). Models have to be calibrated with locally relevant data to interpret the monitoring data (e.g. Hunter and Walton, 2008). Even so, because of the complexities and sizes of catchments involved and the inevitable limitations of the models, it may not prove possible to detect trends in the monitoring data over the short- to medium-term.

Model estimates that upscale from paddock to catchment scales are required to indicate the likely water quality improvements associated with changed management practices, even if these cannot be confirmed through monitoring at that time. The time lags for trends to be detected in the monitoring data likely vary between contaminants and between catchments, depending on factors such as the dominant transport pathways and transformation processes, the presence of contaminant sinks (stores) and the spatial distribution and extent of practice adoption. Field validation of modelled increases to sediment and nutrient yields is required using additional and more direct proxies (perhaps sediment dating, review of fertiliser application tonnages).

Improved understanding of the uncertainties associated with existing catchment transport modelling tools has been an important component of recent research, with the limitations summarised by Post et al. (2007) and Wilkinson et al. (2008).

For example, sediment tracing work underway in the Bowen River indicates much more gully erosion is occurring than model predictions, (Wilkinson, 2008). This illustrates the need for broader data collection on erosion rates and model validation. Limited gully mapping is an important source of model uncertainty in the Burdekin (Kuhnert *et al.,* 2007) and the Fitzroy (Dougall *et al.,* 2006b) catchments.

A comprehensive overview of the location and extent of water quality modelling activity undertaken in the GBR catchments to support Reef Plan planning and implementation is provided in QNRW (2008b).

A number of models are under development that can assist in predicting the biophysical, social and economic outcomes of various policy interventions, and therefore assist in assessing management effectiveness. For example, the 'SEPIA' model (Single Entity Policy Impact Assessment Model) is being tested in the Burdekin, Tully and Mossman catchments, and uses a range of input data including biophysical characteristics, economic drivers and landholder typologies to determine the probable outcome of a set of policy options (Smajgl *et al.,* 2008); however, further model validation is required. Bayesian approaches are also being used to combine various land use and economic scenarios for GBR water quality and climate change outcomes (Wooldridge, 2007), and to guide managers in prioritising investment (Lynam *et al.,* in review).

5.c. Key uncertainties related to management effectiveness

Key uncertainties related to the effectiveness of current or proposed management intervention in solving the problem include:

- Predictions of the efficacy and efficiency of management interventions exist but quantitative assessments based on field measurements are generally limited.
- Validation of effective and profitable management practices for the GBR region's agricultural industries, especially horticulture and grazing, including environmental, social and economic perspectives.
- Capability to determine the relative importance of the location of the works in the landscape in terms of material delivery.
- The relative importance of the type of groundcover maintained in grazing lands to minimise sediment loss, and the efficiency of different groundcovers in managing hillslope erosion (i.e. 'natural' cover of trees and shrubs or savannah, compared with pasture).
- Impact of different grazing management practices on health and functioning of riparian areas in extensive grazing lands, and management of riparian areas, especially with regard to grazing and spelling.
- The biophysical and economic effectiveness of gully erosion remediation and management measures to reduce gully sediment yields.
- The impact of woody weeds (e.g. rubber vine) and the use of fire to control weeds on sediment loss.
- Socioeconomic benchmarking of the current adoption rates, extension efforts and industry culture by region and commodity.
- Development of a specific metric for each sector group (e.g. grazing) aimed at measuring outcomes from actions to allow comparisons across sectors.
- Understanding the drivers that will lead land managers to change practices for water quality improvement.
- It is too difficult to pick up short-term or medium-term trends in water quality at large scales due to climate variability and inherent difficulties in logistics associated with monitoring at the right spatial and temporal scales. Further work is required to design and resource optimal monitoring and modelling programs in GBR catchments.
- Quantification of the downstream benefits of management change/ restoration efforts and the return on investment to land holders and funders, at appropriate temporal and spatial scales.
- Quantification of the function of wetlands and riparian vegetation as filters for land- based materials in different locations.

6. Discussing the implications of confounding influences including climate change and major land use change

Conclusion: Climate change and major land use change will have confounding influences on GBR health.

Comparisons of the degree of reef degradation and stage and severity of human activity for the GBR compared with other global reef systems shows that although the GBR is in relatively good condition, it is by no means pristine and some way along the path to the degradation seen in many other reef systems (Pandolfi *et al.,* 2003; Brodie *et al.,* 2007a; Bruno and Selig, 2007). The complexities between the impacts of water quality stresses compared with other stresses, such as climate change (bleaching, ocean acidification) and fishing/harvesting and their interaction, are yet to be resolved. The current paradigm considers that a major correlation exists between acute coral mortality following catastrophic events such as cyclones, crown of thorns outbreaks and bleaching mortality, and lack of coral recovery in poor water quality conditions. In good water quality conditions the coral recovers quickly; in poor water quality conditions coral recovery is slow or non-existent due to lack of recruits, poor juvenile survivorship and competition from other benthic organisms such as macroalgae and filter feeders.

The following section provides an overview of the current knowledge related to the implications of confounding influences on the GBR, with an emphasis on the primary confounding influences related to GBR water quality, climate change and major land use change.

Climate change, water quality and GBR health

The present state of knowledge about the vulnerability of GBR species and habitats to climate change has been reviewed in detail (Johnson and Marshall, 2007). Predicted changes in the climate both globally and for the GBR are an increase in the frequency of extreme weather events including heat periods and cold snaps, more intense cyclones, and more frequent droughts alternating with severe flood. Overall, the changing climate as observed and/or predicted within the GBR region will therefore increase the frequency with which coral reefs are being disturbed:

- Increasing concentrations of CO2 in the atmosphere also lead to a reduction in the pH of the seawater, a phenomenon termed 'ocean acidification'. Ocean acidification reduces the ability of corals and other calcifying organisms to grow, and diminishes the capacity of coral reefs to withstand erosion (Guinotte and Fabry, 2008).
- Chronically warmer waters lead to changes in growth rates, altered food availability and ecological functions in most species groups and GBR ecosystems. Periods of extreme seawater temperatures (unusually high or low) lead to coral bleaching and to a greater susceptibility to diseases. It is also likely that ecotoxicological effects (e.g. from herbicide exposure are more severe when organisms are already stressed from high temperatures).
- Increased rainfall variability and intensity of weather events (droughts, floods etc) will make land management more difficult and increase the risk of soil erosion and loss, thereby resulting in increased loads of contaminants into the GBR lagoon. Droughts lead to reduced vegetation cover, making soils more prone to erode and wash into the ocean during floods. The nutrient injection from drought-breaking floods have been associated with the initiation of primary outbreaks of crown-of-thorns starfish (Birkeland, 1982; Brodie *et al.,* 2005). Changing hydrology may have severe effects on catchment water quality.
- Storm energy increases with the cube of wind speed and some forms of storm damage (e.g. the dislodgement of large massive corals) are only observed at cyclone categories three or higher (Fabricius *et al.,* 2008). Therefore, a predicted increase in the intensity of cyclones (Webster et al. 2005; Hoyos et al. 2006; Kossin et al. 2007) will likely lead to a greater frequency of severe reef damage at regional scales.

Successful coral reproduction and recruitment is needed to compensate for the predicted increase in coral mortality from bleaching events, cyclones, floods, and crown-of-thorns outbreaks. Good water quality is essential for successful coral reproduction and the survival of coral recruits on inshore reefs, and for keeping macroalgal cover low (reviewed in Fabricius, 2005; Wooldridge *et al.,* 2006; and De'ath and Fabricius, 2008). Protecting the reefs against high levels of nutrients, sediments and pesticides is therefore considered essential to facilitate resilience during climate change.

Another confounding influence is overfishing. Numerous studies have shown the important role of fishes in structuring benthic assemblages. Fishes strongly influence the balance between macroalgal and coral cover (e.g. Hughes, 1994). Recent research has shown that fish densities increase once reefs are being closed to fishing, clearly demonstrating that the densities of some targeted fish species are reduced way below 'pristine' levels in many parts of the GBR (Russ *et al.,* 2008). Although herbivorous fishes do not tend to be taken on the GBR, studies have shown that the removal of top predators can alter trophic structures in ecosystems (Graham *et al.,* 2003), and such flow-on effects are poorly understood. This has been shown to influence the rate at which coral reefs recover after beaching events (Hughes *et al.,* 2007).

Major land use change

Given the potential climate change scenarios and associated pressure for industries to seek alternative and viable ventures, major land use change in the GBR catchments is possible, which is likely to have implications for the amount of contaminants discharged to the GBR. A number of scenarios can be considered to be probable in the current settings, although longer term scenarios (e.g. to 2050) are highly uncertain but have been attempted by Bohnet *et al.,* (2008a, 2008b). Likely examples and the projected consequences (based on per hectare measure, not overall land area) are estimated below.

Projections are available regarding biofuel industries and indicate that they are not likely to grow substantially in terms of first generation biofuels. Peak oil and escalating petroleum prices are likely to have significant impacts on the land use and management of the GBR, which will present both challenges and opportunities to managing water quality.

The most significant management implication of these scenarios is the short-term planning approaches that typify the management systems relevant to GBR water quality. Longer term projections such as those piloted by Bohnet et al. (2008a) must be incorporated into planning.

Given the uncertainties associated with the long-term impacts of water quality on the GBR in combination with the confounding influences described above, the knowledge base to support management needs to be revisited on at least a five-yearly cycle. It is recommended that this discussion paper is updated in 2013, which coincides with the completion of the current planning cycle of the Reef Plan and the regional water quality plans.

Scenario	Loss of sediment, nutrients, and pesticides
A shift from: fertilised cropping to another fertilised crop	moderate change
A shift from: fertilised cropping to grazing, forestry or reserve	large change, generally reduced
A shift from: grazing or forest to fertilised cropping	large change, generally increased

Part B Evaluate current research and advise on capabilities, gaps and priority research needs

The current gaps and key uncertainties related to water quality in the GBR have been highlighted in each of the Terms of Reference addressed above. However, there are also several issues that are relevant to whole-of-system understanding that have not been covered. Recent assessments of the critical gaps in knowledge to support Reef Plan (e.g. Ferrier, 2007) highlight that integration of the science is key to addressing the complexities and uncertainties of the GBR system.

The present approach of delivering components of the knowledge, without an overarching effort to collate, synthesise and integrate this knowledge, is likely to continue to fail to meet management needs. Currently coordination and integration of Reef Plan science is in a parlous state. Inadequate management of the large GBR water quality science budget has led to implementation of ad hoc projects, that are generally not coordinated or based on rational priorities, has resulted in information that is rarely integrated into knowledge or communicated to management. Establishment of a central point of science coordination is required as a matter of urgency to enable science investment to support and guide Reef Plan implementation.

Of utmost importance, integration of the science for Reef Plan is the key to informing management decisions, and requires additional skills in conceptual and quantitative design and interrogation that go beyond traditional fields of expertise. An integrated approach is required to understand the whole system that results in GBR water quality, and includes relationships:

- within and across catchments to the GBR, so that the linkages between catchment actions and GBR health, and within the components of the system (e.g. between water quality and coral health), can be quantified
- between biophysical, social and economic dimensions of the system so that realistic targets and implementation strategies can be developed and assessed
- across scales, so that the sum of catchment and regional activities can be assessed to determine whether the existing and proposed activities are sufficient to achieve the Reef Plan goal.

Further discussion of an approach to address these issues is provided in Eberhard *et al.,* (2008). The process of establishing a pilot Reef Water Quality Report Card in 2006–2008 (Vandergragt *et al.,* 2008) demonstrated the challenges of providing an integrated assessment to inform management at a GBR scale where science coordination is lacking.

Conclusion: Effective science coordination to collate, synthesise and integrate disparate knowledge across disciplines is urgently needed.

This section provides the following information for each of the areas of research identified in the Terms of Reference:

- Overview of the current major research projects. This is (not intended to provide an exhaustive listing but highlight key projects that were initiated or completed since 2003.
- Commentary on the adequacy of the existing research and capability.
- Identification of priority research needs.

Current major research projects

Project	Primary objectives
MTSRF Project 3.7.1: Marine and estuarine indicators and thresholds of concern Katharina Fabricius, AIMS	• To determine dose-response relationships and thresholds of potential concern for contaminant exposure of selected bioindicators; provide a better understanding of the significance of such thresholds for reef water quality and ecosystem condition. • To progress the development of a composite indicator system to interpret water quality monitoring data and their link to ecosystem condition, and to improve estimates of river contaminant loads from discharge concentrations. Further information: http://www.rrrc.org.au/mtsrf/theme_3/project_3_7_1.html
MTSRF Project 3.7.2: Connectivity and risk: tracing materials from the upper catchment to the reef Jon Brodie, ACTFR	• To characterise and obtain a distinct 'fingerprint' of the fine sediments (mud fraction) and dissolved materials entering the marine environment using their isotopic and elemental properties, and link these to their sources in the major terrestrial catchments. • To examine historical changes in the delivery of terrestrial materials, from the major river systems in the Townsville and Cairns regions, to the marine environment using coral and sediment cores. • To determine the transport mechanism, residences time and fate of terrigenous sediments, nutrients and pesticides in the inshore and mid-reef regions of the GBR, and develop and apply new technologies to specifically trace pathways of the key nutrient elements phosphorus and nitrogen from the terrestrial catchments, through estuaries, to inshore coastal zones and to the mid-reef of the Great Barrier Reef. Further information: http://www.rrrc.org.au/mtsrf/theme_3/project_3_7_2.html Davis et al. in press; Lewis et al. in press.
MTSRF Project 3.7.3: Freshwater indicators and thresholds of concern Richard Pearson, JCU Angela Arthington, Griffith University	• To develop physical, chemical and ecological indicators of freshwater ecosystem health in the Wet and Dry Tropics. • To identify thresholds of potential concern relating to land use, water quality, riparian condition, habitat and food web structure in freshwater ecosystems of the Wet and Dry Tropics. Further information: http://www.rrrc.org.au/mtsrf/theme_3/project_3_7_3.html

Reef Plan Marine Monitoring Program Multiple Providers, led by GBRMPA Coordination: Joelle Prange, RRRC	• To assist in the assessment of the long-term effectiveness of the Reef Plan in reversing the decline in GBR water quality, through four sub-programmes: River mouth water quality monitoring, inshore marine water quality monitoring, marine biological monitoring, and socio-economic monitoring. • Marine biological monitoring includes monitoring benthic cover (algae, hard and soft corals), taxonomic composition and coral demographics (the size classes of corals). Coral settlement rates are also measured at reefs in three regions. Intertidal seagrass meadows are monitored for percent cover, species composition, reproductive health and seagrass tissue nutrient status. This task is assisted by the community-based Seagrass-Watch programme (www.seagrasswatch.org). Further information: http://www.gbrmpa.gov.au/corp_site/key_issues/water_quality/marine_monitoring
Assessing the impacts of pesticides on marine ecosystems Andrew Negri, AIMS	To assess the effects of: • the herbicide diuron on the early life history stages of coral; • chronic herbicide exposure on reproductive output of reef-building corals; • herbicides on photosynthesis and growth of tropical estuarine microalgae; and • insecticides and a fungicide at multiple coral life stages. Further information: Negri *et al.,* (2005); Magnusson *et al.,* (2008); Markey *et al.,* (2007); Cantin *et al.,* (2007)
CRC Catchment to Reef Program – Complete Multiple Providers, coordinated by CRC Reef and Rainforest CRC	• To develop new tools to assess and monitor the health of catchments and aquatic systems in both the Wet Tropics and GBR World Heritage Areas. • The tools will enable land managers to mitigate the effects of human activities on water quality. • The three-year, $5 million project is now complete and is a joint initiative by CRC Reef and Rainforest CRC. Further information: http://www.reef.crc.org.au/research/catchment_to_reef/C2Rresearch.htm
National Action Plan Water Quality Program: Water quality impacts on ecosystem health (WQ06) – Complete Multiple providers	• To assess salinity and water quality impacts on Queensland freshwater ecosystems. Further information: http://www.wqonline.info/index.html

Adequacy of existing research and capability

- Substantial progress has been made on indicator development and assessment of marine water quality impacts since 2003.
- Long-term funding commitments are required to continue to assess water quality impacts and confounding influences.
- Very limited research connections between catchment activities and reef impacts.
- Most of the research has occurred at single geographic scale and is therefore addressing components of the system rather than connections between them.

Priority needs

- Development of a marine and estuarine material transport and biogeochemical model coupled with a detailed hydrodynamic and eco-physiological model for the GBR for improved understanding of the relationship between management actions and Reef ecosystem response.
- Investigation of the impacts of synergistic effects of influences on GBR ecosystem health including land based contaminants, climate change and other external drivers.
- Improvement in understanding of the interactions of pesticides in GBR catchment and marine ecosystems.
- Further development of understanding of cause and effect relationships between water quality and ecosystem health in freshwater ecosystems including quantitative assessment of the different requirements for catchment management for improved instream health.
- Understanding the response of estuarine systems to floods and the role of the coastal floodplain.
- The complexity of the relationship between nutrient enrichment, coral reef decline, macroalgal proliferation and abundances of grazing fishes (and other grazers) still prevents there being a clear consensus view on this specific relationship.

2. Quantify acceptable levels of pollution

Current major research projects

Many of the projects listed in Section 1 of Part B also attempt to quantify acceptable levels of pollution in determining water quality impacts.

Project	Primary objectives
GBRMPA Water Quality Guidelines development project Glenn De'ath and Katharina Fabricius, AIMS	• To provide technical background information and statistical data analysis for defining improved water quality guideline trigger values for the GBR Water Quality Guidelines. • To present spatial and seasonal characterisation of water quality conditions in the NRM regions, spatial characterisation of proxies used for reef ecosystem health, assesses relationships between water quality and reef ecosystem health, suggests trigger values for water quality to protect ecosystem health and assesses predicted improvement in ecosystem health if the trigger values are implemented. Further information: refer to De'ath and Fabricius (2008)

Adequacy of existing research and capability

- Targeted research on thresholds of concern for freshwater and marine ecosystems has commenced as part of the MTSRF program.
- Data integration has occurred for the first time to support the development of water quality guidelines.
- Substantial progress in last 12 months with publication of the report *Water Quality of the Great Barrier Reef: Distributions, effects on Reef biota and trigger values for the protection of ecosystem health*, (De'ath and Fabricius 2008) to support the establishment of GBR Water Quality Guidelines (GBRMPA, 2008).
- Additional capability is required on statistical integration of datasets.

Priority needs

- Refer also to 1 Assess water quality impacts.
- Completion of a risk assessment of the relative importance of sediments, nutrients and pesticides to marine ecosystems at a regional scale.
- Definition of acceptable/desired thresholds for key indicators (i.e. coral, seagrass and biodiversity).
- Knowledge of the response of the GBR ecosystem to different events in different areas, and the ability to recover. Understanding the implications of combined scale and frequency of disturbance to GBR ecosystems.

3. Locate and quantify the sources of pollution

Current major research projects

Many of the projects listed in Section 5 of Part B regarding assessments of the effectiveness of management practices also provide information relevant to locating and quantifying sources of pollution.

Project	Primary objectives
NRW I5 End of Catchment Load monitoring program David Roberts, NRW	• The ultimate goal of the program is to assess the effectiveness of management actions on reducing contaminant loads. • The project involves load monitoring at 31 sites in ten priority (high-risk) catchments – the Normanby, Barron, Johnstone, Tully, Herbert, Burdekin, O'Connell, Pioneer, Fitzroy and Burnett. • The project proposes a combination of water quality monitoring and modelling activities: monitoring of current condition of various scales within each catchment; determination of differences in measured water quality over time using various water quality and other climate and remote sensing information (modelling); determination of the long-term annual average relative contributions to water quality within each catchment; and determination of the level of land use change and the relative changes in water quality these different land use management options have had on a sub-catchment and catchment scale, compared with climatic and catchment condition variability influences (modelling). Further information: http://www.reefplan.qld.gov.au/whosinvolved/activities_monitoring_loads.shtm
Tully WQIP David Haynes, Terrain NRM	Various monitoring programs designed to assess contaminant sources and resource condition. Further information: Kroon, (2008); Terrain NRM (2008) http://www.terrain.org.au/index.php?option=com_content&task=view&id=141&Itemid=52
Sediment and nutrient transport on the Tully floodplain Jim Wallace, CSIRO	• The project describes measurements of sediment and nutrient concentrations in flood waters on the Tully and Murray floodplains, including overbank flow. • The concentrations of contaminants during floods are also assessed and compared with those recorded during channelised flow. The findings have potentially significant implications for future contaminant load monitoring and reporting programs. Further information: Wallace et al. (in press); Karim et al. (2008)

MTSRF Project 3.7.2: Connectivity and risk: tracing materials from the upper catchment to the reef Jon Brodie, ACTFR	See description above in 1 Assess water quality impacts. Includes assessments in the Tully, Burdekin and Mackay Whitsunday regions. Further information: http://www.rrrc.org.au/mtsrf/theme_3/project_3_7_2.html
Burdekin WQIP Ian Dight, Burdekin Dry Tropics NRM	Various monitoring programs designed to assess contaminant sources and resource condition including: event monitoring; current condition of regional water bodies; current condition and extent of riparian vegetation and wetlands, and their effectiveness in trapping contaminants; fate of contaminants in the GBR; and pesticide investigations in the Lower Burdekin. Further information: http://www.bdtnrm.org.au/cci/monitoring/
Burdekin Rangeland Condition Monitoring project Bob Karfs, DPIF; Brett Abbott, CSIRO	• The program identifies D condition lands in the Burdekin Rangelands using remote sensing and rapid assessment ground-truthing. • The project has also identified areas that are at risk of slipping into D condition, and this information will be used by BDTNRM to prioritise areas for future on-ground projects. Further information: http://www.bdtnrm.org.au/projects/nap0024.html
Black-Ross WQIP Chris Manning, Townsville Regional Council	Various monitoring programs were designed to assess contaminant sources and resource condition. Further information: http://www.creektocoral.org/cci/element2.html
Mackay Whitsunday WQIP Will Higham, Mackay Whitsunday NRM	Various monitoring programs were designed to assess contaminant sources and resource condition as part of the Healthy Waterways Integrated Monitoring Program. Further information: http://www.mwnrm.org.au/programs/
Fitzroy Regional NRM Plan Nathan Johnston, Fitzroy Basin Association	Various monitoring programs were designed to assess contaminant sources and resource condition. Further information: http://www.fba.org.au/programs/regional_water_quality_monitoring_and_reporting.html http://www.fba.org.au/programs/priority_neighbourhood_catchments_water_quality_monitoring_program.html
Burnett-Baffle WQIP Sandra Grinter, Burnett Mary NRM	Various monitoring programs were designed to assess contaminant sources and resource condition. Further information: http://www.bmrg.org.au/index.php
CRC for Coastal Zone Estuary and Waterway Management - Complete Multiple Providers	The project was initially part of the CRC for Coastal Zone Estuary and Waterway Management and studied biogeochemistry, primary production and material transport of various water quality parameters in the Fitzroy Estuary. Further information: http://www.ozcoasts.org.au/search_data/crc_pubs.jsp Webster *et al.,* 2006; Herzfeld *et al.,* 2006; Robson *et al.,* 2006a, 2006b; Douglas *et al.,* 2005; Margvelashvili *et al.,* 2003; Webster *et al.,* 2003
Receiving waters receiving model for the Fitzroy Estuary Barbara Robson, CSIRO	Recent work by CSIRO with the FBA aims to link catchment material transport models with these estuary models. Further information: Robson and Brando, 2008

DEWHA Project 9: Remote-sensing of GBR Waters to assist performance monitoring of Water Quality Improvement Plans in Far North Queensland Vittorio Brando, CSIRO	To assist GBR WQIPs by providing remote sensing capability to monitor chlorophyll, suspended sediment, water clarity and the colour dissolved organic matter. Involves the continued development of regionally appropriate algorithms for accurately reporting these parameters and the development of methods of reporting the information in ways useful to WQIP reporting and adaptive implementation. Further information: Vittorio.Brando@csiro.au
Reef Plan Nutrient Management Zones project (D8) Rebecca Paine, Department of Primary Industries and Fisheries	Nutrient Management Zones (NMZs) are geographical areas identified as high risk in terms of nutrient loss to waterways. By identifying NMZs, effort and assistance to improve nutrient management on farms can be focused to improve the quality of water entering waterways and the GBR lagoon. Further information: Brodie (2007); http://www.reefplan.qld.gov.au/library/pdf/D8_FAQs.pdf
NRW QScape Modelling Initiative Ken Brooks, Department of Natural Resources and Water	• The QScape project seeks to improve knowledge of how changes in land use, land management and climate affect land condition, water quality and ecosystem health, and additionally to contribute associated research products to other land, vegetation and water resources research. • QScape is virtual in organisation, integrating expertise from across existing NRW Natural Resource Sciences and regional science, with some direct supplementation of new remote sensing and modelling staff. QScape seeks to provide a flexible series of modular components for a variety of uses. Further information: Ken.Brooks@nrw.qld.gov.au
National Action Plan Water Quality Program: Modelling landscape processes, management impacts and catchment loads (WQ03) –Complete Multiple providers	To use spatial and temporal models to provide regions with user-friendly outputs related to landscape processes and the impacts of management practices on water quality. Further information: http://www.wqonline.info/index.html

Adequacy of existing research and capability

- Immense improvements in last five to six years through targeted monitoring and modelling programs in many catchments.
- Lack of whole-of-GBR approach for all contaminants even though knowledge may be adequate at some WQIP scales or across GBR catchments for a single contaminant (e.g. Nutrient Management Zones).
- Inconsistent information across regions and land uses.
- Long-term efforts are required.

Priority needs

- Refinement of model approaches that predict contaminant loads by incorporating finer temporal resolution, characterisation of hydrological processes, nutrient speciation and better techniques for quantifying uncertainty.
- Determination of the relative contributions of surface runoff and groundwater to loads and consideration of the role of groundwater transported contaminants (especially nitrate) from paddock to coastal waters.
- Investigation of the relative importance of gully erosion compared with hillslope erosion and whether targeted management is required, including review and integration of land-based modelling of sediment sources in the dry tropical catchments.
- Identification of major drivers of suspended sediment concentrations, both natural and/or anthropogenic, from different dry tropical sub-catchments, and identification of the specific origin of fine-grained, washload (non-settling) suspended sediment that may be transported large distances offshore.
- Improved nutrient budgets are needed to quantify the relative contributions of all sources in GBR waters; while all terrigenous sediments and pesticides are land-derived, some of the dissolved nutrients are sourced from deepwater upwelling and from nitrogen fixing blue-green algae.
- Understanding of the relationship between increased suspended sediment loads caused by increased erosion from agricultural and urban development in major rivers and increased regional turbidity from resuspension in inshore areas of the GBR lagoon.
- Improved conceptual and quantitative understanding of the transport and fate of nutrients and sediments in the GBR, particularly during non-flood times, through the development of process studies and implementation of supporting monitoring strategies.
- Analysis of the function of the coastal/estuarine interface in contaminant transport and transformation.
- Further development of high frequency, low cost data through the application of innovative monitoring techniques such as remote sensing to enable more comprehensive assessment of the presence and extent of contaminants in the GBR.

4. Identifying management practices to reduce pollution from key sources

Current major research projects

Refer also to Section 5 of Part B below regarding assessing management effectiveness.

Project	Primary objectives
DEWHA Project 11: The Model Farms Project: Systematic implementation of nutrient and sediment source controls on wet and dry tropical cane farms Multiple providers, led by Adam West, Department of Primary Industries and Fisheries	To make available to producers and management agencies model farming enterprises that demonstrate the economic and GBR water quality benefits of new generation farming systems, where those farming systems incorporating all applicable BMP and the development of new and evolving technologies, over a full sugarcane production cycle (three to five years). Case study areas – lower Burdekin and Tully. Further information: Adam.West@dpi.qld.gov.au
Wambiana grazing management: Impact of grazing strategies and variable rainfall on pasture composition Peter O'Reagain, DPI&F	• To compare grazing management strategies under variable rainfall conditions. • To demonstrate the benefits of sustainable management of grazing lands through trial of variable stocking rates and measurement of pasture condition, biodiversity, soil condition and surface runoff water quality. Further information: http://savanna.cdu.edu.au/publications/savanna_links_issue33.html?tid=250863
Improved environmental outcomes and profitability through innovative management of nitrogen (SRDC project CSE011; SRDC component complete) Peter Thorburn, CSIRO	• To test approaches to reduce nitrogen fertiliser application in sugarcane industry and to trial the N-Replacement concept. • The project involved on-farm experiments from the Wet Tropics of Queensland to northern New South Wales, covering a range of soil types and cane varieties. • Further validation of the approach is underway in GBR catchments. Further information: http://www.csiro.au/files/files/pjdh.pdf; Thorburn et al. (2003a, b; 2007), http://www.srdc.gov.au/ProjectReports/ViewReports.aspx?ProjectNo=CSE011
Adopting systems approaches to water and nutrient management for future cane production in the Burdekin (CSE012) – Complete 2008 Multiple providers, funded by SRDC	• To develop a range of proven farm management options for improved water, nutrient and crop management that will maintain or increase profitability, while controlling rising water tables, reducing the risk of irrigation-induced salinity and improving off-farm water quality. • To carry out assessments of the economic feasibility of the proven farm management options within the context of future water pricing and water allocation scenarios in the Lower Burdekin. • To establish industry reference sites with grower participation to provide robust benchmarks and to assist in the dissemination of project learnings. Further information: http://www.srdc.gov.au/ProjectReports/ViewReports.aspx?ProjectNo=CSE012

Sustainable grazing for a healthy Burdekin catchment – Complete 2006 (MLA project NBP.314) Multiple providers, led by David Post, CSIRO and Peter O'Reagain, DPI&F	To implement grazing land best management practices (full wet season spelling and forage budgeting) on Virginia Park Station in the Burdekin catchment in order to examine the impact of these practices on land condition recovery, landscape health and the consequent leakiness of water, sediment, and nutrients both from the hillslope and the catchment. Further information: Post *et al.,* 2006 http://www.clw.csiro.au/publications/science/2006/sr62-06.pdf
Accelerated adoption of best-practice nutrient management – Complete 2008 Multiple providers, funded by SRDC, led by Bernard Schroeder, BSES	• To improve on-farm profitability (reducing fertiliser costs by $60/ha or 65 c/t of cane) and ensure greater environmental accountability and responsibility through accelerated adoption of integrated nutrient management. • To improve knowledge of the constraints to the adoption of best-practice nutrient management using grower surveys. • To develop a Soil Capability and Management Package (SCAMP) for improving on-farm management decision-making and facilitate the use of nutrient management plans at block and farm scales and the implementation of soil/site specific fertiliser applications using a participative approach. • To assess the risks of on- and off-site impacts of land management practices using vulnerability maps at catchment scale. • To demonstrate the benefits of best nutrient management practices with on-farm strip trials. Further information: http://www.srdc.gov.au/ProjectReports/ViewReports.aspx?ProjectNo=BSS268
Sustainable Agriculture State-level Investment Program (AgSIP) – various projects – Complete 2007 Multiple providers	• AgSIP was a state-level investment program of the National Action Plan for Salinity and Water Quality. The program ran from August 2004 until June 2007. • To develop new processes, tools and frameworks to facilitate agricultural practice change where needed in order to help regional NRM groups design, refine, deliver and review their regional investment strategies and natural resource management plans. • The project involved looking at existing practices, developing new recommended practices where needed, filling data gaps, designing integrated landscape monitoring systems, and developing better training and decision-support tools across cotton, cane grazing and horticulture industries.

Adequacy of existing research and capability

- Substantial improvements in the last five years.
- WQIPs are the first attempt to target 'key contaminants' in a restricted area. Established qualitatively good practices but quantitative assessments are inadequate.
- Grazing land management practices will successfully deal with hillslope erosion, while riparian vegetation management is able to minimise streambank erosion, but practices related to management of gully erosion requires further investigation.

Priority needs

- Completion of robust triple bottom line evaluations of current and proposed management actions as a basis to design more cost-efficient management interventions in the future.
- Development of new land management practices for improved water quality outcomes.
- Investigation of the social/economic/ institutional aspects of delivering practice change.
- Establishment of capability to determine the relative importance of the location of the works in the landscape in terms of material delivery.
- Assessment of the relative importance of the type of groundcover maintained in grazing lands to minimise sediment loss, and the efficiency of different groundcovers in managing hillslope erosion (i.e. 'natural' cover of trees and shrubs or savannah, compared to pasture).
- Development and testing of sustainable grazing and fire management guidelines for riparian and frontage country in the extensive dry rangelands.

5. Assess the effectiveness of actions to reduce pollution

Current major research projects

Refer also to Section 4 in Part B regarding identification of management practices, many of these projects test the effectiveness of the actions.

Project	Primary objectives
DEWHA Project 4.2: Implementing agricultural source controls through accredited Farm Management Systems in the Mossman Mill District Peter Bradley, Terrain NRM	To target components of the Douglas Shire Fertiliser Management Strategy and the Douglas Shire Cane Drain management Strategy as identified in the Douglas WQIP. These and other BMPs will be implemented and monitored. Further information: peter.bradley@DSC.qld.gov.au
Douglas WQIP Fertiliser management trials Tony Webster, CSIRO	To test variable nitrogen fertiliser application rates in sugarcane in Mossman and assess the water quality and economic benefits. Further information: Tony.Webster@csiro.au
Mackay Whitsunday management practices (rainfall simulator) experiment Ken Rohde, Department of Natural Resources and Water	To assess sediment, nutrient and herbicide runoff from canefarming practices in the Mackay Whitsunday region: a field-based rainfall simulation study of management practices Further information: Masters *et al.*, 2008
Wetland filter function David McJannet, CSIRO	To develop a detailed understanding of the potential for wetlands on the Tully-Murray floodplain to regulate and filter agricultural runoff before it drains to the GBR lagoon. Further information: http://csiro.au/science/ps3ox.html; McJannet (2007
MTSRF Project 3.7.5: Socio-economic constraints to and incentives for the adoption of land use and management options for water quality Martijn van Grieken, CSIRO	• Evaluate the socio-economic constraints to and risks associated with the adoption of land use and management options for water quality improvement at the private and social level. • Identify and assess instruments that are most cost-effective in promoting the adoption of these 'best' land use and management options by community embedded agents in rural and urban areas in North Queensland's catchments. Further information: http://www.rrrc.org.au/mtsrf/theme_3/project_3_7_5.html
Case study applications of a Single Entity Policy Impact Assessment model Alex Smajgl, CSIRO	The SEPIA (Single Entity Policy Impact Assessment) model simulates land-use decision making enacted by agents involved in agricultural production. The current application includes sugarcane, tree fruit, and beef cattle (grazing) producers, and is applied in the Douglas Shire, Burdekin region and Tully catchments. Further information: http://www.csiro.au/news/newsletters/0411_water/story1.htm
DEWHA Project 6: Decision Support Tools for Nutrient Management in Tropical Horticulture Phil Moody, NRW	Reduce nutrient loadings to the GBR by working with producer reference groups and industry associations in the Johnstone, Tully and Don/Burdekin catchments to develop science-based tools for improved nutrient management in tropical horticulture. Further information: phil.moody@nrw.qld.gov.au

Adequacy of existing research and capability

- Significant gaps in quantitative knowledge of the effectiveness of practices – rudimentary knowledge across practices.
- Substantial uncertainty between the relationship of improved water quality at a paddock scale, reduced loads and the effect on the GBR, and therefore, uncertainty in exact target setting to achieve specific GBR outcomes.
- Limited investigation of the tradeoffs (if any) between BMPs, profitability and production, especially in extensive grazing lands.
- Major opportunity to measure the effectiveness of improvements through Reef Rescue investment.

Priority needs

- Establishment of a GBR-wide initiative to effectively validate management practices across land uses in the GBR catchments, including the efficacy of practices in regionally specific applications, from the perspective of water quality outcomes and profitability.
- Establishment of modelling and monitoring systems that quantify the responses of the catchment socio-ecological system to management interventions.
- Commencement of a GBR-wide monitoring program to undertake socio-economic benchmarking of the current adoption rates, extension efforts and industry culture by region and commodity.
- Development of a specific metric for each sector group (e.g. grazing) aimed at measuring outcomes from actions to allow comparisons across sectors.
- Assessment of the drivers that will lead land managers to change practices for water quality improvement.
- Investigation of the design of optimal monitoring and modelling programs in GBR catchments that enable detection of short- or medium-term trends in water quality at large spatial and temporal scales.

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