2013 Scientific Consensus Statement

Chapter 4
Sources of sediment, nutrients, pesticides and other pollutants in the Great Barrier Reef catchment

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This document was prepared by an independent panel of scientists with expertise in Great Barrier Reef water quality. This document does not represent government policy.

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Executive summary

Estimates of river pollutant loads to the Great Barrier Reef lagoon have greatly improved since the last Consensus Statement in 2008. The results confirm that water discharged from the Great Barrier Reef catchment into the Great Barrier Reef lagoon continues to be of poor quality in many locations. Furthermore, enhanced modelling and monitoring of total suspended solids, nitrogen, phosphorus and photosystem inhibiting herbicides, and provenance tracing of sediment, has significantly enhanced our knowledge of major sources and processes contributing to these river pollutant loads. The main land uses contributing to these loads are rangeland grazing for sediment, both rangeland grazing and sugarcane for total nitrogen and total phosphorus, and sugarcane for photosystem II inhibiting herbicides. The Wet Tropics, Burdekin and Fitzroy catchments contribute most to these river pollutant loads.

Supporting evidence:

- Compared to pre-European conditions, mean-annual river loads to the Great Barrier Reef lagoon have increased; 3.2 to 5.5-fold for total suspended solids; two to 5.7-fold for total nitrogen; and 2.5 to 8.9-fold for total phosphorus. Mean-annual loads of photosystem inhibiting herbicides, namely ametryn, atrazine, diuron, hexazinone, tebuthiuron and simazine, are estimated to range between 16,000 and 17,000 kilograms per year. The total pesticide load to the Great Barrier Reef lagoon is likely to be considerably larger, given that a total of 34 pesticides have already been detected in the Great Barrier Reef catchments.
- The Fitzroy and Burdekin catchments contribute at least 70 per cent of the anthropogenic total suspended solids load to the Great Barrier Reef lagoon, with grazing lands (gully and hillslope erosion) (45 per cent) and streambank erosion (39 per cent) the main sources. The dominant sediment supply to many rivers in the Great Barrier Reef catchment is from a combination of gully and streambank erosion, and subsoil erosion from hillslope rilling, rather than broad-scale hillslope sheetwash erosion. Fine sediment (under 16 micrometres) material is the fraction most likely to reach the Great Barrier Reef lagoon, and is present at high proportions in monitored total suspended solids in the Burdekin, Fitzroy, Plane, Burnett, and Normanby catchments.
- The Fitzroy, Burdekin and Wet Tropics contribute over 75 per cent to the anthropogenic total nitrogen load to the Great Barrier Reef lagoon. Particulate nitrogen comprises by far the largest proportion followed by dissolved inorganic and dissolved organic nitrogen. Sediment erosion processes, particularly in grazing lands are sources of particulate nitrogen; sugarcane and grazing are sources of dissolved inorganic nitrogen, and land use changes in filter and buffer capacity are the main sources of dissolved organic nitrogen.
- The Fitzroy and Burdekin catchments contribute approximately 55 per cent of the anthropogenic total phosphorus load to the Great Barrier Reef lagoon. Particulate phosphorus comprises by far the largest proportions of the mean-annual anthropogenic total phosphorus loads, followed by dissolved inorganic and dissolved organic phosphorus. Sediment erosion processes, particular in grazing lands are sources of particulate phosphorus; sources of dissolved inorganic phosphorus and dissolved organic phosphorus are currently unclear.
- Most particulate nitrogen and particulate phosphorus is lost or mineralised from fine sediment following delivery to the Great Barrier Reef lagoon and could be readily available for uptake in Great Barrier Reef ecosystems. The dominant (sub-catchment) sources and pathways that contribute to this bio-available nitrogen and phosphorus in the Great Barrier Reef lagoon need to be determined, through the application of provenance tracing in combination with existing direct flux monitoring and catchment modelling.
- The Wet Tropics, Burdekin and Mackay-Whitsundays catchments contribute over 85 per cent to the total photosystem inhibiting herbicides load to the Great Barrier Reef lagoon, with sugarcane being the main source (94 per cent). Groundwater may potentially be an important source of photosystem II inhibiting herbicides (as well as dissolved nutrients) to critical near-

shore ecosystems of the Great Barrier Reef lagoon; however, insufficient information is currently available to evaluate the risks.

- The role of modified freshwater flow regimes in the Great Barrier Reef catchments in driving pollutant transport and affecting reef condition, through surface water diversion, dam construction, and wetland drainage and deforestation, has until now not been considered, but is likely to be highly significant.
- Other sources of pollutants to the Great Barrier Reef lagoon include point sources such as intensive animal production, manufacturing and industrial, mining, rural and urban residential, transport and communication, waste treatment and disposal, ports/marine harbour, and shipping. Compared to diffuse sources, most contributions of such point sources are relatively small but could be locally and over short time periods highly significant. Point sources are generally regulated activities, however, monitoring and permit information is not always available.

Introduction

Globally, humans have altered terrestrial fluxes of freshwater (Vörösmarty and Sahagian 2000), sediment (Syvitski *et al.,* 2005), and nutrients (Mackenzie *et al.,* 2002, Canfield *et al.,* 2010) to coastal marine waters, including to coral reef environments (McCulloch *et al.,* 2003a). Freshwater flow regimes have been modified through land use change (e.g. deforestation, wetland drainage), aquifer mining, surface water diversion, and dam construction (Vörösmarty and Sahagian 2000). Sediment fluxes have increased as a result of soil erosion associated with deforestation, coastal development, agricultural practices, and mining, whilst reductions are primarily due to retention within impoundments (Syvitski *et al.,* 2005). Nitrogen and phosphorus fluxes have increased due to changes in land use, agricultural crop and livestock production, discharge of urban and industrial wastewater, and fossil fuel burning (Mackenzie *et al.,* 2002). For example, riverine fluxes to the Great Barrier Reef have increased six-fold for suspended solids, six-fold for nitrogen, and nine-fold for phosphorus, relative to pre-European conditions (Kroon *et al,*. 2012).

Consequent declines in reef water quality have resulted in detrimental impacts on physical, ecological and physiological processes of reef-building corals (Coles and Jokiel 1992, Fabricius 2011). Extended exposure to lowered salinities associated with increased freshwater flows leads to reduced coral growth, coral bleaching, disease, and mortality. Long-term or high levels of sedimentation are harmful to all coral life history stages, including settlement of larvae, survival of recruits, and growth of adults. Nutrient enrichment increases phytoplankton biomass, abundance of macroalgae, risk of coral bleaching, and prevalence of coral diseases. High phytoplankton biomass may facilitate population outbreaks of the coral-eating crown-of-thorns starfish (Fabricius *et al.,* 2010), one of the main causes of coral cover declines on the Great Barrier Reef (De'ath *et al.,* 2012). Increased turbidity, caused by suspended sediment or phytoplankton blooms, reduces benthic light availability for photosynthesis and hence coral productivity. Overall, the effect of a long-term decline of reef water quality is loss of coral diversity, structure and function (Coles and Jokiel 1992, Fabricius 2011).

Reduction of land-based pollution has been widely advocated to reverse coral reef degradation (De'ath and Fabricius 2010) and enhance the resilience of the preferred, coral-reef dominated state (Hughes *et al.,* 2010, Mumby and Steneck 2011), particularly in the face of more extreme perturbation events forecast with climate change (Wooldridge and Done 2009). To ensure the future of coral reefs, the 2012 Consensus Statement on Climate Change and Coral Reefs has called for management of anthropogenic pressures including reducing land-based pollution (The Consensus Statement on Climate Change and Coral Reefs 2012). To achieve such reductions in riverine pollutant loads to coastal marine waters, it is critical to identify the main sources and pathways of pollutants.

In this chapter, the scientific evidence on sources and pathways of sediment, nutrients, pesticides and other pollutants in the Great Barrier Reef catchment is examined. First, the synthesis process and review the findings of the last Consensus Statement (Brodie *et al.,* 2008) are described. Next, an overview of the science activities in the Great Barrier Reef since then, as pertaining to identifying sources and pathways of pollutants, is provided. Then the relative importance of sources of pollutants is described, followed by a more detailed synthesis of river loads and catchment sources for individual pollutants. The chapter is concluded with a summary of the main findings, followed by key knowledge gaps summarised in the Appendix.

Synthesis process

In this chapter, definitions of pollutant are derived from the ANZECC guidelines (ANZECC & ARMCANZ 2000). A pollutant is defined as 'unwanted components into waters, air or soil, usually as result of human activity; e.g. hot water in rivers, sewage in the sea, oil on land' (ANZECC & ARMCANZ 2000). A pollutant is defined as biological (e.g. bacterial and viral pathogens) and chemical (e.g. toxicants) introductions capable of producing an adverse response (effect) in a biological system, seriously injuring structure or function or producing death' (ANZECC 2000 & ARMCANZ).

The authors first examine the pollutants and their sources that were considered in Reef Plan 2009 (Queensland Department of the Premier and Cabinet, 2009) (Table 2.1). In addition, they examine other pollutants that could pose a threat to the ecosystems of the Great Barrier Reef, as well as their potential sources, that were not considered in Reef Plan 2009.

The authors considered scientifically reviewed and publicly available evidence, in particular evidence that has become available since the last Consensus Statement (Brodie *et al.* 2008). The lead author kept a master copy of the chapter and circulated updated versions for input and comment to the team on a regular basis from December 2012 until final submission to Department of the Premier and Cabinet. This is a synthesis document, and as such we refer to the references provided for more detailed information on sources of sediment, nutrients, pesticides and other pollutants.

This chapter has been co-written by a group of scientists from the following research organisations: CSIRO Ecosystem Sciences, Queensland Department of Science, Information Technology, Innovation and the Arts, Griffith University, Queensland CSIRO Land and Water, Department of Natural Resources and Mines, and James Cook University. All scientists are active researchers on water quality monitoring and modelling in coastal catchments, and have a track record of peer-reviewed published research in the Great Barrier Reef context. The authors would like to acknowledge the contributions from Petra Kuhnert, Peter Thorburn (CSIRO), Jane Waterhouse, Jon Brodie (James Cook University), Rae Huggins, Rohan Wallace (Department of Science, IT, Innovation and the Arts), and Chris Chinn (Department of the Premier and Cabinet).

Previous Consensus Statement findings

The 2008 Scientific Consensus Statement on Water Quality in the Great Barrier Reef (Brodie *et al.,* 2008) states that the main sources of sediment, nutrients and pesticides have been identified using monitoring and modelling. The concentrations of these pollutants in waterways show strong regional variation and are related to specific forms of land use. No information was included on the sources of pollutants other than sediment, nutrients and pesticides. A summary of the main sources as per Brodie *et al.,* (2008) is provided below.

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.

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.

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.

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

Nutrients

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. Concentrations of nitrate are elevated in groundwater in many areas under intensive agriculture.

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.

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 Great Barrier Reef.

Pesticides

Concentrations of pesticides in waterways are highest in areas of intensive agricultural activity including sugarcane and cotton.

Of the herbicide residues most commonly found in surface waters in the Great Barrier Reef region, diuron, atrazine, ametryn, hexazinone derive largely from areas of sugarcane cultivation, while tebuthiuron is derived from rangeland beef grazing areas. Herbicide residues are present in groundwater at many locations.

Overview of Great Barrier Reef science activities since last consensus statement

Improvements in estimation of sediment, nutrients, and photosystem inhibiting II herbicides loads

Since the last consensus statement (Brodie et al., 2008), considerable improvements have been made to both the models and the monitoring that are used to estimate river loads of total suspended solids, nitrogen, phosphorus and photosystem inhibiting herbicides.

Firstly, the Source Catchments modelling framework (eWater CRC 2010) is used as a synthesis tool that incorporates new information on paddock modelling of total suspended solids, speciated nitrogen and phosphorus, and photosystem II inhibiting herbicides, plus spatially and temporally remote sensed inputs, to report a consistent set of end-of-catchment pollutant loads for each of the 35 Great Barrier Reef basins. A fixed climate period is used (1986–2009) for all model runs to normalise for climate variability and a consistent representation of pre-development and anthropogenic generated catchment loads. In addition, SedNet/ANNEX functionality has been incorporated into Source Catchments to represent hillslope, gully and streambank erosion and floodplain deposition processes (Waters and Carroll 2012). Catchment monitoring sediment, nutrient and pesticide data are used to calibrate and/or verify the catchment modelling outputs (Joo *et al.,* 2012, Turner *et al.,* 2012, in press, Smith *et al.,* 2012).

Other improvements to models include:

- Synthesis of all published pre-European and current load estimates extending to all Great Barrier Reef basins (up to 2010) (Kroon *et al.,* 2010, 2012)
- Identification of the need for a flood load correction for monitoring based load estimates in most Great Barrier Reef rivers, to account for loads delivered by ungauged overbank discharge (Wallace *et al.,* 2009, 2012)
- An improved algorithm to predict sediment trapping efficiency in large reservoirs which spill frequently (Lewis *et al*., 2013).

Secondly, since 2006 large scale monitoring along the length of the Great Barrier Reef (the Great Barrier Reef Catchments Loads Monitoring Program) has generated detailed loads for total suspended solids and dissolved and total forms of nutrients for up to 13 high priority catchments (Turner *et al.,* 2012, in press). These catchments were previously identified as posing the greatest risk to the Great Barrier Reef based on inputs from the regional National Action Plan for Salinity, Water Quality Program officers, the Great Barrier Reef Marine Park Authority, and the Australian Centre for Tropical Freshwater Research (DERM 2011) and risk assessments (Shaw *et al*., 2011). The same program commenced monitoring for photosystem II inhibiting herbicides in nine catchments in 2009. Importantly, these monitored loads are not the total pollutant loads discharged into the Great Barrier Reef lagoon, as (i) not all 35 basins that discharge into the Great Barrier Reef are monitored, and (ii) monitoring sites are not located at the river or creek mouth. The unmonitored portion of the catchment or sub-catchment may contribute, transform, or remove pollutants. The results presented here are for annual loads for 2006-2007 to 2010-2011 (total suspended solids, nitrogen, phosphorus) and for 2009-2010 to 2010-2011 (photosystem II inhibiting herbicides).

Other improvements to estimating loads from monitoring data include:

- Improved sampling over the hydrograph and enhanced quality assurance and quality control procedures (Joo *et al.,* 2012, Turner *et al.,* 2012, in press)
- Development and application of the loads regression estimator tool as an improved approach for quantifying the export of loads and the corresponding uncertainty from river systems, where data are limited (Kuhnert and Henderson 2010, Kuhnert *et al.,* 2009, 2012, Wang *et al.,* 2009, 2011)

- Application of the loads regression estimator tool to a comprehensive compilation of available catchment water quality and flow monitoring data across all Great Barrier Reef basins (up to 2008-2009) (Kroon *et al.,* 2010, 2012)
- Application of the loads regression estimator tool to quantify sediment trapping in the Burdekin Falls Dam (Lewis *et al*., 2013)
- Development of a framework that identifies the best loads estimation method for individual events, based on the number of samples collected over an event and their distribution over the hydrograph and the methods to be used if an error of 20 per cent or less is required (Thomson *et al.,* 2013)
- Numerous smaller scale studies that provide more detailed information on photosystem II inhibiting herbicide run-off in specific catchments and sub-catchments.

Improvements in determining sources of sediment, nutrients, and photosystem II inhibiting herbicides

Determining the dominant (sub-catchment) source of total suspended solids, speciated nitrogen and phosphorus, and photosystem II inhibiting herbicides in a basin often requires a combination of techniques including direct flux monitoring, provenance tracing and catchment modelling. Detailed knowledge about management practices in specific land uses such as fertilizer and pesticide application also contributes to identifying critical sources.

Since the last consensus statement (Brodie *et al*., 2008), the following, main improvements have been made in identifying the dominant sources of total suspended solids, nitrogen, phosphorus and photosystem II inhibiting herbicides:

- Enhanced monitoring and modelling to identify specific land uses or sub-catchments contributing to sediment (Turner *et al.,* 2012, in press, Wilkinson *et al.,* in press), nutrients (Hunter and Walton 2008, Mitchell *et al.,* 2009, Turner *et al.,* 2012, in press), and pesticide loads (Lewis *et al.,* 2009, Shaw *et al.,* 2010, Davis *et al.,* 2012, Smith *et al.,* 2012, Davis *et al.,* in press, Turner *et al.,* 2012, in press) (see also Bainbridge *et al.,* 2009, Packett *et al.,* 2009, Murphy *et al.,* in press)
- Calculation of yields (loads per hectare) for specific agricultural land-uses (e.g. Turner *et al.,* in press)
- Application of provenance tracing to improve understanding of catchment processes contributing to loads of sediment (Douglas *et al.,* 2008, Smith *et al.,* 2008, Hughes *et al.*, 2009, Tims *et al.,* 2010, Wilkinson *et al.,* in press)
- Application of the D-SedNet model in Source catchments incorporating updated datasets and parameter values (Waters and Carroll 2012)
- Improved knowledge of groundwater as a potential source of nutrients and photosystem II inhibiting herbicides (Hunter 2012)
- Improved knowledge about management practices applied in broadscale land uses (e.g. Queensland Department of the Premier and Cabinet 2011).

Use of information derived from Source Catchments modelling in this chapter

Since the last consensus statement (Brodie *et al.,* 2008), the Source Catchments modelling framework has been developed to estimate pollutant loads and determine sources. Whilst the modelling framework itself has been reviewed by an external panel (Queensland Department of the Premier and Cabinet 2012), the estimates for pollutant loads or contributing sources presented here have not been scientifically peer reviewed and are currently not publicly available. Hence, these pollutant load estimates are not considered to have superseded previous load estimates, in particular those recently published by Kroon *et al.,* (2010, 2012). These latter estimates are based on a (i) synthesis of all published pre-European and current load estimates extending to all Great Barrier Reef basins (up to 2010), and (ii) application of the loads regression estimator tool to a comprehensive compilation of available catchment water quality and flow monitoring data across all Great Barrier Reef basins (up to 2008-2009). Similarly, contributing sources identified by the Source Catchments model will be considered in the context of scientifically peer reviewed and publicly available information.

Relative importance of sources of pollutants to the Great Barrier Reef

Research into sources of pollutants to the Great Barrier Reef lagoon has identified that the vast majority of sediment and nutrient loads are derived from diffuse agricultural sources (e.g. McKergow *et al.,* 2005a, b). This has been confirmed by recent studies on the contribution of point sources, such as urban lands, sewage treatment plants, sugar mills and aquaculture (e.g. Kroon 2008, Lewis *et al.,* 2008, Rohde *et al.,* 2008). Recent Source Catchments modelling also indicates that sewage treatment plants contribute less than four percent of the total phosphorus and total nitrogen load in any one natural resource management region (Waters *et al*., in press). Great Barrier Reef Catchment Loads Monitoring Program monitoring between 2007 and 2010 confirmed low contributions of sewage treatment plants to average annual loads for total suspended solids (0.005 per cent), and total nitrogen and total phosphorus (1.8 per cent) (R. Turner pers. comm.). Thus, whilst the relative contribution of point sources to the overall mean annual total suspended solids, nutrient and photosystem II inhibiting herbicide loads appear to be relatively minor (e.g. less than or equal to 7.5 per cent in Tully basin, Kroon 2008), contributions can be high in some smaller stream networks (e.g. approximately 60 per cent of total nitrogen and 45 per cent of total phosphorus loads in Bohle River, Lewis *et al.,* 2008). However, monitoring and permit information is not always available for each regulated point source of pollution (e.g. resorts, caravan parks and holiday villages, extractive industries, boat discharges, and unsewered residential areas in Tully basin, Kroon 2008). Hence, the relative contribution of point sources to the overall pollutant load is likely to be somewhat underestimated.

The latest Source Catchments modelling considered both broadscale land use and urban lands (Waters *et al*., in press). These results, in combination with more recent monitoring (Turner et al. 2012, in press), are consistent with previous modelling studies (e.g. McKergow *et al*., 2005a, b) that the largest loads of total suspended solids, nutrients and photosystem II inhibiting herbicides are derived from diffuse agriculture sources. Grazing landscapes, primarily in the Fitzroy and Burdekin catchments, contribute 75 per cent of the total suspended solids load, 40 per cent of the total nitrogen load and 54 per cent of the total phosphorus load to the Great Barrier Reef lagoon (Waters *et al*., in press). Nutrients derived from grazing landscapes are primarily particulates, most of which are mineralised from fine sediment following delivery to the lagoon (McCulloch *et al.,* 2003b, Webster *et al.,* 2006) and could be readily available for uptake in Great Barrier Reef ecosystems. Sugarcane landscapes, primarily along the coast in the Wet Tropics and Mackay Whitsunday natural resource management regions, contribute disproportionate amounts of anthropogenic total nitrogen (46 per cent of total nitrogen), comprising of dissolved inorganic nitrogen (51 per cent of total dissolved inorganic nitrogen), dissolved organic nitrogen (51 per cent of total dissolved organic nitrogen), and particulate nitrogen (38 per cent of total particulate nitrogen). Total nitrogen loads per hectare from sugarcane are double horticulture and 10 times higher than cropping per unit area. Sugarcane also contributes 94 per cent of the total photosystem II inhibiting herbicide load.

A recent review indicates that groundwater potentially may be an important source of dissolved nutrients and photosystem II inhibiting herbicides to the Great Barrier Reef lagoon (Hunter 2012). Natural attenuation processes may reduce levels of these contaminants in groundwater over time. Nevertheless, any contaminants discharged via groundwater may have disproportionately greater impacts compared with those in surface water discharges, due to; (i) the presence of highly sensitive ecosystems in groundwater receiving environments; and (ii) the prolonged period of exposure of these ecosystems to groundwater discharge during drier months when there is less potential for dilution and dispersion.

Sources of sediment, nutrients, pesticides and other pollutants

Total suspended sediment

River loads

The most recent estimates show that mean annual total suspended solids loads to the Great Barrier Reef lagoon have increased 3.2 (Waters *et al.,* in press) to 5.5 (Kroon *et al.,* 2010, 2012) times compared to pre-European loads. An estimated 6000 (Waters *et al.* in press) to 14,000 (Kroon *et al.,* 2010, 2012) kilotonnes per year of current loads are of anthropogenic origin (Figure 4.1). Both estimated increases in mean-annual total suspended solids loads to the Great Barrier Reef lagoon lie within the range of previous estimates, being 2.9–6.8 (NLWRA 2001, Furnas 2003, McKergow *et al.,* 2005a). However, the 3.2 increase reported in Waters *et al.,* (in press) is lower than the estimated five- to 10-fold increase in sediment delivery based on coral cores (McCulloch *et al.,* 2003a). Comparing mean annual total suspended solids loads by individual basin showed good agreement between estimates derived from modelling and monitoring (Fig. 2 in Kroon *et al.,* 2012; Waters *et al.,* in press), with modelled estimates within 80 per cent confidence intervals for all basins examined (Kroon *et al.,* 2010, 2012).

Measured annual total suspended solids loads are highly variable over time and between catchments (Joo *et al.,* 2012, Turner *et al.,* 2012, in press) (see also Kuhnert *et al.,* 2012 for the Burdekin specifically). Annual total suspended solids loads for individual catchments ranged from 0.3 kilotonnes (under very low flow conditions in the Burnett in 2006-2007) to 10,500 kilotonnes (Burdekin in 2007-2008) (Turner *et al.,* 2012, in press).

Catchment sources

Sediment can be eroded from surface (hillslope) sources or from subsurface sources, namely gully or river bank sediments. In the grazed landscapes of the Great Barrier Reef catchment, hillslope erosion was generally considered to be the dominant source due to low pasture cover (McKergow *et al.,* 2005a). However, the importance of gully erosion has been highlighted in recent research (Caitcheon *et al.,* 2012), including in the Normanby (Brooks *et al.,* 2012), the Herbert (Tims *et al.,* 2010), Burdekin (Bartley *et al.,* 2010a,b, Wilkinson *et al.,* in press) and Fitzroy (Douglas *et al.,* 2008, Hughes *et al.,* 2009, Smith *et al.,* 2008) Rivers. This research has elucidated that the dominant sediment supply to many rivers in the Great Barrier Reef catchment is from a combination of gully and streambank erosion, and subsoil erosion from hillslope rilling. This is supported by results from Source Catchments modelling suggesting that over half of the total suspended solids supply to the Great Barrier Reef lagoon is from gully and streambank erosion (Waters *et al.,* in press). This has major management implications for designing effective practice changes which are discussed in later in this chapter.

Across the six natural resource management regions in the Great Barrier Reef, the Fitzroy and Burdekin contribute at least 50 per cent of the mean annual anthropogenic total suspended solids load to the Great Barrier Reef lagoon (Kroon *et al.,* 2010, 2012, Waters *et al.,* in press) (Table 4.2). However, the total suspended solids load per unit area remains highest in Mackay Whitsunday and Wet Tropics relative to other regions (Thorburn and Wilkinson in press, Hughes *et al.* ,2009, Murphy *et al.,* in press, Waters *et al*., in press), due mainly to their climate and soil characteristics. The Great Barrier Reef Catchment Loads Monitoring Program revealed that the Burdekin catchment was the largest contributor to the total measured annual total suspended solids loads from 2006-2007 to 2010-2011, followed by the Fitzroy catchment. The remaining catchments combined contributed less than the Fitzroy (Joo *et al.,* 2012, Turner *et al.,* 2012, in press). The total suspended solids contribution of the Burnett River was low due to minimal flow to the Great Barrier Reef lagoon during these years being contained within Paradise Dam, and would be expected to be much larger under annual average rainfall.

Source Catchments model outputs indicates that 44 per cent of the current total suspended solids load is from grazing lands (hillslope and gully erosion), with a further 34 per cent from stream bank erosion. Assuming the majority of the streambank erosion is from the extensive grazing areas in the Great Barrier Reef catchment, then the results support previous findings that approximately three quarters of the current total suspended solids load (20 micrometres) to the Great Barrier Reef is from grazing lands, as estimated by Thorburn and Wilkinson (in press) using data from Brodie *et al.,* (2003). An additional 16 per cent is from nature conservation and sugarcane with the remainder from cropping, forestry, horticulture and urban areas. However, the total suspended solids load per unit area is higher from inland cropping lands compared to grazing (Packett *et al.,* 2009; Murphy *et al.,* in press).

Fine sediment particles (less than 16 micrometres) are the total suspended solids fraction most likely to reach the Great Barrier Reef lagoon (Douglas *et al.,* 2008, Smith *et al.,* 2008, Bainbridge *et al.,* 2012). These particles comprise a greater proportion of the monitored total suspended solids in the Burdekin, Fitzroy, Plane, Burnett and Normanby catchments compared to other monitored catchments, suggesting that they are likely to contribute proportionally more fine particles to the Great Barrier Reef lagoon (Turner *et al.,* in press). Recent research has further demonstrated that these fine particles readily pass through the Burdekin Falls Dam, in contrast to sediment particles of more than 30 micrometres which are almost totally trapped (Lewis *et al*., 2013). Hence, sediment trapping by the Burdekin Falls dam has little effect on reducing the risk from total suspended solids to the Great Barrier Reef ecosystems, and management of erosion processes should occur both above and below the dam.

Within the Burdekin catchment, a four-year monitoring program suggests that the major source of the annual clay and silt (less than 16 micrometres) sediment load are the Upper Burdekin (approximately 29 per cent), the Bowen (approximately 41 per cent), and the Lower Burdekin/Bogie (approximately 26 per cent) sub-catchments (Bainbridge *et al.,* in review). These sub-catchments were also the dominant source of the very fine clay and fine silt of less than 16 micrometres sediment fraction, which is transported more than approximately seven to 12 kilometres offshore in river flood plumes (Bainbridge *et al.,* 2012). Coarser fractions could also be transported offshore during wind-driven re-suspension events (see Orpin *et al.,* 2004). Sub-surface (gully, bank and scald) erosion is the dominant process responsible for the fine sediment exported from the Bowen and Upper Burdekin catchments in recent times (Wilkinson *et al.,* in press). In this catchment, the relative proportions of these erosion sources are gully (54 per cent), hillslope (37 per cent) and streambank (nine per cent) sources (Waters *et al*., in press).

In the Fitzroy catchment, sediments deposited in Keppel Bay were from a combination of sedimentary, granitic and basaltic soil types (Smith *et al.,* 2008). However, the greatest enrichment of less than 10 micrometres sediment fraction relative to catchment and estuary locations was derived from the Tertiary basalt sources (Douglas *et al.,* 2008, Smith *et al.,* 2008), which are predominantly located in the north-western part of the catchment, indicating the high efficiency with which these sediments are delivered to the Great Barrier Reef lagoon. Erosion rates in the basaltic sediment areas are higher in cultivated cropping rather than grazed areas (Hughes *et al.,* 2009, Murphy *et al.,* in press). The relative proportion of different erosion sources in the Fitzroy River are streambank (37 per cent), gully (34 per cent), and hillslope (29 per cent) (Waters *et al.,* in press).

The Burdekin and Fitzroy catchments are also part of two distinct catchment clusters with a greater percentage of clays (less than four micrometres) in monitored total suspended solids, together with the Plane, Burnett and Normanby catchments (Turner *et al.,* in press) (Figure 4.2a, b). A larger percentage of silt (four to 62 micrometres), fine sand (62 to 250 micrometres) and course sand (250 to 2000 micrometres) was detected in two other catchment clusters comprising the Barron, Tully, Barratta, Johnstone, Herbert and Pioneer catchments (Figure 4.2a, b). This suggests that the catchments in clusters one and two are likely to contribute proportionally more fine particles to the Great Barrier Reef lagoon (Turner *et al.,* in press). These catchments may also affect a greater area of the Great Barrier Reef lagoon as the fine particles take longer to settle out, although this remains to be experimentally verified.

Finally, erosion may be severe in areas of cropping and urban development on high slope lands but such areas are of relatively small extent. For example, urban development can contribute very elevated concentrations of total suspended solids at a localised scale (Lewis *et al.,* 2008, Rohde *et al.,* 2008). Mining may also contribute to erosion and total suspended solids loads (Lucas *et al.,* 2010), but this is an under-researched area in the Great Barrier Reef context.

Summary

- Mean-annual river loads to the Great Barrier Reef lagoon for total suspended solids have increased 3.2 to 5.5-fold compared to pre-European conditions
- Comparing mean annual total suspended solids loads by individual basin showed good agreement between estimates derived from modelling and monitoring
- The main sources for the anthropogenic total suspended solids load to the Great Barrier Reef lagoon are
  - Grazing lands (gully and hillslope erosion) (45 per cent) and streambank erosion (39 per cent,
  - The Fitzroy and Burdekin catchments (at least 70 per cent), and
  - A combination of gully and streambank erosion and subsoil erosion from hillslope rilling, rather than broad-scale hillslope sheetwash erosion.
- Monitored total suspended solids in the Burdekin, Fitzroy, Plane, Burnett, and Normanby catchments contain a high proportion of fine sediment (less than 10 micrometres) material, which is the fraction most likely to reach the Great Barrier Reef lagoon.

Nitrogen

River loads

The most recent estimates show that mean annual total nitrogen loads to the Great Barrier Reef lagoon have increased two (Waters *et al.,* in press) to 5.7 (Kroon *et al.,* 2010, 2012) times compared to pre-European loads. An estimated 18,000 (Waters *et al.,* in press) to 66,000 (Kroon *et al.,* 2012) tonnes per year of this is of anthropogenic origin (Figure 4.1). These estimated increases in mean-annual total nitrogen loads to the Great Barrier Reef lagoon are slightly lower (Waters *et al.,* in press) and slightly higher (Kroon *et al.,* 2010, 2012) than the range of 2.5 to 4.5 times reported in previous studies (NLWRA 2001, Furnas 2003, McKergow *et al.,* 2005b). The slightly higher estimates in Kroon *et al.,* (2010, 2012) are partly due to over-estimation of particulate nutrient loads in some SedNet-ANNEX modelling studies (Cogle *et al.,* 2006, Sherman and Read 2008).

Comparing mean annual total nitrogen loads by individual basin showed reasonable agreement between estimates derived from modelling and monitoring (Fig. 2 in Kroon *et al.,* 2012, Waters *et al.,* in press), with modelled estimates either within (Barron, Johnstone, Tully, Burdekin) or above

(Herbert, Pioneer) the 80 per cent confidence intervals for all basins examined (Kroon *et al.,* 2010, 2012).

Measured annual total nitrogen loads are highly variable over time and between catchments (Joo *et al.,* 2012, Turner *et al.,* 2012, in press). Annual total nitrogen loads for individual catchments ranged from 31 (low flow in the Burnett in 2008-2009) to 36,000 tonnes (Fitzroy in 2010-2011) (Turner *et al.,* 2012, in press). Recent research indicates that current monitoring may be underestimating mean-annual loads of total nitrogen in most Great Barrier Reef basins by not accounting for the contribution of overbank flooding discharges (Wallace *et al.,* 2009, 2012).

Catchment sources

Nitrogen can be derived from both natural and modified landscapes, with different nitrogen constituents dominating runoff from different land uses. Nitrogen export from Australia's pristine forested catchments is low and predominantly in the form of dissolved organic nitrogen (Harris 2001), including in runoff from undisturbed forests in the Great Barrier Reef catchment (Eyre *et al.,* 1999, Brodie and Mitchell 2005). Clearing and conversion to agriculture and urban development results in increased nitrogen export, now dominated by dissolved inorganic nitrogen derived from fertiliser and sewage wastes (Eyre *et al.,* 1999, Hunter and Walton 2008, Lewis *et al.,* 2008, Rohde *et al.,* 2008, Bainbridge *et al.,* 2009, Mitchell *et al.,* 2009, Thorburn *et al.,* 2011, Waterhouse *et al.,* 2012) and particulate nitrogen derived from soil erosion (Brodie and Mitchell 2005, McKergow *et al.,* 2005b, Waterhouse *et al.,* 2012). Recent research indicates that dissolved organic nitrogen loads from the Tully basin have doubled due to landscape changes in filter and buffer capacity (Wallace *et al.,* 2009). In contrast to total suspended solids, no provenance tracing of nitrogen has been conducted in surface waters discharging into the Great Barrier Reef lagoon to better elucidate catchment processes that contribute to loads of nitrogen constituents.

Approximately 40 per cent of the mean annual anthropogenic total nitrogen load to the Great Barrier Reef lagoon is contributed by the Fitzroy and Burdekin natural resource management regions (Kroon *et al.,* 2010, 2012, Waters *et al.,* in press) (Figure 4.1, Table 4.2). Over 70 per cent of the mean annual anthropogenic total nitrogen load to the Great Barrier Reef lagoon is derived from grazing lands (40 per cent) and sugarcane (31 per cent) (Waters *et al.,* in press). The Great Barrier Reef Catchment Loads Monitoring Program revealed that the Fitzroy catchment was the single largest contributor of the total nitrogen loads from 2006-2007 to 2010-2011, followed by the Burdekin. The combined contribution of all remaining catchments was approximately 75 per cent of the Burdekin and Fitzroy combined (Joo *et al.,* 2012, Turner *et al.,* 2012, in press).

The mean annual anthropogenic total nitrogen load to the Great Barrier Reef lagoon mostly consists of particulate nitrogen (40 per cent in Waters *et al.,* in press, 76 per cent in Kroon *et al.,* 2010, 2012) (Fig. 2.3). Most particulate nitrogen is lost from fine sediment following delivery to the Great Barrier Reef lagoon (Webster *et al.,* 2006), and could be readily available for uptake in Great Barrier Reef ecosystems. Recent and previous modelling efforts do not agree on which natural resource management regions contribute most to the mean annual anthropogenic particulate nitrogen load: either the Burdekin and Wet Tropics (Waters *et al.,* in press) or Fitzroy and Burnett Mary (Kroon *et al.,* 2010, 2012) (Figure 4.1, Table 4.3). The Great Barrier Reef Catchment Loads Monitoring Program revealed that the annual particulate nitrogen loads for individual catchments ranged from less than one (in the Burnett during 2006-2009) to 23,000 tonnes (Burdekin in 2007-2008) (Turner *et al.,* 2012, in press). The Burdekin and Fitzroy catchments were the largest contributors to the total measured annual particulate nitrogen loads from 2006-2007 to 2010-2011; the summed load from the remaining catchments was less than the load from the Burdekin (Joo *et al.,* 2012, Turner *et al.,* 2012, in press). Results from Source Catchments modelling suggest that approximately half of the particulate nitrogen is from grazing lands, including hillslope, gully and streambank erosion (Waters *et al.,* in press).

Dissolved inorganic nitrogen makes up about one-fifth of the mean annual anthropogenic total nitrogen load to the Great Barrier Reef lagoon (29 per cent in Waters *et al.,* in press, 16 per cent in Kroon *et al.,* 2010, 2012) (Figure 4.3). These studies show that the Wet Tropics, Burdekin and Mackay Whitsunday natural resource management regions contribute 80 per cent to the mean annual anthropogenic dissolved inorganic nitrogen load to the Great Barrier Reef lagoon (Figure 4.1, Table 4.2). The Great Barrier Reef Catchment Loads Monitoring Program revealed that the annual dissolved inorganic nitrogen loads for individual catchments range from less than one (low flow in the Burnett in 2006-2007) to 3900 tonnes (Fitzroy in 2010-2011) (Turner *et al.,* 2012, in press). The Burdekin catchment was the largest single contributor to the total measured annual dissolved inorganic nitrogen loads from 2006-2007 to 2010-2011, followed by the Fitzroy; the Johnstone, Tully and Herbert catchments combined contributed more dissolved inorganic nitrogen than the Burdekin catchment (Joo *et al.,* 2012; Turner *et al.,* 2012, in press). Results from Source Catchments modelling suggest that sugarcane (34 per cent), grazing (30 per cent) and nature conservation (20 per cent) contribute the majority of the total dissolved inorganic nitrogen load to the Great Barrier Reef (Waters *et al.,* in press). River monitoring supports that dissolved inorganic nitrogen originates from fertilized land use, including loss of fertilizer from sugarcane (e.g. Mitchell *et al.,* 2009). On the other hand, the sources of dissolved inorganic nitrogen from grazing and nature conservation lands are unclear.

In groundwater, concentrations of nitrate are elevated and are increasing with time in the lower Burdekin (Barnes *et al.,* 2005); probable increasing trends are also evident in the Pioneer Valley and the lower Herbert (McNeil and Raymond 2011). In the Johnstone River system, groundwater is a major source of nitrate (Walton and Hunter 2009, Rasiah *et al.,* 2003b). Red Ferrosol soils in that catchment temporarily hold an average of 1550 kilograms nitrate-nitrogen per hectare deep in the soil profile under sugarcane, but not under rainforest (Rasiah *et al.,* 2003a). This nitrate has the potential to leach to groundwater over a period of decades (Donn and Menzies 2005). Nitrate can be transported from within the crop rooting zone to rivers and streams via shallow groundwater drains; for example, as measured in low-lying areas of the Herbert (Bohl *et al.,* 2000) and Tully (Rasiah *et al.,* 2010) catchments. Under certain conditions natural attenuation processes such as denitrification may reduce nitrate concentrations in groundwater (Hunter 2012, see also Lenahan 2012, Thayalakumaran *et al.,* 2008). This suggests nitrate concentrations and loads in groundwater discharged from such areas may be negligible, however, these findings need much further investigation to assess their broader temporal and spatial applicability. For example, a recent study in the Wet Tropics has shown that the riparian zone is ineffective at removing (denitrifying) groundwater nitrate before it is discharged into surface waters (Connor *et al*., in press).

The estimated proportion of dissolved organic nitrogen in the mean annual anthropogenic total nitrogen load to the Great Barrier Reef lagoon ranges from 10 (Kroon *et al.,* 2010, 2012) to 32 per cent (Waters *et al.,* in press) (Fig. 2.3). These studies show that the Burdekin and Mackay Whitsunday natural resource management regions contribute 42-49 per cent to the mean annual anthropogenic dissolved organic nitrogen load to the Great Barrier Reef lagoon (Figure 4.3, Table 4.2). The Great Barrier Reef Catchment Loads Monitoring Program revealed that the annual dissolved organic nitrogen loads for individual catchments ranged from less than one (low flow in the Burnett in 2006-2009) to 15,000 tonnes (Fitzroy in 2010-2011) (Turner *et al.,* 2012, in press). The Burdekin and Fitzroy catchments were the largest single contributor to the total measured annual dissolved organic nitrogen loads from 2006-2007 to 2010-2011, followed by the Herbert, Tully and Normanby catchments; the summed load from the remaining catchments was less than the Fitzroy (Joo *et al.,* 2012, Turner *et al.,* 2012, in press). Results from Source Catchments modelling suggest that grazing (48 per cent), nature conservation (24 per cent) and sugarcane (14 per cent) contribute the majority of the total dissolved organic nitrogen load to the Great Barrier Reef (Waters *et al.,* in press). Recent research suggests that land use changes in filter and reduced floodplain buffering capacity may have doubled dissolved organic nitrogen loads to the Great Barrier Reef lagoon (Wallace *et al.,* 2009). This has major management implications for designing effective land use changes which are discussed in Chapter 5 (Thorburn *et al.,* 2013).

Summary

- Mean annual river loads to the Great Barrier Reef lagoon for total nitrogen have increased two to 5.7-fold compared to pre-European conditions.
- Comparing mean annual total nitrogen loads by individual basins showed reasonable agreement between estimates derived from modelling and monitoring.
- Particulate nitrogen comprises by far the largest proportions of the mean annual anthropogenic total nitrogen loads, followed by dissolved inorganic and dissolved organic nitrogen.
- Most particulate nitrogen is lost or mineralised from fine sediment following delivery to the Great Barrier Reef lagoon and could be readily available for uptake in Great Barrier Reef ecosystems.
- The main sources for the anthropogenic total nitrogen load to the Great Barrier Reef lagoon are:
    - grazing lands (40 per cent) and sugarcane (31 per cent)
    - the Fitzroy, Burdekin and Wet Tropics catchments (over 75 per cent)
    - sediment erosion processes, particularly in grazing lands are sources of particulate nitrogen; fertilized land uses, particularly sugarcane, are sources of dissolved inorganic nitrogen; and land use changes in filter and buffer capacity are the main sources of dissolved organic nitrogen. Further measurements are needed, particularly in grazing landscapes, to determine sources and pathways.
- The dominant (sub-catchment) source that contribute to bio-available nitrogen in the Great Barrier Reef lagoon need to be determined, through the application of provenance tracing in combination with existing direct flux monitoring and catchment modelling.

Phosphorus

River loads

The most recent estimates show that mean annual total phosphorous loads to the Great Barrier Reef lagoon have increased 2.5 (Waters *et al.,* in press) to 8.9 (Kroon *et al.,* 2010, 2012) times compared to pre-European loads. An estimated 3800 (Waters *et al.,* in press) to 14,000 (Kroon *et al.,* 2012) tonnes per year of this is of anthropogenic origin (Figure 4.1). These estimated increases in mean annual total phosphorus loads to the Great Barrier Reef lagoon are slightly lower (Waters *et al.,* in press) and slightly higher (Kroon *et al.,* 2010, 2012) than the range of 3.9 to 6.4 times reported in previous studies (NLWRA 2001, Furnas 2003, McKergow *et al.,* 2005b). The slightly higher estimates in Kroon *et al.,* (2010, 2012) are partly due to over-estimation of particulate nutrient loads in some SedNet-ANNEX modelling studies (Cogle *et al.,* 2006, Sherman and Read 2008).

Comparing mean annual total phosphorus loads by individual basin showed reasonable agreement between estimates derived from modelling and monitoring (Fig. 2 in Kroon *et al.,* 2012, Waters *et al.,* in press), with modelled estimates either within (Johnstone, Burdekin, Pioneer) or above (Barron, Tully, Herbert) the 80 per cent confidence intervals for all basins examined (Kroon *et al.,* 2010, 2012).

Measured annual total phosphorus loads are highly variable over time and between catchments (Joo *et al.,* 2012, Turner *et al.,* 2012, in press). Annual total phosphorus loads for individual catchments ranged from two (low flow in the Burnett in both 2006-2007 and 2008-2009) to 15,000 tonnes (Fitzroy in 2010-2011) (Turner *et al.,* 2012, in press). Recent research indicates that current monitoring may be slightly underestimating mean annual loads of total phosphorus in most Great Barrier Reef basins by not accounting for the contribution of overbank flooding discharges (Wallace *et al.,* 2009, 2012).

Catchment sources

Similarly to nitrogen, phosphorus can be derived from both natural and modified landscapes, with different phosphorus constituents dominating run-off from different land uses. Phosphorus export from Australia's pristine forested catchments is low (Harris 2001), including from undisturbed forests in the Great Barrier Reef catchment (Eyre *et al.,* 1999, Brodie and Mitchell 2005). Clearing and conversion to agriculture and urban development results in increased phosphorus export due to fertilizer use (Mitchell *et al.,* 2009), sewage wastes (Harris 2001, Lewis *et al.,* 2008), and soil erosion (Brodie and Mitchell 2005, Rohde *et al.,* 2008). McCulloch *et al.,* (2003b) used tracing techniques to show that alkali basalts in the Wet Tropics catchments dominate the particulate phosphorus supply to the Great Barrier Reef lagoon in this area. No further provenance tracing of phosphorus constituents has been conducted in surface waters discharging into the Great Barrier Reef lagoon to better elucidate catchment processes that contribute to loads of phosphorus constituents.

The Fitzroy and Burdekin natural resource management regions contribute 45 per cent (Kroon *et al.,* 2010, 2012) to 55 per cent (Waters *et al.,* in press) to the mean annual anthropogenic total phosphorus load to the Great Barrier Reef lagoon (Figure 4.3, Table 4.2). Eighty-five percent of the mean annual anthropogenic total phosphorus load to the Great Barrier Reef lagoon is derived from grazing lands (42 per cent), streambank erosion (23 per cent) and cane lands (20 per cent) (Waters et al., in press). The Great Barrier Reef Catchment Loads Monitoring Program revealed that the Burdekin catchment was the single largest contributor to the total measured annual total phosphorus loads from 2006-2007 to 2010-2011, followed by the Fitzroy; the combined contribution of all remaining catchments was less than the Fitzroy (Joo *et al.,* 2012, Turner *et al.,* 2012, in press). In the Fitzroy catchment, basaltic soils have been identified as a disproportionate contributor to total phosphorus fluxes, due to their higher total phosphorus concentrations (Douglas *et al.,* 2006b).

The mean annual anthropogenic total phosphorus load to the Great Barrier Reef lagoon primarily consists of particulate phosphorus (76 per cent in Waters *et al.,* in press, 98 per cent in Kroon *et al.,* 2010, 2012) (Fig. 2.3). Most particulate phosphorus is mineralised from fine sediment following delivery to the lagoon (McCulloch *et al.,* 2003b, Webster *et al.,* 2006), and could be readily available for uptake in Great Barrier Reef ecosystems. Across the six natural resource management regions in the Great Barrier Reef, the Burdekin and Fitzroy contribute approximately 50 per cent to the mean annual anthropogenic particulate phosphorus load to the Great Barrier Reef lagoon (58 per cent in Waters *et al.,* in press, 43 per cent in Kroon *et al.,* 2010, 2012) (Figure 4.1, Table 4.2). The Great Barrier Reef Catchment Loads Monitoring Program revealed that the annual particulate phosphorus loads for individual catchments ranged from less than one (in the Burnett during 2006-2009) to 8700 tonnes (Fitzroy in 2010-2011) (Turner *et al.,* 2012, in press). The Burdekin and Fitzroy catchments were the largest single contributor to the total measured annual particulate phosphorus loads from 2006-2007 to 2010-2011, followed by the Johnstone and Herbert catchments; the summed loads from the remaining catchments were approximately half of the Fitzroy (Joo *et al.,* 2012, Turner *et al.,* 2012, in press). Results from both monitoring and modelling indicate that particulate phosphorus is mostly derived from grazed areas (Hunter and Waltson 2008, Bainbridge *et al.,* 2009), with over 50 per cent of the mean annual particulate phosphorus load to the Great Barrier Reef lagoon derived from grazing lands (Waters *et al.,* in press).

Dissolved inorganic phosphorus contributes less than 20 per cent to the mean annual anthropogenic total phosphorus load to the Great Barrier Reef lagoon (17 per cent in Waters *et al.,* in press, eight per cent in Kroon *et al.,* 2010, 2012) (Figure 4.3). Across the six natural resource management regions in the Great Barrier Reef, the Burdekin and Fitzroy contribute 50 per cent to the mean annual anthropogenic dissolved inorganic phosphorus load to the Great Barrier Reef lagoon (Kroon *et al.,* 2010, 2012, Waters *et al.,* in press) (Figure 4.1, Table 4.2). The Great Barrier Reef Catchment Loads Monitoring Program revealed that annual dissolved inorganic phosphorus loads for individual catchments ranged from one (low flow in the Burnett in 2006-2007) to 5080 tonnes (Fitzroy in 2010-2011) (Turner *et al.,* 2012, in press). The Fitzroy catchment was the single largest contributor to the total measured annual dissolved inorganic phosphorus loads, followed by the Burdekin. The combined contribution of all remaining catchments was less than the Burdekin catchment (Joo *et al.,* 2012, Turner *et al.,* 2012, in press). Results from Source Catchments modelling suggest that grazing (42 per cent), sugarcane (19 per cent) and nature conservation (15 per cent) contribute the majority of the total dissolved inorganic phosphorus load to the Great Barrier Reef (Waters *et al.,* in press).

Dissolved organic phosphorus contributes less than 10 per cent to the mean annual anthropogenic total phosphorus load to the Great Barrier Reef lagoon (six per cent in Waters *et al.,* in press, three per cent in Kroon *et al.,* 2010, 2012) (Figure 4.3). Recent and previous modelling efforts do not agree on which natural resource management regions contribute most to the mean annual anthropogenic dissolved organic phosphorus load: either the Burdekin and Mackay Whitsunday (Waters *et al.,* in press) or Mackay Whitsunday and Wet Tropics (Kroon *et al.,* 2010, 2012) (Figure 4.1, Table 4.3). The Great Barrier Reef Catchment Loads Monitoring Program revealed that the annual dissolved organic phosphorus loads for individual catchments ranged from less than one (low flow in the Burnett in 2006-2009) to 1500 tonnes (Fitzroy in 2010-2011) (Turner *et al.,* 2012, in press). The Burdekin catchment was the largest single contributor to the total measured annual dissolved organic phosphorus loads from 2006-2007 to 2010-2011, followed by the Fitzroy, Herbert, Tully and Johnstone catchments. The summed load from the remaining catchments was less than the Herbert (Joo *et al.,* 2012; Turner *et al.,* 2012, in press). Results from Source Catchments modelling suggest that grazing (45 per cent), nature conservation (29 per cent) and sugarcane (10 per cent) contribute the majority of the total dissolved organic phosphorus load to the Great Barrier Reef. (Waters *et al.,* in press).

Summary

- Mean annual river loads to the Great Barrier Reef lagoon for total phosphorus have increased 2.5 to 8.9-fold compared to pre-European conditions.
- Comparing mean annual total phosphorus loads by individual basin showed reasonable agreement between estimates derived from modelling and monitoring.
- Particulate phosphorus comprises by far the largest proportions of the mean annual anthropogenic total phosphorus loads, followed by dissolved inorganic and dissolved organic phosphorus.
- Most particulate phosphorus is lost or mineralised from fine sediment following delivery to the Great Barrier Reef lagoon and could be readily available for uptake in Great Barrier Reef ecosystems.
- The main sources for the anthropogenic total phosphorus load to the Great Barrier Reef lagoon are
    - Grazing lands (42 per cent), streambank erosion (23 per cent) and cane lands (20 per cent)
    - The Fitzroy and Burdekin catchments (approximately 55 per cent)

  - Sediment erosion processes in particular in grazing lands (particulate phosphorus); sources of dissolved inorganic phosphorus and dissolved organic phosphorus are currently unclear.
- The dominant (sub-catchment) source that contribute to bio-available phosphorus in the Great Barrier Reef lagoon need to be determined, through the application of provenance tracing in combination with existing direct flux monitoring and catchment modelling.

Pesticides

Reef Plan 2009, and associated monitoring and modelling efforts to determine pesticide loads and sources, has focused on photosystem II inhibiting herbicides, specifically ametryn, atrazine, diuron, hexazinone and tebuthiuron (Queensland Department of the Premier and Cabinet 2009). Of the at least 28 pesticides being detected in Great Barrier Reef catchments (Lewis *et al.,* 2009, Packett *et al.,* 2009, Shaw *et al.,* 2010, Davis *et al.,* 2012, Smith *et al.,* 2012; Turner *et al.,* in press), these five photosystem II inhibiting herbicides are the most commonly detected (Smith *et al.,* 2012), and detected at the highest concentrations (Lewis *et al.,* 2009, 2012, Smith *et al.,* 2012, Kennedy *et al.,* 2012).

Pesticide usage in the Great Barrier Reef catchment, however, is constantly changing in response to new pesticides being developed, as well as costs and regulations. For example, in some catchments a large peak in diuron concentrations was observed in 2011-2012 (Smith pers. comm.), just prior to the introduction of changed rules regarding permitted usage patterns for diuron by APVMA (APVMA 2012). Preliminary monitoring results also suggest that herbicides such as metribuzin (another photosystem II inhibiting), isoxaflutole, and metolachlor are being detected in higher concentrations and with greater frequency in recent years (Lewis S pers. comm.) indicating a shift in usage patterns. Whilst the current focus of Reef Plan 2009 is on photosystem II inhibiting herbicides (see below), future efforts should reflect the relative risk of individual or combinations of all pesticides to receiving aquatic environments.

River loads

The total photosystem II inhibiting herbicide loads calculated from both modelling and monitoring data are based on the summation of the mass loads of the individual photosystem II inhibiting herbicide loads. For estimates based on monitoring this includes ametryn, atrazine, diuron, hexazinone and tebuthiuron, for estimates based on modelling this also includes simazine (another photosystem II inhibiting herbicide). The resultant equal weighting of individual photosystem II inhibiting herbicides does not account for the differences in their relative risk to aquatic organisms and ecosystems.

The two most recent estimates of the mean annual photosystem II inhibiting herbicide loads to the Great Barrier Reef lagoon correspond well; being 16,700 kilograms per year (Waters *et al.,* in press) (Fig. 2.1) and 15,700 ± 830 kilograms per year (Lewis *et al.,* 2011). These estimates are lower than the 30,000 kilograms per year reported in Kroon *et al.,* (2010, 2012), and are based on more recent data on agricultural land use area and herbicide loads (from streams in the Wet Tropics, Burdekin, Mackay Whitsunday, Fitzroy and Burnett Mary natural resource management regions; Rohde *et al.* 2008, Lewis *et al.,* 2009, Packett *et al.,* 2009, Smith *et al*., 2012). The total pesticide load to the Great Barrier Reef lagoon is likely to be considerably larger than the photosystem II inhibiting herbicide loads reported here, given that at least 28 pesticides have been detected in Great Barrier Reef catchments in addition to the five photosystem II inhibiting herbicides for which loads are calculated (Lewis *et al.,* 2009, Packett *et al.,* 2009, Shaw *et al.,* 2010, Davis *et al.,* 2012, Smith *et al.,* 2012; Turner *et al.,* 2012, in press). These include five other photosystem II inhibiting herbicides, a growth inhibitor herbicide, synthetic auxins, insecticides, organophosphates, organochlorins, synthetic pyrethroids and fungicides (Smith *et al.,* 2012).

Across the six natural resource management regions, the Wet Tropics and Mackay Whitsunday natural resource management regions contribute 74-79 per cent to the mean annual photosystem II inhibiting herbicide load to the Great Barrier Reef lagoon (Lewis *et al.,* 2011, Waters *et al.* in press). Comparing mean annual photosystem II inhibiting herbicide loads by individual basins showed large variability between estimates reported in Lewis *et al.,* (2011) and Waters *et al.,* (in press). For example, much higher (more than or equal to four times) loadings were estimated for the Mackay Whitsunday basins by Lewis *et al.,* (2011). These higher estimates in the Mackay Whitsunday region are supported by photosystem II inhibiting herbicide yields derived from the latest Great Barrier Reef Catchment Loads Monitoring Program monitoring data (see below). Conversely, the Source catchments model (Waters *et al.,* in press) predicts much higher loads in basins of the Wet Tropics and Burnett Mary regions.

Measured annual photosystem II inhibiting herbicide loads are highly variable over time and between catchments (Smith et al., 2012, Turner *et al.,* 2012, in press). The largest annual photosystem II inhibiting herbicides load estimates originated from the Fitzroy and were approximately four tonnes (2009-2010) and 12.5 tonnes (2010-2011), the marked increase reflecting the larger annual discharge in 2010-2011 (Smith *et al.,* 2012, Turner *et al.,* 2012, in press).

Catchment sources

In the Great Barrier Reef catchment, photosystem II inhibiting herbicides have been registered for the following main land use types: cropping, forestry, horticulture, grazing and sugarcane (Table 4.3). Atrazine, ametryn, hexazinone and diuron originate predominantly from the sugarcane industry (Bainbridge *et al.,* 2009a, Davis *et al.,* 2012, in press), with atrazine also being used in grains cropping, and tebuthiuron and simazine originating from the beef grazing industry and forestry plantations, respectively (Lewis *et al.,* 2009, Shaw *et al.,* 2010, Waterhouse *et al.,* 2012).

Across the six natural resource management regions in the Great Barrier Reef, the Wet Tropics natural resource management region contributes the highest mean annual photosystem II inhibiting herbicide load to the Great Barrier Reef lagoon (Kroon *et al.,* 2010, 2012, Waters *et al.,* in press) (Table 4.2). The Great Barrier Reef Catchment Loads Monitoring Program revealed that the Mackay Whitsunday and Fitzroy natural resource management regions contributed on average approximately 70 per cent of the total annual photosystem II inhibiting herbicide load in both 2009-2010 and 2010-2011 (Joo *et al.,* 2012, Turner *et al.,* 2012, in press). At least three photosystem II inhibiting herbicides were detected in every monitored catchment in both years. Atrazine and diuron were detected at all sites in both years, except for diuron in the Burdekin in 2010-2011, whilst tebuthiuron was detected in five (2009-2010) and four (2010-2011) catchments, respectively. Importantly, some of the smaller catchments (e.g. Baratta and Sandy Creeks) contribute disproportionately high loads and have some of the highest photosystem II inhibiting herbicide concentrations (Davis *et al.,* 2012, Smith *et al.,* 2012, Turner *et al.,* 2012, in press). Due to their low discharge the impacts of these small catchments on the Great Barrier Reef ecosystems is likely to be localised, but could still be locally significant. Further research into the contribution of such small catchments to overall photosystem II inhibiting herbicide loads is required.

Low concentrations of photosystem II inhibiting herbicide residues, namely atrazine, diuron, hexazinone, desethyl atrazine and desisopropyl atrazine, have also been detected in groundwater at several potential discharge areas in the lower Burdekin floodplain (Shaw *et al.,* 2012). In all cases, concentrations of these were considerably below respective guideline trigger values for ecosystem protection in surface waters (ANZECC and ARMCANZ 2000).

Comparing yields[1] of photosystem II inhibiting herbicides showed that diuron had by far the highest average yield (0.82 kilograms per square kilometre) followed by atrazine (0.23 kilograms per square kilometre) (Table 4.3). The remaining three photosystem II inhibiting herbicides had considerably smaller average yields with values ranging from 0.02 to 0.13 kilograms per square kilometre. For ametryn, atrazine and diuron, the Pioneer and Plane catchments always had the highest yields (Table 4.3). For hexazinone, the Tully and the Plane catchments had the highest yields by a factor of at least three. For tebuthiuron, the Fitzroy and Burdekin catchments had the highest yield, with the Fitzroy yield approximately seven times larger than that of the Burdekin. Results from Source Catchments modelling suggest that over 90 per cent of the modelled photosystem II inhibiting herbicide load is from sugarcane, with minor contribution from cropping and grazing lands in particular from the Fitzroy basin (Waters *et al.,* in press).

The above discussion of the relative importance of various sources of pesticides is based on the mass of the pesticides. However, the toxicity of pesticides to species is highly variable, thus one kilogram of a pesticide may have a markedly different biological effect than the same mass of another pesticide. It has therefore been argued that pesticide loads should be expressed in terms of their toxicity (Smith *et al.,* 2012). The use of a toxic loads approach places a more ecologically relevant emphasis on the relative importance of various sources and likely lead to a different prioritisation of land-uses and catchments targeted for land management change.

Summary

- The total mean-annual load of photosystem II inhibiting herbicides, namely ametryn, atrazine, diuron, hexazinone, tebuthiuron and simazine, is estimated to range between 16,000 and 17,000 kilograms per year.
- The total pesticide load to the Great Barrier Reef lagoon is likely to be considerably larger, given that at least 28 pesticides have been detected in the Great Barrier Reef catchments, including five other photosystem II inhibiting herbicides, a growth inhibitor herbicide, synthetic auxins, insecticides, organophosphates, organochlorins, synthetic pyrethroids and fungicides.
- Comparing mean annual photosystem II inhibiting herbicide loads by individual basins showed large variability between estimates derived from modelling and monitoring.
- The main sources for the photosystem II inhibiting herbicides load to the Great Barrier Reef lagoon are
    - sugarcane (94 per cent)
    - the Wet Tropics, Burdekin and Mackay Whitsunday catchments (more than 85 per cent).

Other pollutants

In the Great Barrier Reef, research on pollutants has focussed predominantly on managing non-point source pollution from broad-scale land use, specifically fluxes of total suspended solids, nitrogen, phosphorus and pesticides, as their detrimental impacts on reef ecosystems have been well documented (Fabricius 2011). Given the current and projected development along the Great Barrier Reef coast, however, it is timely to assess other sources of pollutants in the context of those derived from broadscale land use.

[1] Yields for each of the five photosystem II inhibiting herbicides were calculated by dividing the 2010-2011 annual load for each herbicide by the total surface area of land where each pesticide is registered for use in each catchment (Turner *et al.,* in press). These yield estimates are likely to underestimate actual yields as not all land registered for herbicide use will have had herbicides applied.

Diffuse sources of other pollutants

Other potential diffuse sources of pollution to the Great Barrier Reef lagoon include coastal development and air pollution including aeolian dust. Coastal development in the Great Barrier Reef catchment has substantially altered natural river flow regimes through surface water diversion, dam construction, and wetland drainage and deforestation (Great Barrier Reef Marine Park Authority 2009, Pena-Arancibia *et al*., 2012). Impoundments and diversion of surface water enhance evaporation and reduce runoff, altering the magnitude and timing of freshwater flows. In contrast, the loss of water storage capacity associated with wetland drainage and deforestation results in lower evaporation, increased runoff, and more variable hydrographs. The resulting changes in long-term net runoff, as well as timing and magnitude of downstream peak and low flows, have modified coastal salinity, nutrient stoichiometry and biogeochemistry on coral reefs (Porter *et al*., 1999). In the Great Barrier Reef context, restoration of more natural freshwater flow regimes to the Great Barrier Reef lagoon has not been considered by management, despite affecting reef condition (Coles and Jokiel 1992, Berkelmans *et al*., 2012) and transport of other pollutants (e.g. Wallace *et al*., 2009).

Urban development releases a variety of contaminants (e.g. fluoride, gasses, particulates, metals, organic chemicals) into the air. In large urban development, industry can be a major pollutant source to the air but also to nearby waters through wet and dry deposition of airborne contaminants. Further work such as the Gladstone air monitoring program is required in order to provide accurate estimates of the importance of this source. Aeolian transport (air-borne transport of soil particles) could also contribute to pollutant loads being received by the Great Barrier Reef lagoon (Shaw *et al*., 2008), including pollutants that are bound to soil particles such as metals (naturally found in soil or introduced through fertiliser use) or pesticides from agriculture practices.

Point sources of other pollutants

Generally, point sources are regulated activities, meaning that they have been assessed, deemed to have met environmental management considerations and conditioned accordingly. Licensed environmentally relevant activities in the Great Barrier Reef catchment comprise (based on QLUMP) intensive animal production, manufacturing and industrial, mining, rural and urban residential, transport and communication, waste treatment and disposal, and ports/marine harbour. Whilst point sources are generally regulated activities, monitoring and permit information is not always available. In addition, extensive monitoring for many pollutants from point sources has not been conducted in the Great Barrier Reef region. Combined, this makes it difficult to assess the contribution and impact of pollutants derived from point sources in the context of those derived from broad-scale land use. It is expected that most contributions of point sources are relatively small compared to those by diffuse sources, however, these contributions could be locally and over short time periods highly significant.

For example, pollutants that have been found in Australian and international **sewerage discharges** include:

- pharmaceuticals - e.g. analgesics, anti-inflammatory, beta-blockers, lipid regulators, antiepileptic, antibiotics, cancer treatment and contraceptive drugs (Watkinson *et al.,* 2007), flu vaccine (Ghosh *et al.,* 2010), and psychiatric drugs (Brodin *et al.,* 2013)
- natural and synthetic hormones (e.g. Tan *et al.,* 2007, Ternes *et al.,* 1999)
- a range of industrial chemicals (e.g. polychlorinated biphenyls (PCBs), Sydney Water 1996) originating from trade wastes accepted into the sewage system
- illegal drugs (e.g. cocaine, morphine, amphetamines, methadone, ecstasy, cannabinoids, metabolites of heroine) and the compounds used in their generation (e.g. Zuccato and Castigliori 2008)
- components of personal care products – including triclosan (Yu *et al.,* 2006)
- cleaning agents, e.g. nonyl phenol ethoxylate (Sydney Water 2010)

- endocrine disrupting chemicals (e.g. Chapman 2003, Tan *et al.,* 2007, Williams *et al*., 2007)
- pesticides from domestic and domestic veterinary use, e.g. chlorfenvinphos (Bailey *et al.,* 2009b), diazinon (Bailey *et al.,* 2009a)
- nanomaterials in sewage (Klaine *et al.*, 2009).

There is no reason to assume that patterns of usage in the Great Barrier Reef region would be markedly different to those areas where studies have been conducted.

In highly **industrialised areas** a wide variety of pollutants, particularly metals, can be produced and released. For example, the port of Gladstone has cement works, aluminium refineries, fertiliser factories, and explosive manufacturers. Pollutants known to be released include aluminium, cyanide, molybdenum, copper, and arsenic (DEHP 2012).

In the Great Barrier Reef catchment, **mining** comprises coal, coal seam gasification, underground coal gassification, liquid natural gas, oil shale mining and refining and metalliferous ores. Coal mines are licensed to discharge water to surface waterways. Potential pollutants associated with these releases are salinity, metals, and acidity/alkalinity (EPA 2009, 2012g). Potential pollutants associated with coal seam gasification, liquid natural gas, and oil shale mining are organic chemicals, such as benzenes, toluene, xylenes, phenols, napthalenes, pyridines, and dioxins (Stuermer *et al.,* 1982), although highly saline product waters are also produced. Metalliferous mines such as Lady Annie copper mine in north Queensland and the abandoned Mount Morgan mine site can release quite substantial quantities of metals (Davies 2011, EPA 2009, Moss and Costanzo 1998).

Finally, **shipping** is a potential source of pollution to the Great Barrier Reef lagoon – via accidents (sinking, breaching hulls, spills etc), via the discharge of ballast water, or via slow but continual release of components of anti-fouling paints (particularly copper and diuron) (Great Barrier Reef Marine Park Authority 2009, Angel *et al.,* 2012). The expected increased usage of the Great Barrier Reef shipping lanes, which is predicted with increased port development, may result in an increased risk of pollution from shipping.

Summary

- The role of modified freshwater flow regimes in the Great Barrier Reef catchments in driving pollutant transport and affecting reef condition, through surface water diversion, dam construction, and wetland drainage and deforestation, has up to now not been considered but is likely to be highly significant.
- Other sources of pollutants to the Great Barrier Reef lagoon include point sources such as intensive animal production, manufacturing and industrial, mining, rural and urban residential, transport and communication, waste treatment and disposal, ports/marine harbour and shipping. Compared to diffuse sources, most contributions of such point sources are relatively small but could be locally and over short time periods highly significant. Point sources are generally regulated activities, however, monitoring and permit information is not always available.

Overall conclusions

Since the last consensus statement (Brodie *et al*., 2008), considerable improvements have been made to both the models and the monitoring that are used to estimate river loads of total suspended solids, speciated nitrogen and phosphorus, and photosystem II inhibiting herbicides. In addition, major improvements have been made in determining the dominant (sub-catchment) source of total suspended solids, speciated nitrogen and phosphorus, and photosystem II inhibiting herbicides through direct flux monitoring and catchment modelling, as well as provenance tracing (total suspended solids only). Improved knowledge about management practices in specific land uses such as fertilizer and pesticide application has also contributed to identifying critical sources.

Recent pollutant load estimates confirm that water discharged from the Great Barrier Reef catchment into the Great Barrier Reef lagoon continues to be of poor quality in many locations. Specifically, compared to pre-European conditions mean-annual river loads to the Great Barrier Reef lagoon have increased 3.2 to 5.5-fold for total suspended solids, two to 5.7-fold for total nitrogen, and 2.5 to 8.9-fold for total phosphorus. Particulate nutrients comprise by far the largest proportions of the mean-annual anthropogenic total nitrogen and total phosphorus loads, followed by dissolved inorganic and dissolved organic nutrients. Mean-annual loads of photosystem II inhibiting herbicides, namely ametryn, atrazine, diuron, hexazinone, tebuthiuron and simazine, are estimated to range between 16,000 and 17,000 kilograms per year. The total pesticide load to the Great Barrier Reef lagoon is likely to be considerably larger, given that at least a total of 28 pesticides have been detected in the Great Barrier Reef catchments, including five other photosystem II inhibiting herbicides, a growth inhibitor herbicide, synthetic auxins, insecticides, organophosphates, organochlorins, synthetic pyrethroids and fungicides.

Pollutant load estimates derived from modelling and monitoring showed a good agreement for total suspended solids, reasonable agreement for total nitrogen and total phosphorus, and large variability for photosystem II inhibiting herbicides. This demonstrates that continued improvement in the integration of the Great Barrier Reef Catchments Loads Monitoring Program data and the Source Catchment modelling framework is required to provide an improved framework for prediction, forecasting and uncertainty assessment at different spatial and temporal scales.

Recent source identification of pollutants to the Great Barrier Reef lagoon confirms that the vast majority of sediment and nutrient loads are derived from diffuse agricultural sources. Grazing lands contribute 45 per cent to the total suspended solids load, with a further 39 per cent from streambank erosion, to the Great Barrier Reef lagoon, with the Fitzroy and Burdekin catchments contributing at least 50 per cent. A combination of gully and streambank erosion and subsoil erosion from hillslope rilling, rather than broad-scale hillslope sheetwash erosion, has now been identified as the main erosion source. The Burdekin, Fitzroy, Plane, Burnett, and Normanby catchments contain a high proportion of fine sediment (less than 16 micrometres) material, which is the fraction most likely to reach the Great Barrier Reef lagoon.

Grazing lands (40 per cent) and sugarcane (31 per cent) contribute mostly to the mean annual anthropogenic total nitrogen load to the Great Barrier Reef lagoon, with the Fitzroy and Burdekin catchments contributing approximately 40 per cent. Sources differ depending on the nitrogen constituents, with increases in particulate nitrogen mostly linked with sediment erosion processes in particular in grazing lands, dissolved inorganic nitrogen with sugarcane and grazing, and dissolved organic nitrogen associated with land use changes in filter and buffer capacity. Grazing lands (42 per cent), streambank erosion (23 per cent) and cane lands (20 per cent) contribute mostly to the mean annual anthropogenic total phosphorus load to the Great Barrier Reef lagoon, with the Fitzroy and Burdekin catchments contributing approximately 50 per cent. Sources differ depending on the phosphorus constituents, with increases in particulate phosphorus mostly linked with sediment erosion processes in particular in grazing lands, whilst the sources of dissolved inorganic nitrogen and dissolved organic nitrogen currently being unclear. For both nitrogen and phosphorus, the dominant (sub-catchment) sources that contribute to bio-available nitrogen and phosphorus in the Great Barrier Reef lagoon need to be determined, through the application of provenance tracing in combination with existing direct flux monitoring and catchment modelling.

Sugarcane contributes 94 per cent to the total photosystem II inhibiting herbicide load to the Great Barrier Reef lagoon, with the Wet Tropics and Mackay Whitsunday catchments contributing over 70 per cent.

A recent review indicates that groundwater potentially may be an important source of dissolved nutrients and photosystem II inhibiting herbicides to the Great Barrier Reef lagoon. Natural attenuation processes may reduce levels of these contaminants in groundwater over time. Nevertheless, any contaminants discharged via groundwater may have disproportionately greater impacts compared with those in surface water discharges, due to; (i) the presence of highly sensitive ecosystems in groundwater receiving environments; and (ii) the prolonged period of exposure of these ecosystems to groundwater discharge during drier months when there is less potential for dilution and dispersion.

Other sources of pollutants to the Great Barrier Reef lagoon include coastal development and air pollution including aeolian dust, and point sources such as intensive animal production, manufacturing and industrial, mining, rural and urban residential, transport and communication, waste treatment and disposal, ports/marine harbour, and shipping. Coastal development in the Great Barrier Reef catchment has substantially altered natural river flow regimes through surface water diversion, dam construction, and wetland drainage and deforestation. The role of these modified freshwater flow regimes in driving pollutant transport and affecting reef condition has up to now not been considered but is likely to be highly significant. Point sources are generally regulated activities, however, monitoring and permit information is not always available. In addition, extensive monitoring for many pollutants from point sources has not been conducted in the Great Barrier Reef region. Whilst it is expected that most contributions of point sources to the Great Barrier Reef lagoon are relatively small compared to those by diffuse agricultural sources, these contributions could be locally and over short time periods highly significant.

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Tables

Table 4.1 Pollutants and their sources considered in Reef Plan 2009 (Queensland Department of the Premier and Cabinet, 2009).

Pollutant	Sources
Sediment (TSS)	Non-point source pollution from broadscale land use, including *agriculture* (e.g. grazing, cropping, horticulture and forestry) and *other tenures of public land* (e.g. national parks and reserves), but *not urban land uses*.
Nitrogen • Total nitrogen (TN) • Particulate nitrogen (PN) • Dissolved organic nitrogen (DON) • Dissolved inorganic nitrogen (DIN)	
Phosphorus • Total phosphorus (TP) • Particulate phosphorus (PP) • Dissolved organic phosphorus (DOP) • Dissolved inorganic phosphorus (DIP)	
Pesticides • Ametryn • Atrazine • Diuron • Hexazinone • Tebuthiuron	

Table 4.2 Ranking of six natural resource managements regions in the Great Barrier Reef catchment, based on anthropogenic pollutant loads, based on estimates reported in Waters *et al.,* (in press) and Kroon *et al.,* (2012).

Total	TSS		TN		DIN		DON		PN		TP		DIP		DOP		PP		PSII	
	Waters et al. in press	Kroon et al. 2012	Waters et al. in press	Kroon et al. 2012	Waters et al. in press	Kroon et al. 2012	Waters et al. in press	Kroon et al. 2012	Waters et al. in press	Kroon et al. 2012	Waters et al. in press	Kroon et al. 2012	Waters et al. in press	Kroon et al. 2012	Waters et al. in press	Kroon et al. 2012	Waters et al. in press	Kroon et al. 2012	Waters et al. in press	Kroon et al. 2012
1	Burdekin	Burdekin	WT	Fitzroy	WT	WT	WT	Burdekin	Burdekin	Fitzroy	Burdekin	Fitzroy	Burdekin	Burdekin	Burdekin	MW	Burdekin	Fitzroy	WT	WT
2	Fitzroy	Fitzroy	Burdekin	MB	Burdekin	MW	Burdekin	CY	WT	MB	WT	MB	MW	MB	MW	WT	WT	MB	Burdekin	MW
3	WT	MB	Fitzroy	Burdekin	MW	Burdekin	MW	MW	Fitzroy	CY	Fitzroy	Burdekin	Fitzroy	Fitzroy	CY	MB	Fitzroy	Burdekin	MW	Burdekin
4	MB	WT	MW	WT, CY	Fitzroy	CY	Fitzroy	Fitzroy	MB	Burdekin	MW	MW	WT	WT	WT	Burdekin	MB	MW	MB	Fitzroy
5	MW	CY	MB		MB	MB	MB	MB	CY	WT	MB	WT	MB	MW	Fitzroy	CY	MW	WT	Fitzroy	MB
6	CY	MW	CY	MW	CY	Fitzroy	CY	WT	MW	MW	CY	CY	CY	CY	MB	Fitzroy	CY	CY	CY	n/a

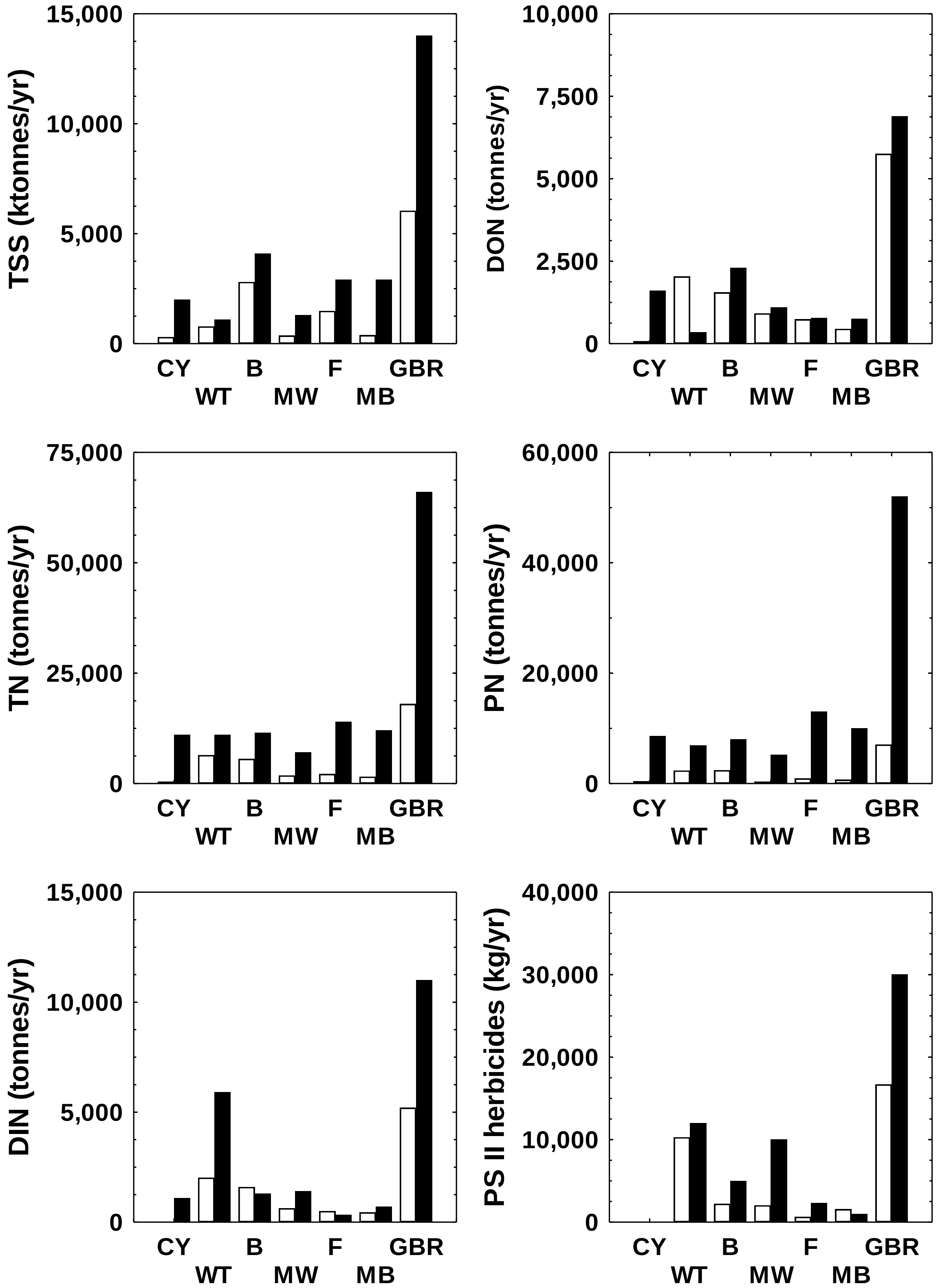
TSS = total suspended solids
DIN = dissolved inorganic nitrogen
DON = dissolved organic nitrogen
PN = particulate nitrogen
TN = total nitrogen
DIP = dissolved inorganic phosphorus
DOP = dissolved organic phosphorus
PP = particulate phosphorus
TP = total phosphorus
PSII = herbicides
WT = Wet Tropics
MB = Mary Burnett
MW = Mackay Whitsunday
CY = Cape York
n/a = not applicable

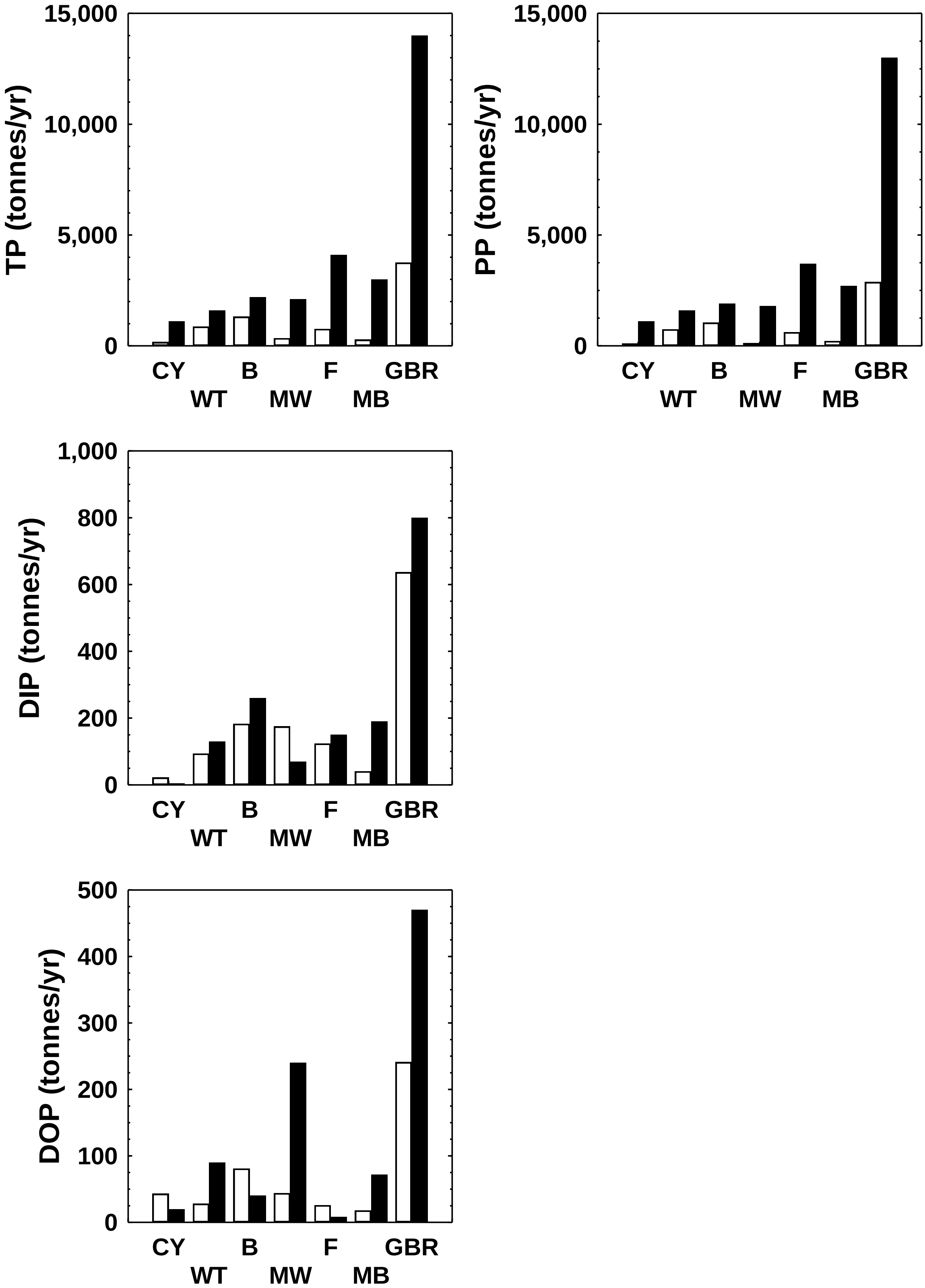
Table 4.3 Herbicide yields for five photosystem II herbicides (Turner *et al.*, in press).
nc = not calculable.

Catchment / River	Monitoring location	PSII inhibitor herbicide	Yield (kg km^{-2})	Registered land use types				
				Cropping	Forestry	Horticulture	Grazing	Sugarcane
North Johnstone River	Tung Oil	Ametryn	Nc			x		x
		Atrazine	0.068	x	x	x	x	x
		Diuron	0.87	x		x		x
		Hexazinone	0.003	x	x		x	x
		Tebuthiuron	Nc	x			x	
Tully River	Euramo	Ametryn	Nc			x		x
		Atrazine	0.343	x	x	x	x	x
		Diuron	1.038	x		x		x
		Hexazinone	0.455	x	x		x	x
		Tebuthiuron	Nc	x			x	
Herbert River	Inghan	Ametryn	0.069			x		x
		Atrazine	0.017	x	x	x	x	x
		Diuron	0.455	x		x		x
		Hexazinone	0.007	x	x		x	x
		Tebuthiuron	Nc	x			x	
Barratta Creek	Northcote	Ametryn	0.007			x		x
		Atrazine	0.39	x	x	x	x	x
		Diuron	0.296	x		x		x
		Hexazinone	0.023	x	x		x	x
		Tebuthiuron	0.002	x			x	
Burdekin River	Home Hill	Ametryn	Nc			x		x
		Atrazine	0.001	x	x	x	x	x
		Diuron	Nc	x		x		x
		Hexazinone	Nc	x	x		x	x
		Tebuthiuron	0.007	x			x	
Pioneer River	Dumbleton Head Water	Ametryn	0.239			x		x
		Atrazine	0.446	x	x	x	x	x
		Diuron	1.691	x		x		x
		Hexazinone	0.109	x	x		x	x
		Tebuthiuron	Nc	x			x	
Sandy Creek	Homebush	Ametryn	0.204			x		x
		Atrazine	0.792	x	x	x	x	x
		Diuron	2.146	x		x		x
		Hexazinone	0.337	x	x		x	x
		Tebuthiuron	Nc	x			x	
Fitzroy River	Rockhampton	Ametryn	Nc			x		x
		Atrazine	0.018	x	x	x	x	x
		Diuron	0.015	x		x		x
		Hexazinone	0	x	x		x	x
		Tebuthiuron	0.05	x			x	
Burnett River	Ben Anderson Barrage Head Water	Ametryn	Nc			x		x
		Atrazine	0.006	x	x	x	x	x
		Diuron	0.046	x		x		x
		Hexazinone	0.002	x	x		x	x
		Tebuthiuron	0.005	x			x	

Figures

Figure 4.1 Mean-annual anthropogenic river loads delivered to the Great Barrier Reef lagoon by individual natural resource management regions and the Great Barrier Reef catchment. Data derived from Waters *et al.,* (in press – white bars) and Kroon *et al.,* (2012 – solid bars).




15,000
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MB
GBR
500
400
300
200
100
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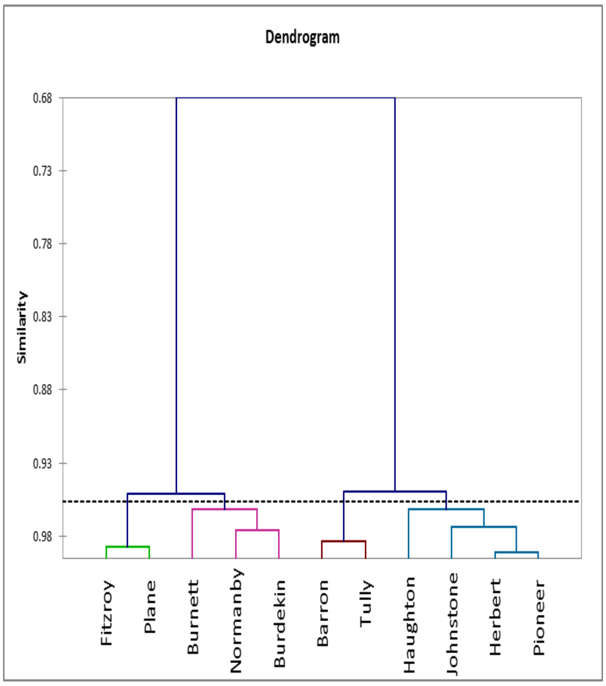
DOP (tonnes/yr)
CY
WT
B
MW
F
MB
GBR

Figure 4.2 Particle size distribution of total suspended solids in eleven catchments monitored by the Great Barrier Reef Catchment Loads Monitoring Program.
(a) an agglomerative hierarchical clustering of the full particle size distribution
(b) cumulative frequency plot of the four clusters identified in (a) (Turner *et al.,* in press).



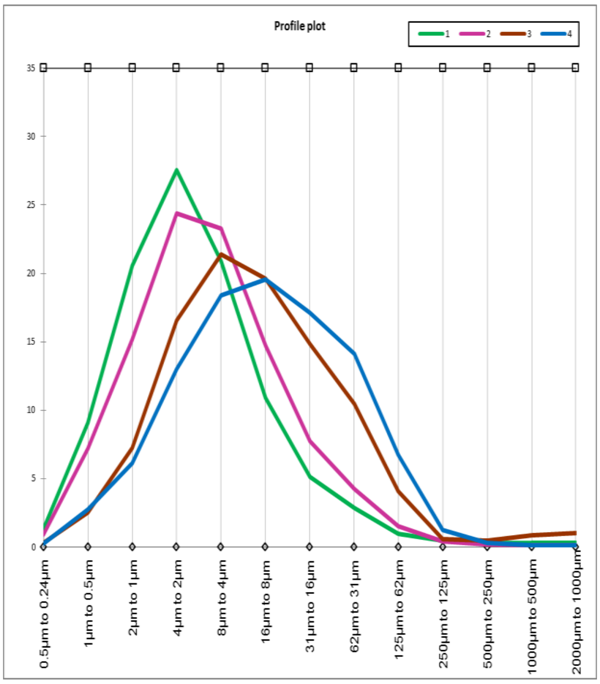
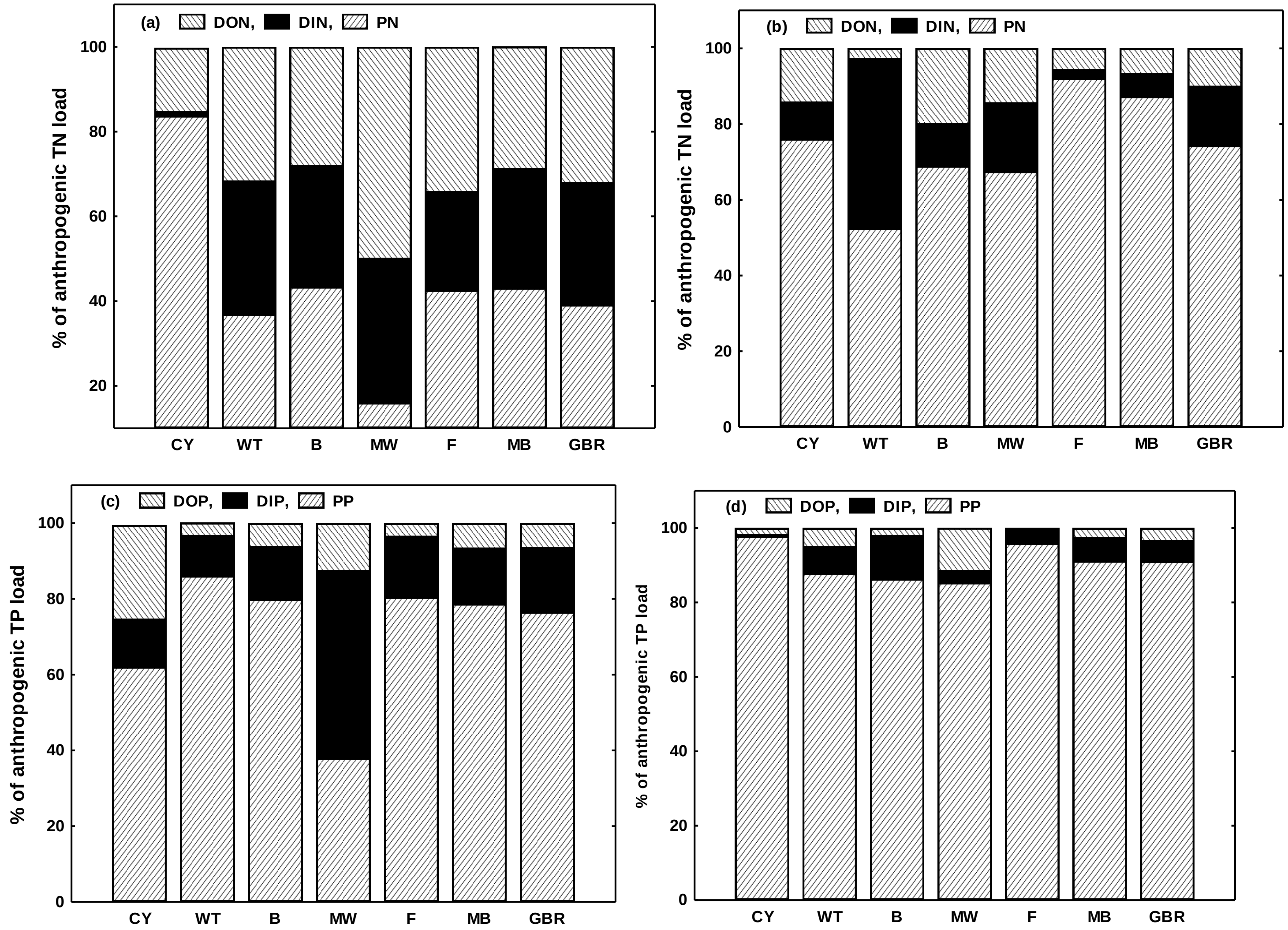


Figure 2.3 Proportional contribution of nitrogen and phosphorus constituents to mean annual anthropogenic loads by individual natural resources management regions and the Great Barrier Reef catchment. Data for (a) and (c) derived from Waters *et al.,* (in press), and for (b) and (d) derived from Kroon *et al.,* (2012).



Appendix 1 - Key knowledge gaps

- Continued improvement in the integration of the Great Barrier Reef Catchments Loads Monitoring Program data and the Source Catchment modelling framework is required to provide an improved framework for prediction, forecasting and uncertainty assessment at different spatial and temporal scales.
- Assessment of the Paddock to Reef program design, including the Great Barrier Reef Catchment Loads Monitoring Program, to:
    - ensure groundwater fluxes of pollutants are adequately represented in estimates of fluxes from catchments to the Great Barrier Reef lagoon
    - consider the spatial and temporal design to identify critical gaps (or redundancies) for each set of data
    - determine the power to detect trends in the data and tipping points (or thresholds)
    - improve confidence in reporting progress towards Reef Plan 2020 goals.
- Improvement of predictions from Source catchment modelling framework through:
    - 'documentation of a program of sensitivity, uncertainty and validation work that is linked to the various assumptions that are being made' (Queensland Department of the Premier and Cabinet 2012)
    - improved spatial resolution of management practice information both for baseline and change scenarios
    - field research of material flux processes (e.g. Rustomji *et al.,* 2008). In the Great Barrier Reef catchments, water quality data require long time-series (i.e. decades) to be effective in detecting changes (Darnell *et al.,* 2012). Several alternative techniques are available for constraining models, including radionuclide tracing, isotope tracing (e.g. Barnes and Raymond 2010, Verburg and Kendall 2013), cosmogenic nuclides (e.g. Hewawasam 2003), and optical dating techniques
    - contribution of overland flows to mean-annual loads of total suspended solids and nutrients in most Great Barrier Reef catchments (Wallace *et al.,* 2012)
    - quantification of changes in current and pre-European erosion rates to provide more accurate estimates of critical erosion sources, using, for example, sediment archives from within river catchments, or terrestrial cosmogenic nuclides (Hewawasam 2003)
    - improved mapping of gully extent and volume across the Great Barrier Reef catchment,
    - quantification of nitrogen and phosphorus fluxes in groundwater flows to the Great Barrier Reef lagoon, including temporal and spatial patterns and the age of groundwater discharged
    - quantification of temporal dynamics of river pollutant fluxes at daily to weekly timescales rather than decadal mean loads (for input into receiving water models).
- Improved understanding of several processes that may affect total suspended solids loads, including river bank slumping, sediment deposition of overland flows, and trapping by constricted flow, dams and weirs (e.g. Lewis *et al.,* 2013).
- Identification of catchment sources of bio-available nitrogen and phosphorus constituents in the Great Barrier Reef lagoon, through improved understanding of nutrient dynamics in riverine, estuarine and marine environments (e.g. Lourey *et al*., 2001) through the use of provenance tracing (e.g. Barnes and Raymond 2010, Verburg and Kendall 2013).
- Improvement of spatial and temporal contribution of pollutant delivery to the Great Barrier Reef lagoon by groundwater, including:
    - quantification of the amount of nitrate temporarily held deep in the profile of agricultural soils across the Wet Tropics, on Red Ferrosols and other soils with anion exchange capacity at depth

  - identification and characterisation of coastal and riverine ecosystems that receive surface and /or groundwater discharges, including their potential to mitigate pollutant loads and their need for rehabilitation
  - the quantity of photosystem II inhibiting herbicide residuals in groundwater flows and in areas of potential groundwater discharge.
- Improved understanding of total pesticide fluxes to the Great Barrier Reef lagoon, including
  - quantified information on the amounts of pesticides applied to land and to which land use, to derive more accurate load yields and a better understanding of the environmental fate of each pesticide
  - use of a toxic loads approach to place a more ecologically relevant emphasis on the relative importance of individual pesticides and their sources. It would likely lead to a different prioritisation of land-uses and catchments targeted for land management change.
- Improved spatial and temporal understanding of the contribution of pollutants by point sources to the Great Barrier Reef lagoon, in particular for pollutants other than total suspended solids, nutrients and photosystem II inhibiting herbicides that may pose a high risk to Great Barrier Reef ecosystems.