



Identification of priority pollutants and priority areas in the Great Barrier Reef catchments



Compiled by J. Waterhouse and J. E. Brodie



Australian Government
Department of the Environment,
Water, Heritage and the Arts



Identification of priority pollutants and priority areas in the Great Barrier Reef catchments

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Acronyms and Abbreviations

ACTFR	Australian Centre for Tropical Freshwater Research
BRIA	Burdekin River Irrigation Area
BSES	Bureau of Sugar Experiment Stations
COTS	Crown-of-thorns starfish
DERM	Queensland Department of Environment and Resource Management
DEWHA	Commonwealth Department of the Environment, Water, Heritage and the Arts (now Sustainability, Environment, Water, Population and Communities)
DIN	Dissolved Inorganic Nitrogen
DIP	Dissolved Inorganic Phosphorus
DON	Dissolved Organic Nitrogen
EMC	Event mean concentrations
GBR	Great Barrier Reef
GPS	Geographical Positioning System
ha	hectares
kg	kilogram
m	metres
MTSRF	Marine and Tropical Sciences Research Facility
N	Nitrogen
NRM	Natural Resource Management
PAM	Pulse-Amplitude-Modulated
PN	Particulate Nitrogen
PS-II	Photosystem II
RRRC	Reef & Rainforest Research Centre Ltd.
SEWPaC	Commonwealth Department of Sustainability, Environment, Water, Population and Communities
SS	Suspended Sediment
SST	Sea Surface Temperature
STM	Short term modelling
t	tonnes
TSS	Total Suspended Sediment
WQIP	Water Quality Improvement Program

About this Report

This report provides a synthesis of the key findings of research conducted under the Australian Government's Marine and Tropical Sciences Research Facility (MTSRF) relevant to defining priority pollutants for management of water quality in the Great Barrier Reef (GBR), and identification of areas for prioritising management. The report summarises the findings of three collaborative projects supported by MTSRF, the Department of Environment, Water, Heritage and the Arts (DEWHA) and the Department of the Environment and Resource Management (DERM). The DEWHA-funded project involved an assessment of the best estimate of pollutant loads delivered to the GBR for input to the Reef Rescue Multi Criteria Analysis for determining investment priorities. This information was used as the basis of two reports funded by DERM, firstly to undertake a relative risk assessment of contaminant loads between the GBR catchment Natural Resource Management (NRM) regions and, subsequently, load estimations at a basin and sub-basin scale for the Wet Tropics, Burdekin, Mackay Whitsunday and Fitzroy regions. Some of the information in this report is extracted from these project reports with the permission of the authors.

A key achievement of the MTSRF has been strong cooperation and collaboration between research institutions in project development and implementation. The findings presented in this report were derived from collaborative projects funded from several sources including the MTSRF, and the research institutions have also contributed significant in-kind resources. It should be noted that supporting information external to the MTSRF is included in this report to provide context or to complete the discussion. The publications specifically generated by the MTSRF are identified in the reference list.

The report is one in a series of information products that summarise MTSRF research findings relevant to managing water quality in the GBR. Other synthesis products – companion reports to this synthesis report – related to water quality include:

- A summary of MTSRF Water Quality Program highlights (Waterhouse and Devlin, 2010);
- 'Improved understanding of biophysical and socio-economic connections between catchment and reef ecosystems (Wet and Dry Tropics case studies)' (referred to as the 'Catchment to Reef Connections' companion report; Devlin and Waterhouse, 2010);
- 'Optimising water quality and impact monitoring, evaluation and reporting programs' (referred to as the 'Water Quality Monitoring and Evaluation in the GBR' companion report; Waterhouse, 2010a);
- 'Thresholds of major pollutants with regard to impacts on instream and marine ecosystems' (referred to as the 'Pollutant Thresholds' companion report; Waterhouse, 2010b);
- A comprehensive review of pesticides in the Great Barrier Reef (Martin, 2010); and
- A synthesis of water quality and climate change interactions, and socio-economic influences on water quality management in the Great Barrier Reef (Martin, in prep.).

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Thanks are extended to the Commonwealth Department of the Environment, Water, Heritage and the Arts (DEWHA, now SEWPaC), Queensland Department of the Environment and Resource Management (DERM) and the Marine and Tropical Sciences Research Facility (MTSRF) for funding the research and the Reef and Rainforest Research Centre (RRRC) for supporting this program over the past four years. The ongoing involvement of primary end users including the DEWHA, DERM and regional Natural Resource Management groups has focused the research outputs, such that they are already being applied to prioritising investment in land management activities aimed at reducing pollutant loads to the GBR.

Executive Summary

This report provides a synthesis of MTSRF-funded research relevant to defining priority pollutants for management of water quality in the GBR, and identifying areas for management intervention. The report contains an overview of the identification of priority pollutants, methods for calculating pollutant loads and current pollutant load estimates. Regional results of an assessment of the relative contribution of different sub-catchments and land uses to overall regional pollutant loads are presented. A relative risk assessment of regions and land uses from a water quality perspective is summarised, and the outcomes of a recent study on the exposure of plume waters in the GBR are included. Management implications, data limitations and future research directions are also described.

The priority pollutants derived from anthropogenic land uses considered most likely to pose a threat to the quality of runoff water entering the GBR ecosystem are suspended sediment, dissolved inorganic nitrogen (DIN) and photosystem II (PS-II) herbicides. The current pollutant load estimations do enable 'hot spots' of pollutant delivery to the GBR to be identified with a reasonable degree of certainty and, to date, management prioritisation is based on these estimates (see Brodie *et al.* 2009c). The assessment by Brodie and Waterhouse (2009), presented in this report, indicates that the Wet Tropics and Mackay Whitsunday regions have the highest priority ranking (High), the Burdekin and Fitzroy catchments a relatively high priority (Medium-high) and the Burnett Mary catchments a moderate priority in terms of the contribution and influence of land-based pollutants. The Cape York catchments were not included in the assessment but are expected to be relatively low priority. This information is represented in Figure i.

The results of regional pollutant load assessments indicate that:

- The land uses and areas generating the highest pollutant loads are: DIN – sugarcane in the Burdekin and Wet Tropics regions; suspended sediments – grazing lands in the Burdekin and Fitzroy regions; and PS-II herbicides – sugarcane in the Wet Tropics and Mackay Whitsunday regions.
- A large proportion of the anthropogenic load of DIN (approximately 80%) is derived from sugarcane fertiliser losses (Wet Tropics 84%, lower Burdekin 80%, Mackay Whitsunday 88%), except in the Fitzroy region where almost all of the DIN load is from cereal grains and cotton.
- Hillslope erosion contributes the most suspended sediment to the overall load across the GBR catchments in comparison to bank and gully erosion.
- Diuron is the dominant herbicide found in the Wet Tropics, lower Burdekin and Mackay Whitsunday regions. It is generally associated with areas of sugarcane but is also found in other cropping areas.
- Tebuthiuron is the dominant herbicide in the Burdekin and Fitzroy regions associated with grazing lands. Atrazine is associated with other crops in the Fitzroy region.

In addition to these findings, the key achievements of MTSRF-funded research that have assisted in understanding priority pollutants and priority areas for management intervention in the GBR catchments are summarised below.

- Collaborative projects were undertaken between the ACTFR and regional NRM groups to establish pollutant load targets for the regional water quality plans. These target setting processes require definition of priority pollutants and priority areas for pollutant generation. Examples of this work in the Burdekin catchment include Bainbridge *et al.* (2006a, 2006b, 2007a, 2008) and in the Tully catchment, Bainbridge *et al.* (2009a, 2009b) and Mitchell *et al.* (2009). Brodie *et al.* (2009a) also described the target setting

approach applied in the Burdekin and Tully catchments. These are all projects that were partly supported through the MTSRF. MTSRF researchers also participated in similar projects in other regions including the Mackay Whitsunday region (e.g. Rhode *et al.* 2008).

- Brodie and others at the ACTFR completed a project funded by the Australian Government and supported by the MTSRF to establish the best estimates of current pollutant loads for all of the GBR catchments. These estimates were entered into the Reef Rescue Multi Criteria Analysis for determining investment priorities across the GBR (Brodie *et al.* 2009b).
- The best estimates of pollutant loads for the GBR referred to above were then used as the basis for two reports funded by the Queensland Government, firstly to undertake a relative risk assessment of contaminant loads between the GBR catchment NRM regions (Brodie and Waterhouse, 2009) and, subsequently, to develop load estimations at a basin and sub-basin scale for the Wet Tropics, Burdekin, Mackay Whitsunday and Fitzroy regions (Brodie *et al.* 2009c). These projects were also supported by the MTSRF.
- Techniques for calculating pollutant loads have been improved through the MTSRF with considerable effort put towards quantifying uncertainty in load estimations. For example, Kuhnert and others have developed the Loads Regression Estimator (LRE) package (Kuhnert *et al.* 2009; Kuhnert and Henderson, 2010) to estimate suspended sediment loads from the Burdekin catchment. This approach deals with the uncertainty inherent in the large episodic flow events that are typical of the Burdekin catchment. In addition, statistical and modelling work has shown the importance of including variability of the system in the calculation of pollutant load estimates (e.g. Kuhnert *et al.* 2007, 2008, 2009, 2010; Kuhnert and Henderson, 2010).
- Priority management practices for reducing sediment, nutrient and pesticide runoff from agricultural areas and the cost effectiveness of these practices have also been established through MTSRF-funded research by van Grieken and others (e.g. van Grieken *et al.* 2010a, 2010b; Roebeling *et al.* 2007a, 2007b). Results of their analyses of the cost effectiveness of various management practices have already been used directly as part of the Reef Plan Paddock to Reef Integrated Monitoring, Modelling and Reporting Program (Queensland Department of the Premier and Cabinet, 2010).
- In parallel to the efforts identified above, a number of MTSRF-funded research projects focused on understanding pollutant transport and trapping (e.g. Lewis *et al.* 2009a; Wallace *et al.* 2010a, 2010b; Wolanski *et al.* 2008; Bainbridge *et al.* 2009a, 2010), water quality impacts on freshwater ecosystems (e.g. Pearson *et al.* 2010a), estuarine ecosystems (e.g. Sheaves *et al.* 2010) and marine ecosystems (e.g. Fabricius, 2011a, 2011b; Cooper *et al.* 2009; Negri *et al.* 2009). The outcomes of these studies and the ways in which they fit together to improve capacity to manage water quality issues in the GBR region are described in the companion MTSRF synthesis reports 'Catchment to Reef Connections' (Devlin and Waterhouse, 2010) and 'Water Quality Monitoring and Evaluation in the GBR' (Waterhouse, 2010a).
- While the study of the relative risk assessment of priority pollutants within and between regions (Brodie and Waterhouse, 2009) provides useful information for managers to determine investment priorities for land management in the GBR catchments, it was not intended to provide a water quality risk assessment for the GBR. An example of a recent project that does attempt to identify exposure and risk of GBR ecosystems to priority pollutants is a collaborative project between the GBRMPA and the ACTFR that aimed to identify areas of high frequency exposure to plume waters in the GBR, and the probability of water quality parameters exceeding the Water Quality Guidelines for the Great Barrier Reef Marine Park (Devlin *et al.* 2010). The input data for this project were largely derived from MTSRF-funded research and the Reef Rescue Marine Monitoring Program.

Many of these findings have already been used by managers making decisions directing effort and guiding investment priorities in the GBR. For example, and of considerable significance, the management responses presently being assisted through Reef Rescue initiatives and the *Great Barrier Reef Protection Amendment Act 2009* ('Reef Protection Package') are focused on the prioritised areas and industries identified in the overall risk assessment of priority pollutants and priority areas presented in this report. However, it is recognised that uncertainties do exist in this information and a number of future research priorities are identified to continue the delivery of applied research outcomes equivalent to those generated through the MTSRF. A number of these are presented in this report.

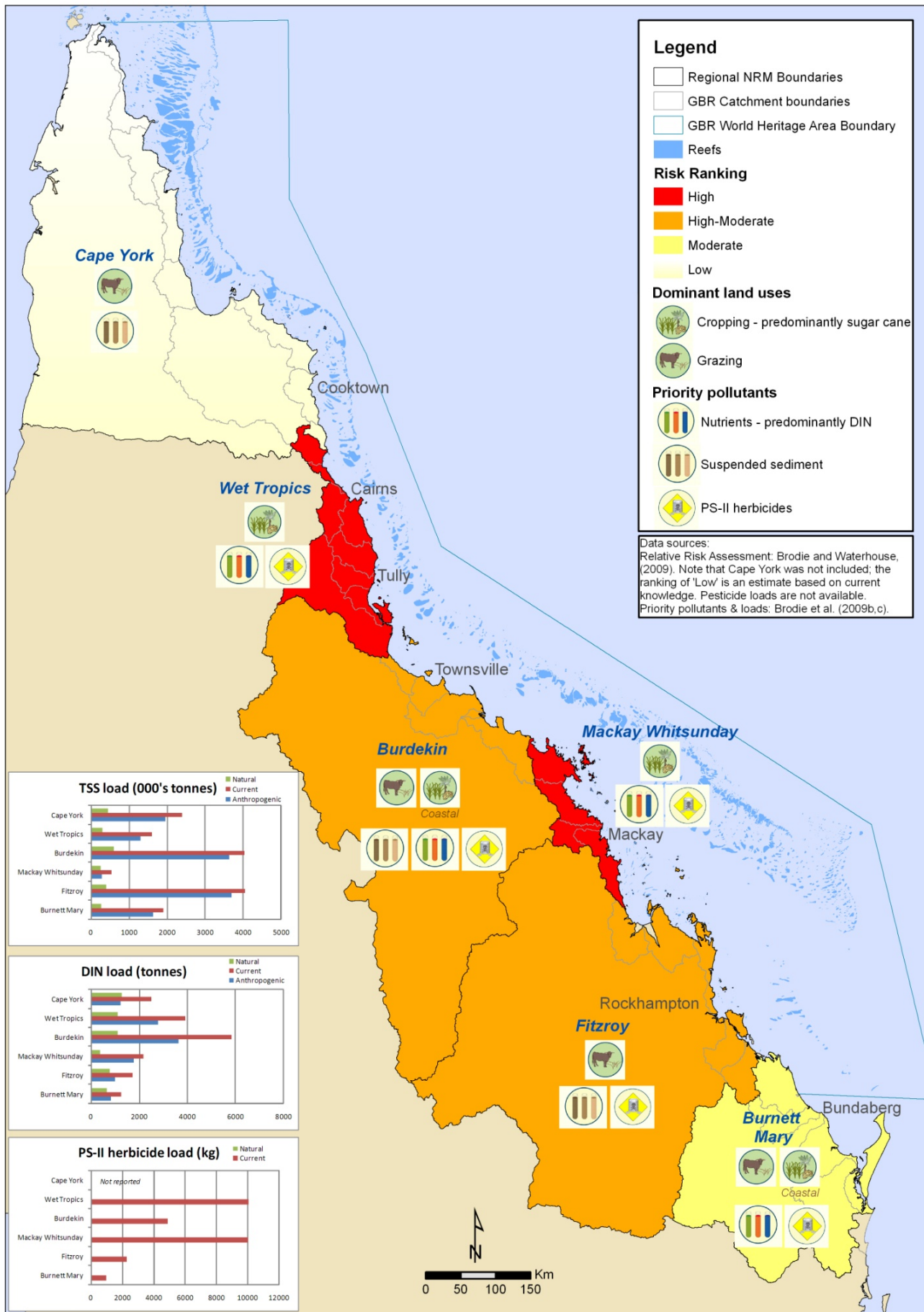


Figure i: Summary of priority pollutants, pollutant loads and priority areas for water quality management in the GBR catchments.

1. Introduction

The Great Barrier Reef (GBR) is an iconic ecosystem with very high ecological and socio-economic values. It was declared a Marine Park in 1975 and is managed as a zoned, multi-use area. Over 30% of the total area covered by its 70 bioregions is protected in high conservation, no take zones incorporated into a park-wide zoning plan (Day *et al.* 2004).

The catchment area adjacent to the GBR also maintains considerable ecological and socio-economic value, but has received much less protection. However, the health of the GBR is intimately connected to the environmental management of these catchments due to runoff of pollutants (Haynes *et al.* 2007), and this connection is likely to become even more important with the projected impacts of climate change (Johnson and Marshall, 2007). The health of the catchments is largely influenced by ambient water quality conditions, among other factors (Pearson *et al.* 2010a), while the health of coastal waters is mostly influenced by the discharge from large river flow events (Brodie *et al.* 2007; Devlin and Brodie, 2005).

The management implications regarding the health of the GBR and the anthropogenic effect of water quality from catchment activities are complex. The GBR receives freshwater inputs from the diverse river catchments along the adjacent Queensland coast, which vary in size, land use, biophysical and socio-economic characteristics. There is well documented evidence of the adverse impacts of anthropogenic contaminants on the health of aquatic ecosystems both within the catchment and in the GBR (for example, see Brodie *et al.* 2008a) and the relationship between land use, catchment management, declining water quality and GBR ecosystem health (De'ath and Fabricius, 2010; Lewis *et al.* 2009b; Fabricius *et al.* 2005; Fabricius, 2011b; Brodie *et al.* 2007, 2010). In the *Synthesis of evidence to support the Scientific Consensus Statement on Water Quality in the Great Barrier Reef* a review of the scientific literature concluded that 'land-derived contaminants, including suspended sediments, nutrients and pesticides are present in the GBR at concentrations likely to cause environmental harm' (Brodie *et al.* 2008a).

A variety of evidence clearly indicates that export of pollutants (sediment, nutrients and pesticides) from catchments adjacent to the GBR have increased substantially with catchment development, although the magnitude of the increases compared with natural conditions is not precisely known (Brodie *et al.* 2008a, 2008b; Brodie and Waterhouse, 2009). Most recent estimates indicate that sediment loads have increased by approximately five times, while total nitrogen loads have increased approximately six times and total phosphorus approximately nine times (Kroon *et al.* 2010). Cattle grazing, sugarcane production and horticulture are the predominant land uses in the GBR catchments. Each of these primary industries uses management practices that vary within and between different regions, depending on many factors. Export of pollutants consequently occurs to varying extents, predominantly during the wet season, depending on the management practices adopted (Brodie and Waterhouse, 2009).

To combat the adverse impacts of anthropogenic contaminants on GBR ecosystems, the Reef Water Quality Protection Plan ('Reef Plan') was established in 2003 with Australian and Queensland Government endorsement (Queensland Department of the Premier and Cabinet, 2003); and was revised in 2009 (Queensland Department of the Premier and Cabinet, 2009). In 2007 the Australian Government initiated 'Reef Rescue' to provide incentive programs, research, development, monitoring and reporting to address water quality issues in the GBR (Australian Government, 2007; <http://www.nrm.gov.au/funding/2008/reef-rescue.html>). To progress the intent of the Reef Plan the Queensland Government introduced the *Great Barrier Reef Protection Amendment Act 2009* ('Reef Protection Package'). The regulations focus on the major catchments delivering the most probable impact on the GBR based on estimates of the quantity of land-based contaminants

discharged from the region, the proximity of the catchment to vulnerable reef ecosystems, the existing condition of the reef ecosystems and the nature of the industries contributing contaminant loads. Further information on this legislation is available at <http://www.reefwise farming.qld.gov.au>. Guidance for the selection of priority areas for the regulations was provided through research supported by the Marine and Tropical Sciences Research Facility (MTSRF).

Given the issues outlined above, it is evident that managers need to understand the areas in the GBR catchment that generate the most pollutants and which pollutants are associated with different land uses and regions. With the introduction of regional water quality planning processes in GBR catchments around 2007, effort to define priority pollutants and pollutant sources in the catchments was increased and recognised as being essential for directing management intervention. Consequently, a considerable amount of MTSRF-funded effort has been directed towards identifying priority pollutants and priority areas for management in GBR catchments in collaboration with regional Natural Resource Management (NRM) groups and research providers.

The primary areas of MTSRF-funded research that have assisted in understanding priority pollutants and priority areas for management intervention in the GBR catchments include:

- Establishment of pollutant load targets for the regional water quality plans (e.g. Brodie *et al.* 2009a).
- Development of 'best estimates' of current pollutant loads for all of the GBR catchments (Brodie *et al.* 2009b).
- A relative risk assessment of pollutant loads between the GBR catchment NRM regions (Brodie and Waterhouse, 2009), and subsequently, development of load estimations at a basin and sub-basin scale for the Wet Tropics, Burdekin, Mackay Whitsunday and Fitzroy Regions (Brodie *et al.* 2009c).
- Improvements in techniques for calculating pollutant loads with considerable effort towards quantifying uncertainty in load estimations (e.g. Kuhnert and Henderson, 2010);
- Definition of priority management practices for reducing sediment, nutrient and pesticide runoff from agricultural areas and assessment of the cost effectiveness of these practices (e.g. van Grieken *et al.* 2010a, 2010b).
- Understanding pollutant transport and trapping (e.g. Lewis *et al.* 2009a; Wallace *et al.* 2010a, 2010b; Wolanski *et al.* 2008; Bainbridge *et al.* 2009a, 2010), water quality impacts on freshwater ecosystems (e.g. Pearson *et al.* 2010a), estuarine ecosystems (e.g. Sheaves *et al.* 2010) and marine ecosystems (e.g. Fabricius, 2011a, 2011b; Cooper *et al.* 2009; Negri *et al.* 2009). The outcomes of these studies are described in further detail in the individual reports, and in the companion MTSRF synthesis reports by Devlin and Waterhouse (2010) and Waterhouse (2010a).
- A number of collaborative projects have advanced our understanding of the exposure of marine ecosystems to land-based pollutants (e.g. Devlin *et al.* 2010; Devlin and Schaffelke, 2009), and in some cases, attempted to define risk to several factors including water quality and climate change (e.g. De'ath, 2006; Wooldridge, 2009; De'ath and Fabricius, 2010). However, further understanding of the relationships between exposure and ecosystem response is required to support a fully qualitative risk assessment of water quality impacts in the GBR.

This report provides a synthesis of MTSRF-funded research relevant to defining priority pollutants for management of water quality in the GBR and identifying areas for prioritising management intervention. The findings presented here are largely drawn from research outcomes presented by Brodie *et al.* (2009b), Brodie and Waterhouse (2009), Brodie *et al.*

(2009c) and Devlin *et al.* (2010). The report contains an overview of the identification of priority pollutants, methods for calculating pollutant loads and current pollutant load estimates. Regional results of an assessment of the relative contribution of different sub-catchments and land uses to overall regional pollutant loads are presented. A relative risk assessment of regions and land uses from a water quality perspective is summarised, and the outcomes of a recent study on the exposure of plume waters in the GBR are presented. Management implications, data limitations and future research directions are also described.

2. Identification of priority pollutants

The GBR catchment area is defined by six NRM regions: Cape York, Wet Tropics, Burdekin, Mackay Whitsunday, Fitzroy and Burnett-Mary (Figure 2.1). The Cape York region remains mostly undeveloped and is thus considered to have the least impact on GBR ecosystems from existing land based activities. In contrast, the Wet Tropics, Burdekin, Mackay Whitsunday, Fitzroy and Burnett-Mary regions are characterised by agricultural land uses including sugarcane, grazing, bananas and other horticulture, cropping such as grains and cotton, mining and urban development (Brodie and Waterhouse, 2009).

This section presents an overview of several MTSRF projects that were successful in identifying priority pollutants for water quality management in the GBR, starting with an overview of relevant water quality monitoring programs, before presenting an overview of the priority pollutants for management action.

2.1 Identifying priority pollutants

As part of the Reef Plan, regional Water Quality Improvement Plans (WQIPs) were developed for many of the GBR catchments in the period between 2006 and 2009. MTSRF-funded researchers participated in, and in some cases led, several components of these WQIPs, particularly in the development of pollutant load targets. The results of water quality monitoring programs established to measure pollutant concentrations from different land uses have been used to identify the pollutants with high potential for environmental impact ('priority pollutants') in each area. Examples of these comprehensive monitoring programs include those established in the Tully (e.g. Bainbridge *et al.* 2009b; Mitchell *et al.* 2009), Burdekin (e.g. Bainbridge *et al.* 2006a, 2006b, 2007a, 2007b, 2008, 2010), Mackay Whitsunday (e.g. Mitchell *et al.* 2005; Rohde *et al.* 2008) and Fitzroy (e.g. Packett *et al.* 2009) catchments. These programs have shifted in focus from defining priority pollutants to measuring the effect of implementing improved management practices funded through Reef Plan and Australian Government Reef Rescue initiatives. A comprehensive overview of these monitoring programs is provided in the companion MTSRF synthesis report by Waterhouse (2010a).

The usefulness of monitoring programs to detect short-term (within five years) changes in pollutant loads as a result of changed management practices has several limitations, including uncertainties in the estimation of pollutant loads and target values, time lags associated with contaminant transport within catchments and timeframes required by funding programs to assess performance (Bainbridge *et al.* 2009a). In response, substantial MTSRF-funded research effort has been directed to improving the design of monitoring programs for measuring and tracing pollutants in the GBR and its catchments. Assessment of the timeframes likely to be involved in measuring signals of change in the priority pollutants for the GBR has been reported by Bainbridge and others (Bainbridge *et al.* 2009a) and is summarised in Table 2.1. For example, responses to erosion control mechanisms for grazing lands (such as riparian fencing and wet season spelling) may be detected at the paddock/plot scale after 2-3 wet seasons and at a local scale within five to ten years depending on system noise; but greater than ten years at the sub-catchment scale, more than fifty years at the end of catchment and even longer time frames to detect any signal from this management action at the estuarine and marine scale. For nutrients, the timeframes range from months to decades, and for pesticides it is estimated that changes could be detected at the marine scale within two years.

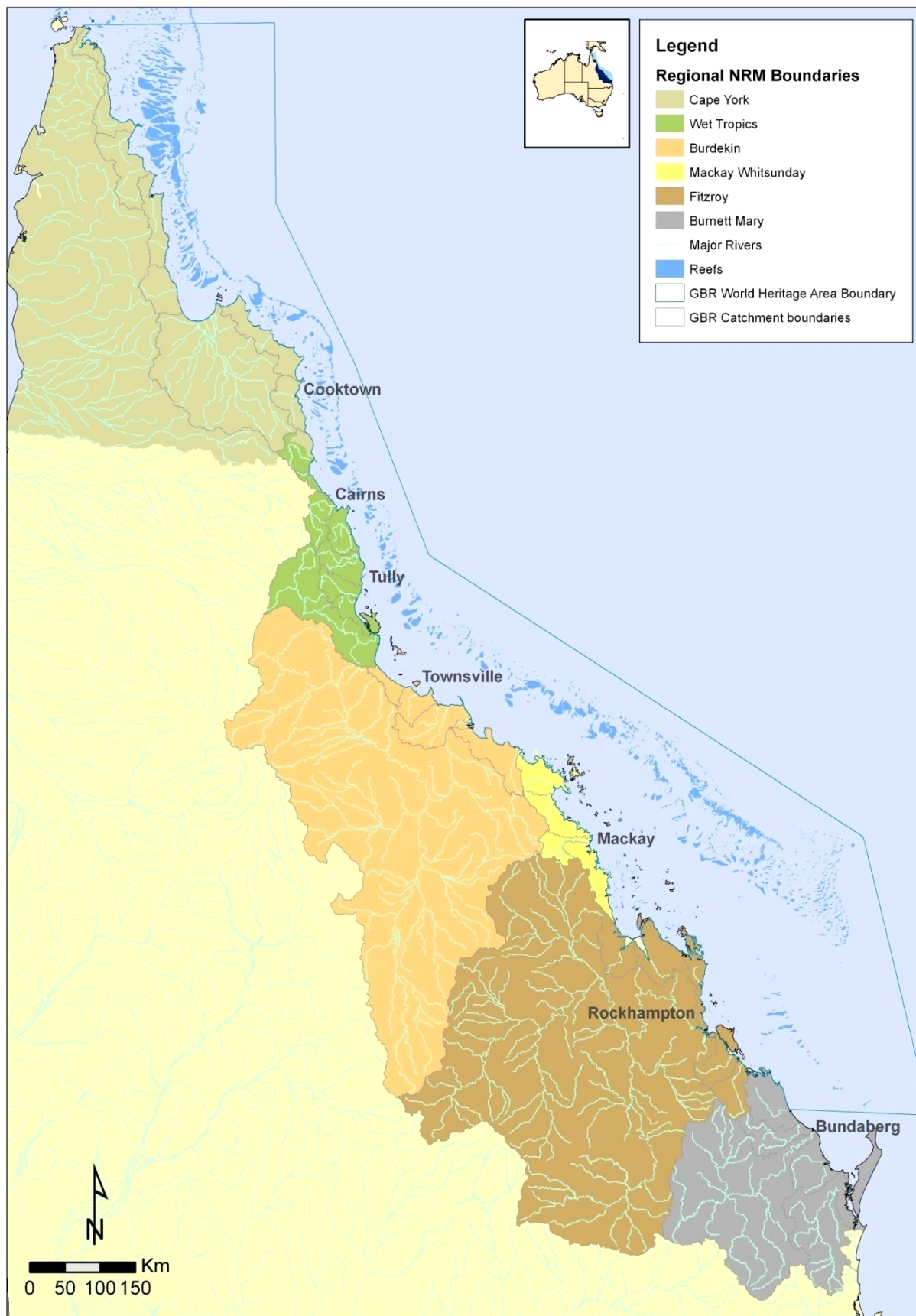


Figure 2.1: Great Barrier Reef catchments and regional NRM regions.

Due to the limitations associated with system variability (temporal and spatial), time lags and 'noise' in the system signal, a combined monitoring and modelling approach to assess performance of water quality improvements in the GBR is required in order to detect change within a reasonable timeframe (Bainbridge *et al.* 2009a). This combined approach overcomes many of the uncertainties associated with monitoring at shorter time scales as well as the shortfalls of the models available through data input and calibration. However, this approach may have errors propagated through the scaling of monitoring and modelling data (e.g. paddock to sub-catchment scale, end-of-river to marine). Based on these concepts, an integrated framework for monitoring water quality in the GBR has been established, supported by MTSRF research. The basic framework developed for the overall design for monitoring and evaluation of water quality in the GBR is shown in Figure 2.2. It involves the monitoring and modelling of a range of attributes including management practices and water quality at the paddock, sub-catchment, catchment and marine scales. This approach, which requires the ability to link the monitoring and modelling outputs at each scale, and then across scales, is described in further detail by Bainbridge and others (2009a). This framework has been adopted in many regional WQIPs, and forms the basis of the design of the Reef Plan Paddock to Reef Integrated Monitoring, Modelling and Reporting Program (the 'Paddock to Reef Program'). Further detail of this framework is provided in the companion MTSRF synthesis report by Waterhouse (2010a).

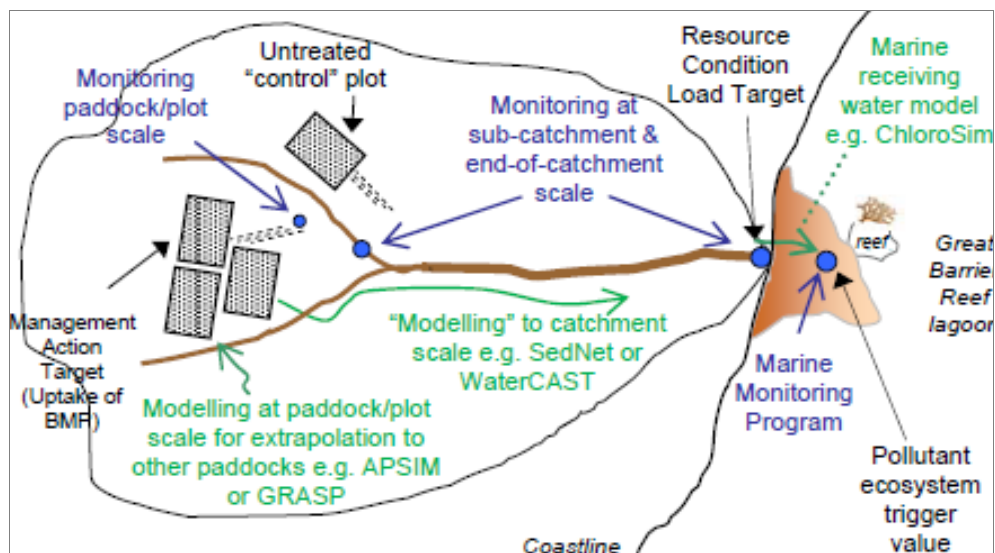


Figure 2.2: Monitoring from paddock/plot to marine ecosystem scale. Management action targets, resource condition targets and GBR lagoon trigger values are also highlighted. Source: Bainbridge *et al.* (2009a).

Table 2.1: Timeframes for water quality trends/signals to be detected for three example parameters at varying spatial scales from the paddock to the reef as a result of management actions implemented. Source: Bainbridge *et al.* (2009a). Suspended sediment in the Burdekin Rangelands, dissolved inorganic nitrogen in the lower Burdekin, and herbicides on the Tully floodplain have been used as examples to demonstrate differences between scales.

Management Actions / Remedial Activity	Water Quality Parameter		
	Suspended Sediment	Dissolved Nitrogen	Herbicides
	Erosion control mechanisms for grazing lands <i>e.g. riparian fencing and wet season spelling</i>	Reduction of fertiliser use in cropping lands <i>e.g. implement The Six Easy Steps Approach¹</i>	Minimise/optimize pesticide use through new technologies <i>e.g. shielded sprayers, control traffic</i>
Timeframe of water quality trends/signals being detected at different spatial scales			
Paddock/ Plot Scale	Change likely to be detected after two to three wet seasons <i>e.g. Virginia Park Station</i>	Months to three years, dependent on the nitrogen stored in the system (e.g. soil, organic matter) <i>e.g. Burdekin River Irrigation Area paddock</i>	Months to one year, dependent on previous usage and residuals in the system <i>e.g. Tully paddock</i>
Local Scale <i>e.g. immediate drainage line/ local waterway</i>	Likely to be detected within five to ten years depending on system noise <i>e.g. Weany Creek</i>	Likely to be detected within one to three years, depending on rate of adoption within local area and system noise <i>e.g. local cane drain</i>	Likely to be detected <1 year due to relatively short half life (i.e. diuron half life in soil is 90 days, and likely complete life less than two years) <i>e.g. local cane drain</i>
Sub-catchment Scale	Greater than ten years, even for major scale land management interventions across the sub-catchment <i>e.g. Fanning River</i>	Expect to measure change <10 years if sugarcane is dominant land use in catchment and management change is widely adopted; particularly if detailed pre-monitoring data are available. <i>e.g. Upper Barratta Creek</i>	Expect to measure change within two years if sugarcane is dominant land use in catchment and management change is widely adopted; particularly if detailed pre-monitoring data are available. <i>e.g. Davidson Creek</i>
End-of-catchment Scale	Likely >50 years (major erosion control management intervention across the Burdekin); dilution of signal as only small percentage of total catchment area under improved management at any one time, and hydrological variability or noise is high. <i>e.g. Burdekin River (Inkerman)</i>	Expect to measure change <10 years if sugarcane is dominant land use in catchment and management change is widely adopted; particularly if detailed pre-monitoring data are available. <i>e.g. Barratta Creek (Bruce Highway)</i>	Change detected less than two years, however may be dilution effect depending on amount of cane in catchment, and proportion of uptake by the industry within this catchment <i>e.g. Tully River (Euramo)</i>
Estuarine and Marine Scale <i>e.g. coastal waters within adjacent bay</i>	Likely >50 years before change in turbidity; limited likelihood of detecting signal from this management action due to size of catchment. <i>e.g. Upstart Bay</i>	Likely to detect change in chlorophyll from this management action (major nitrogen fertiliser reduction across the lower Burdekin sugar lands) less than twenty years, with variability due to other sources of nutrients (e.g. Burdekin plume), seasonal variations in nitrogen cycling and sea water mixing <i>e.g. Bowling Green Bay</i>	Changes likely to be detected within two years in the flood plume, however signal may be difficult to detect if the coastal waters are also influenced by larger river flood plumes (e.g. Herbert or Murray Rivers) <i>e.g. Dunk Island and Family Islands Group</i>

¹ BSES Ltd Best-Practice Nutrient Management: The Six Easy Steps Approach (<http://www.bses.org.au/InfoSheets/2008/IS08006.pdf>)

2.2 Priority pollutants for GBR water quality

A number of different pollutants of concern are discharged into the GBR from its catchments, and each pollutant has different sources, pathways and impacts on GBR ecosystems. The three main pollutant categories of concern include:

- Sediments, especially the finer, mud-sized fraction (<63 µm) which may potentially be influencing the long-term turbidity of inshore systems;
- Nutrients, particularly dissolved inorganic nitrogen and phosphorus and particulate nitrogen and phosphorus; and
- Pesticides, particularly the Photosystem II inhibiting herbicides (PS-II herbicides) diuron, hexazinone, atrazine, ametryn, tebuthiuron and simazine.

These pollutants are derived from anthropogenic land uses, mainly grazing, cropping and urban use.

Ongoing research has provided a clearer identification and quantification of the losses of suspended sediments, nutrients and pesticides from different land uses and land management practices, showing strong regional differences (as reported in Brodie and Waterhouse, 2009). There is a large difference in the pollutants of concern between wet and dry catchments within the GBR catchment area. Due to the wetter climates and presence of intensive agricultural land uses (sugarcane and horticulture) and their associated fertiliser and pesticide usage, the Wet Tropics and Mackay Whitsunday areas have been identified as regions of high nutrient and pesticide runoff concern (Furnas, 2003; Fabricius *et al.* 2005; Devantier *et al.* 2006; Brodie and Waterhouse, 2009). On the other hand, the significantly larger Fitzroy and Burdekin River catchments (each ~135,000 km²), dominated by unimproved savannah/woodland rangeland grazing, are identified as considerable contributors of suspended sediment to the GBR lagoon (Mitchell and Furnas, 2001; Furnas, 2003; O'Reagain *et al.* 2005; Bainbridge *et al.* 2006a, 2006b, 2007a; Packett, 2007; Packett *et al.* 2009; Waters and Packett, 2007; Brodie and Waterhouse, 2009).

The impact of these different contaminants has not been fully identified at a localised scale throughout the GBR catchment. These contaminants affect the marine environment (see for example, Fabricius 2011b) and also catchment waterways (see for example, Pearson *et al.* 2010a; Arthington and Pearson, 2007; Wallace *et al.* 2010a), including wetlands, creeks, mangroves and estuaries, however the impact in these areas is less understood. The current knowledge of water quality impacts on freshwater, estuarine and marine ecosystems is reviewed in the companion MTSRF synthesis reports 'Catchment to Reef Connections' (Devlin and Waterhouse, 2010), 'Water Quality Monitoring and Evaluation in the GBR' (Waterhouse, 2010a) and 'Pollutant Thresholds' (Waterhouse, 2010b).

The primary characteristics of the three categories of priority pollutants are described below. Much of this knowledge has been acquired through MTSRF-funded research.

Total suspended sediment (TSS)

Most sediment in the GBR catchment originates from grazing lands of the Burdekin, Fitzroy and Burnett Mary regions (Brodie and Waterhouse, 2009). The influence of land use on sediment loads is now well known at a regional scale. In the Dry Tropics, high suspended sediment concentrations in streams are associated with rangeland grazing and locally specific catchment characteristics (Dight, 2009), and overall sediment loads from the Dry Tropics catchments is high mainly due to large catchment areas. In the Wet Tropics, where sugarcane covers only a small proportion of catchment area (e.g. ~10% in the Tully catchment), stream and river sediment concentrations are low due to not only the small land

area contribution of sugarcane, but also improvements in sugarcane management practices such as green cane harvesting, trash blanketing and reduced tillage (e.g. Rayment, 2003; Faithful *et al.* 2005, 2006; Bainbridge *et al.* 2009b). Grazing area sediment fluxes in the Wet Tropics are comparatively lower than those of Dry Tropics regions due to high vegetation cover maintained throughout the year from high and year-round rainfall (e.g. Bainbridge *et al.* 2009b).

More work is required to identify sediment sources at finer scales due to variability associated with hillslope, streambank and gully erosion within individual catchments (e.g. Kuhnert *et al.* 2010), cover and gully density assumptions (Herr and Kuhnert, 2007; Dougall *et al.* 2006; Bartley *et al.* 2010) and particle size (Bainbridge *et al.* 2010). This can be progressed through additional ground-truthing studies, further model refinement and further investigation into potential management responses.

A second-order effect of human development is the loss of natural sediment trapping. This is due to land clearing and grazing, reduced vegetation complexity (e.g. forest to crops), loss of freshwater lagoons and loss of riparian vegetation (Arthington and Pearson, 2007; Pearson *et al.* 2010a, 2010b). It is estimated that over seventy percent of coastal wetlands in the GBR have been lost since the expansion of coastal cropping areas (Pearson *et al.* 2010b).

The impacts of increased suspended sediment in the marine environment are now well known, with considerable contributions from MTSRF-funded research, and are summarised here:

- Increased suspended sediment increases turbidity and results in reduced light availability for benthic communities (Fabricius, 2011b). Benthic irradiance is a crucial factor for reef corals. Light limitation, from increased turbidity for example, reduces photosynthesis, leading to slower calcification and thinner tissues (Anthony and Hoegh-Guldberg, 2003).
- Sedimentation reduces coral recruitment rates and coral biodiversity, with many sensitive species being under-represented or absent in sediment-exposed communities. High sedimentation rates are related to low abundances of corallines in coral reefs (Kendrick, 1991; Fabricius and De'ath, 2001).
- While adult corals can tolerate prolonged periods of low light, competition with macroalgae and moderate levels of sedimentation, settling coral larvae and the survivorship of newly settled young and small colonies is extremely sensitive to sedimentation (Fabricius, 2005). Very little settlement occurs on sediment-covered surfaces, and the tolerance of coral recruits to sediment is at least one order of magnitude lower than that of adult corals. Settlement of coral larvae is also controlled by light intensity and spectral composition; reduced light reduces the depth at which larvae settle (Baird *et al.* 2003).
- Octocorals (soft corals and sea fans) are passive suspension feeders and species richness declines by up to sixty percent along a gradient of increasing turbidity, due to the disappearance of zooxanthellate octocorals (Fabricius and De'ath, 2004).
- The most common cause of seagrass loss is the reduction of light availability. This may be from chronic and pulsed increases in suspended sediments and particles leading to increased turbidity (Schaffelke *et al.* 2005) or chronic increases in dissolved nutrients, which leads to proliferation of algae, thereby reducing the amount of light reaching the seagrass (e.g. phytoplankton, macroalgae or algal epiphytes on seagrass leaves and stems) (Waycott *et al.* 2005). In addition, changes of sediment characteristics may also play a critical role in seagrass loss (Mellors *et al.* 2005).
- The fine sediment fraction is considered to be the most important in the context of GBR ecosystem health because fine particles have many times greater collective surface area than coarser particles, which is important in the transport of pollutants (e.g. adsorbed

pesticides, trace metals and nutrients). Fine particles may also be carried considerable distances in the marine environment and are capable of producing higher turbidity levels in both freshwater and marine environments (Wolanski *et al.* 2008; Bainbridge *et al.* 2010).

Dissolved inorganic nitrogen (DIN) / particulate nitrogen (PN)

The predominant form of nitrogen being delivered to the GBR has changed as a result of anthropogenic influences. Discharge of nitrogen from natural landscapes is predominantly in the form of dissolved organic nitrogen (DON) (Harris, 2001; Brodie and Mitchell, 2005). This is still the case in undisturbed forest stream runoff in the GBR catchment area (Brodie and Mitchell, 2006). However, nitrogen discharge from agricultural and urban lands is now dominated by dissolved inorganic nitrogen (DIN = nitrate+nitrite+ammonium) derived from fertiliser and sewage wastes, and particulate nitrogen (PN) derived from soil erosion (Brodie and Mitchell, 2005). The shift from a predominantly DON discharge in pre-1850 times to a predominantly PN and DIN discharge in modern times has important consequences for the effects of discharged nitrogen (Fabricius, 2005). Nitrate has a higher risk as it is 'bioavailable' for in-stream uptake (e.g. weed growth) and for downstream uptake (e.g. promoting algae on inshore coral reefs). The question of whether nitrogen as either DIN or PN is of concern is regionally specific, and depends on predominant land use and other catchment characteristics.

Dissolved inorganic nitrogen (DIN) is therefore a priority pollutant of concern due to its bioavailability and prevalence as the primary form of nitrogen derived from fertiliser products. A strong relationship exists between the areas of nitrogen-fertilised land use in a catchment and the mean nitrate (assumed here as $\text{NO}_2 + \text{NO}_3 = \text{NO}_x$) concentration found during high flow conditions, implicating fertiliser residues as a major source of nitrate in the GBR system (Mitchell *et al.* 2009; Arthington and Pearson, 2007). Fertiliser application above plant requirements in sugarcane and bananas is indicated by elevated stream concentrations of nitrate (e.g. Rayment, 2003). Nitrate has only a small natural occurrence in north Queensland from pristine sources (Brodie and Mitchell, 2006), slightly more elevated levels from the lightly grazed Normanby River catchment (Furnas *et al.* 2006) but much higher concentrations from cropping and horticulture. Change in land use has also led to the increase in nitrate discharge in some individual catchments being much larger relative to the increase in total nitrogen discharge, for example, an estimated six times in the Johnstone River (Hunter and Walton, 2008) and ten times in the Tully River (Armour *et al.* 2009). The larger increases in the inorganic nitrogen fraction are associated with intensive fertiliser use on sugarcane and banana crops in these catchments.

The largest sources of particulate nitrogen (PN) to the GBR are from the Burdekin and Fitzroy regions (Brodie *et al.* 2009b) and are derived from natural nitrogen in soil. PN loads are now higher than pre-European times due to increased erosion in these regions as a result of land use practices. Increased PN is also likely where erosion of fertiliser enriched soils occurs. For example, in the Johnstone catchment it is estimated that PN increased ten-fold, compared to pre-European levels, during the 1960s (Prove *et al.* 1996). Since that time it is estimated that these levels have decreased due to improved farming practices (minimum till, trash blanketing).

The impacts of increased nitrogen in the marine environment are now well known. Downstream impacts of organic PN, and its bio-availability, are similar to those of DIN, however there is a time lag for its effects. PN is available to the same organisms as DIN, but for a longer time period. The primary impacts of these forms of nitrogen on GBR ecosystems are summarised below. Many of these have been explicated by MTSRF-funded research.

- Most studies show that high levels of DIN and phosphorus can cause significant physiological changes in corals, but do not kill or greatly harm individual coral colonies (reviewed in Fabricius, 2005). However, exposure to DIN can lead to declining calcification, higher concentrations of photo-pigments (affecting the energy and nutrient transfer between zooxanthellae and host; Marubini and Davies, 1996), and potentially higher rates of coral diseases (Bruno *et al.* 2003). In areas of nutrient upwelling or in heavily polluted locations, chronically elevated levels of dissolved inorganic nutrients may so alter the coral physiology and calcification as to cause noticeable changes in coral communities (Birkeland, 1997).
- The main way in which dissolved inorganic nutrients affects corals appears to be by enriching organic matter in the plankton and in sediments (Fabricius, 2011b).
- Macroalgae and heterotrophic filter-feeders benefit more from dissolved inorganic and particulate organic nutrients than do corals. As a result, corals that can grow at extremely low food concentrations may be out-competed by macroalgae and/or more heterotrophic communities that grow best in high nutrient environments (Fabricius, 2011b).
- More frequent outbreaks of crown-of-thorns starfish (COTS) are linked to high nutrient levels (Brodie *et al.* 2005; Houk *et al.* 2007). After primary COTS outbreaks have formed in a region with high phytoplankton concentrations, many of their numerous larvae may be transported by currents to remote regions, and thus secondary COTS outbreaks may form far away from areas of eutrophication.
- Densities of benthic filter feeders – such as sponges, bryozoans, bivalves, barnacles and ascidians – increase in response to nutrient enrichment (Smith *et al.* 1981; Costa Jr. *et al.* 2000). In high densities some filter feeders such as internal macro-bioeroders can substantially weaken the structure of coral reefs and increase their susceptibility to storm damage.
- Elevated tissue nutrient concentrations in the leaves of seagrasses are indicators of excessive nutrient loads (Dennison *et al.* 1993). The ratio of the major nutrients in seagrass tissues is indicative of the status of plant utilisation of available nutrients – when in excess, the plants are saturated and a tendency for the ecosystem to have excessive algal growth occurs (summarised in Waycott and McKenzie, 2010).
- The load of terrestrially-sourced DIN has been quantitatively linked to the upper thermal bleaching thresholds of symbiotic reef corals on inshore reefs on the GBR (Wooldridge, 2009).

Pesticides

Pesticide residues, especially herbicides, are widespread in waterbodies of the GBR region, including streams, wetlands, estuaries, coastal and reefal waters (e.g. Lewis *et al.* 2007b, 2009b; Packett *et al.* 2005; Rohde *et al.* 2006, 2008; Mitchell *et al.* 2005; Shaw *et al.* 2010; Davis *et al.* 2008; Bainbridge *et al.* 2009b). Residues commonly detected are the PS-II herbicides including atrazine, diuron, ametryn, hexazinone and tebuthiuron (Lewis *et al.* 2009b). These substances would not have been present at all before agricultural development of the catchments.

PS-II herbicides are a priority contaminant because they are residual herbicides, relatively soluble and mobile and hence have a higher propensity to reach the marine environment at detectable concentrations. They have a longer half life than many other herbicides and are widely used in agricultural practices throughout the GBR catchment. Concentrations in waterways are highest in areas of intensive agricultural activity, including sugarcane and grains, but also from grazing lands (tebuthiuron) (Packett *et al.* 2009).

Recent MTSRF-supported work on pesticide monitoring in paddocks, rivers and the marine environment has progressed our understanding of the extent and persistence of pesticides in freshwater and marine areas (Lewis *et al.* 2009b; Bainbridge *et al.* 2009b, Shaw *et al.* 2010). Concentrations of pesticides in rivers and streams are highest in areas of intensive agricultural activity, including sugarcane, but also from grazing lands (tebuthiuron) (Lewis *et al.* 2009b; Brodie and Waterhouse, 2009). Concentrations of pesticides in marine waters are likely to be highest off these rivers with intensive agriculture. This is supported by the data collected within the Reef Rescue Marine Monitoring Program (e.g. Paxman *et al.* 2009; Johnson *et al.* 2010).

Concentrations of pesticides are variable over time and space and thus it can be difficult to define the full impact of pesticide concentrations at any given sampling point. Complex transport mechanisms and variability within receiving waters can make it difficult to define the overall risk area within GBR waters. Work commenced by Lewis and others through the MTSRF in the definition and areal extent of risk and impact from pesticides is ongoing. A comprehensive review of the current understanding of pesticides on the GBR has been prepared by the Reef and Rainforest Research Centre as part of the MTSRF (Martin, 2010). The primary impacts of pesticides on GBR ecosystems are summarised below.

- Pesticides are all designed to negatively affect physiological processes through the disruption of biochemical pathways (Negri *et al.* 2005). A given mode of action is typically not specific to a target organism, and hence non-target organisms may be affected by the presence of pesticides. Low-level, chronic exposure to herbicides may exert subtle selective pressure on lower trophic levels due to their mode of action and species-specific differences in sensitivity, with potentially negative consequences for the resilience of the reef ecosystem. While the PS-II herbicides are capable of affecting marine plants directly, they may also impact upon animals such as corals by inhibiting photosynthesis in symbiotic microalgae (Jones and Kerswell, 2003).
- It has been difficult to ascribe measured marine impacts or changes to the increased concentrations of pesticides in GBR waters as the causal links between delivery and impact have not been identified with the marine area. However, laboratory work has also shown impacts of pesticides on reef ecosystems from a cellular to system change within coral, seagrass and algal communities. For example, a shift in the community structure of benthic biofilms was observed following exposure to environmentally relevant concentrations of diuron over a four-week period, resulting in enhanced tolerance to herbicides over time (Magnusson, 2009). These results strongly suggest that inter-specific differences in herbicide sensitivity may alter the primary productivity or other functional characteristics of tropical ecosystems.
- Coral bleaching has been demonstrated to occur following exposure to diuron concentrations of $10 \mu\text{g L}^{-1}$ and above (Jones *et al.* 2003; Negri *et al.* 2005; Cantin *et al.* 2007). Herbicides found in GBR waters have biological effects on coral zooxanthellae at concentrations below $1 \mu\text{g/L}$ (e.g. Jones and Kerswell, 2003; Jones *et al.* 2003; Jones, 2005; Negri *et al.* 2005; Markey *et al.* 2007; Cantin *et al.* 2007). The long-term effect on ecosystem performance of the continuous presence of such residues is not known, but evidence is emerging that some pesticides not only affect the photosynthesis of the endosymbionts but also coral reproduction (Jones, 2005; Negri *et al.* 2005; Markey *et al.* 2007; Cantin *et al.* 2007).
- Recent studies have shown that the combined effects of elevated temperature and reduced water quality (presence of herbicides) were detrimental to the coral *Acropora millepora* in exposure experiments and that the effects of elevated sea surface temperatures (SSTs) and herbicide on photosynthetic efficiency of coral symbionts are additive (Negri *et al.* 2011).

- Herbicides (principally diuron) have been found in coastal and intertidal seagrasses adjacent to catchments with high agricultural use at levels shown to adversely affect seagrass productivity (McMahon *et al.* 2005; Haynes *et al.* 2000). For example, diuron toxicity trials on three tropical seagrass species (*Halophila ovalis*, *Cymodocea serrulata* and *Zostera capricorni*) using Pulse-Amplitude-Modulated (PAM) fluorometry indicated that environmentally relevant levels of diuron (0.1-1.0 µg/l) exhibited some degree of toxicity to one or more of the tested seagrass species (Haynes *et al.* 2000).

3. Priority pollutant loads

3.1 Methods to calculate priority pollutant loads

As estimates of pollutant loads and the detection of an appropriate reduction are major components of the Reef Plan and Reef Rescue targets, it has been an important outcome of the MTSRF to improve our ability to estimate contaminant loading into the GBR (e.g. Lewis *et al.* 2007a; Kuhnert *et al.* 2009; Kuhnert and Henderson, 2010). The selection of a load method is strongly dependent on the concentration/stream flow data available, the hydrological characteristics of the waterway and the desired accuracy required. Load methods (and software programs) have been rigorously assessed over different catchment areas and sampling regimes to understand the optimal sampling intervals and the best available method that will provide the desired accuracy and precision. This work was initially progressed by the CSIRO (e.g. Venables and Harch, 2006), ACTFR (Lewis *et al.* 2007a) and Queensland Government agencies (Marsh *et al.* 2006) with continuing efforts by the CSIRO (Kuhnert and others). The findings of these studies are summarised below.

Lewis and others (2007a) tested a number of load estimation techniques on the same datasets from the Burdekin River, found wide differences in the estimated loads from different algorithms and made recommendations as to which was the best to use in different circumstances.

All software programs provided suitable load methods for the catchments of the GBR (where continuous data were available). At the time of the study, the GUMLEAF program could not be used at smaller catchment scales. The optimal methods were:

- a) *Brolga*: Linear interpolation;
- b) *Loads Tool*: Linear interpolation, inter sample mean concentration, inter sample mean concentration using mean flow; and
- c) *GUMLEAF*: Flow regime stratified flow weighted mean concentration estimator (method # 19), flow regime stratified simple ratio estimator (method # 20), flow regime stratified Kendall's Ratio estimator (method # 21) and flow regime stratified Beale's Ratio estimator (method # 22).

The minimum sampling frequencies recommended for the different catchment areas were:

- a) *Paddock scale*: Six samples evenly spaced over the hydrograph (at least two on rising limb);
- b) *Sub-catchment scale*: Daily sampling (although for catchments with very high material concentrations on the rising limb such as the Bowen, 4-5 samples per day may be required); and
- c) *End-of-catchment scale*: One sample collected every two days.

The practical aspects of this study provided valuable information for the design of event load monitoring programs in the GBR catchment in terms of guiding sampling frequency. While it also provided basic guidance on the selection of a suitable load method for specific catchments, the methods do not adequately address all aspects of uncertainty which can be useful for informing future monitoring activities and reporting on the status of trends in loads (Kuhnert *et al.* 2009), highlighting the need for further investigation of the quantification of uncertainties in load calculation techniques. Subsequently, Kuhnert and others have progressed investigations to quantify the uncertainty in loads; an overview of this work is provided in the companion MTSRF synthesis report, 'Water Quality Monitoring and Evaluation in the GBR' by Waterhouse (2010), with highlights included below.

Kuhnert and others (Kuhnert *et al.* 2009; Kuhnert and Henderson, 2010) have developed and demonstrated a regression approach through simulation and application that appears to be flexible enough for predicting concentration and calculating a load for a range of datasets with varying flow and concentration characteristics. For the Tully and Burdekin Rivers different regression models were used to calculate loads. Depending on the relationship between flow and concentration and the nature of the sampling undertaken, it was possible to calculate a confidence level for the load estimation (Kuhnert *et al.* 2009). This approach offers a statistically robust approach to load estimates (Table 3.1).

Table 3.1: Steps in the estimates of loads using the statistical approach outlined in Kuhnert *et al.* (2009).

Step	Process
1. Estimation steps for flow	Prediction of flow at regular time intervals using a time series model such that the model captures all of the peak flows. The predicted flow is then matched to concentration sampling times and used only when flow was not collected at that specific time interval.
2. Estimation steps for concentration	Prediction of concentration using a generalised additive model (GAM) that incorporates all important covariates in an attempt to capture the underlying hydrological processes concerned with the flow and transportation of sediment and nutrient loads in an attempt to account for knowledge uncertainty.
3. Estimation of the load	An estimate of the load in the third step using the predicted concentration and predicted flow and incorporating a unit-conversion constant for time interval used.
4. Calculation of the standard error of the load	Standard errors are computed incorporating both measurement error and errors due to the spatial location of sampling sites.

A number of different stages of flow have also been identified which show that the characteristics of the flow event are important in the estimation of load measurements. The generalised rating curve approach is novel as it seeks to represent a number of important system processes for GBR catchments to account for expected or implied system behaviours:

- First Flush, the first significant channelised flow in a water year accompanied by high concentrations (represented as a percentile of flow and used in the calculation of other system processes).
- Rising/Falling Limb, which allows higher or lower concentrations on the rising limb when runoff energies are higher and sediment supply may also be high. This is usually represented at shorter time scales than *exhaustion*, which is parameterised for between-event variations. This covariate is based on the first flush defined for that period.
- Exhaustion, representing the limited supply of sediments and nutrients due to previous events (represented by a discounted flow term).
- Hysteresis, representing complex interactions between flow and concentration with strong historical effects and dependence captured by non-linear terms for flow, and incorporating hydrological processes.
- Overbank Flow, described as flow that goes over bank in flood events, which is not well recorded by standard river gauges. This was recently investigated by Wallace and others (2010b) and has not yet been implemented into the statistical model.

Other regionally specific improvements in load estimations have also been delivered through the MTSRF. For example, hydrological modelling by Wallace, Karim and others (e.g. Wallace

et al. 2008a, 2008b, 2009, 2010b; Karim *et al.* 2010a, 2010b) has identified the importance of overbank flow in pollutant delivery to the GBR. Assessment of the trapping efficiency of the Burdekin Dam by Lewis and others (e.g. Lewis *et al.* 2009a) has highlighted the need to understand the impact of manmade structures such as dams on the resultant load calculations.

Further work by Brodie and others (e.g. Brodie *et al.* 2009b, 2009c; Kroon *et al.* 2010) has incorporated a number of the advancements outlined in this section to present 'best estimates' of pollutant loads for each of the GBR catchments. Integration of these sources, plus a number of regionally based measurements and published literature, has permitted catchment risk relative to anthropogenic load, potential exposure and ecosystem status to be ranked (Brodie and Waterhouse, 2009). This information has fed directly into the implementation of the Reef Protection Package introduced by the Queensland Government in 2009. The specific findings of these studies are presented in the following sections.

3.2 Current estimates of priority pollutant loads

Current estimates of the end-of-catchment load for each priority pollutant have recently been determined with support from the MTSRF (Brodie *et al.* 2009b). The study collated available load data for the 33 major river basins discharging to the GBR and calculated the best estimate of the current end-of-catchment loads for the following parameters: suspended sediment, dissolved inorganic nitrogen, dissolved organic nitrogen, particulate nitrogen, dissolved inorganic phosphorus (filterable reactive phosphorus), dissolved organic phosphorus and herbicides. A summary of the results from this study showing best estimates of pollutant loads discharged to the GBR and the modelled 'natural' loads (sourced from Brodie *et al.* 2003) is provided in Table 3.2. Estimates of pollutant loads for each land use in each catchment are also presented in the report and are discussed further in Section 4.

The best estimates of current end-of-catchment load for each sediment and nutrient parameter were derived from the available data using a hierarchical decision system using the following four criteria.

- I. For rivers with greater than ten years' monitoring data (for example, the Burdekin, Fitzroy and Tully Rivers) the best estimate was the flow weighted (adjusted to the Mean Annual Flow) mean annual load, calculated using linear interpolation. The main sources of long term monitoring data were Furnas (2003), Packett *et al.* (2009) and Bainbridge *et al.* (2007a, 2008).
- II. For rivers with a recent individual catchment model run (i.e. Johnstone, Herbert, Proserpine, O'Connell, Pioneer, Plane and Burnett) and short term (3-9 years) monitoring data, the best estimate was based on the modelled result, rounded towards the monitoring data if there were differences.
- III. For rivers where the most recent modelling runs were the overall GBR Short Term Modelling Project (STM; Cogle *et al.* 2006) and there was limited monitoring data, the best estimate was based on the STM result or Brodie *et al.* (2003) for those catchments where STM results were not available, and rounded towards the monitoring data.
- IV. For rivers with no available STM estimate and no available monitoring data, the best estimate was based on Furnas (2003) and Brodie *et al.* (2003). Where there was difference between the results a mean of the two estimates was used.

As there was no comprehensive modelling of herbicide loads at the time of this study, and limited monitoring data for only a few GBR rivers, the herbicide load estimates were derived from a simple model developed by Maughan, Brodie and Waterhouse to provide loads for the GBR Reef Exposure Model (Maughan *et al.* 2008). In the analysis, the total herbicide load was assumed to consist of atrazine, ametryn, hexazinone, simazine, tebuthiuron and diuron,

and called 'Total PS-II Herbicides', as all six herbicides work in a similar way by suppressing photosynthesis. Maughan *et al.* (2008) used available pesticide study data from the Pioneer, Barratta and Haughton Rivers to predict the load and eventual concentration of herbicides in other GBR catchments. For each of the known loads, the land area of sugar and cotton in that catchment was determined, and the loss per hectare calculated. The herbicide-using land area for other GBR river catchments was then calculated and used to estimate the presumed loss per river basin. A flaw in this model is that several land uses which are now known to leak PS-II herbicides, particularly grazing for tebuthiuron, forestry for simazine, crops other than sugarcane and cotton and urban centres, were not included in the analysis. A more robust model is being developed by Lewis and others to overcome these deficiencies.

For each best estimate of the end-of-catchment load, estimated confidence was also defined on a scale of 1 (Low) to 5 (High). Confidence is based on the criteria hierarchy outlined above, where rivers that meet criteria I were given high confidence (4 or 5), rivers that meet criteria II and III are given moderate confidence (2 or 3), and rivers that meet criteria IV are given low confidence (1). Very few estimates received high confidence. These confidence ratings, and a summary of the justification for each best estimate, are included in Brodie *et al.* (2009b).

There are a number of limitations to this study documented in Brodie *et al.* (2009b), including:

- Several limitations in the load estimates developed in Brodie *et al.* (2003) due to limitations in the SedNet model, including underestimation of DIP loads when compared to monitoring data due to the poor soil analysis data input to the SedNet model (Sherman *et al.* 2007); uncertainty in estimates from closed forests due to poor modelling of erosion in these areas; and assumptions in the SedNet model that pre-European conditions had natural vegetation cover, no gullies, and no agriculture or urban development, which may lead to large error margins resulting in negative values when calculating anthropogenic loads.
- The PS-II herbicide loads derived from Maughan *et al.* (2008) were based on only two land use types, sugarcane and cotton, and did not include other land uses such as forestry, grazing, other cropping and urban. As a result, some herbicides associated with these land uses are not included in the calculations and the total loads are likely to be an underestimate. This has since been improved through the work of Lewis and others and is described below.
- A significant limitation of the data used – both modelling and monitoring – is that many studies do not include the whole catchment source area and, as a result, large components of the total load may be overlooked. The problem of excluding near-coastal areas is much larger for monitoring than for modelling load estimates. Modelling generally extends to the river mouth at the coastline. In contrast, monitoring generally occurs upstream from the coast in suitable confined river locations to capture large flood events. The main limitation of monitoring is that there may be significant cropping areas downstream of the monitoring point, and modelling excludes only small coastal floodplain areas which have catchment areas smaller than the modelling threshold. However, modelling to date does not represent enhanced sub-surface drainage directly from paddock to coast, or enhanced drainage caused by irrigation, where these phenomena occur. Therefore, modelling could be considered a superior method than monitoring to represent loads from near-coastal areas. Improved modelling could represent small near-coastal areas and sub-surface drainage better where there are supporting data.

Several of these limitations have been addressed in the refinement of the pollutant loads recently completed in a collaborative project led by the CSIRO (Kroon *et al.* 2010) with input from MTSRF-funded researchers (Brodie, Wallace, Kuhnert and Henderson). To estimate

the baseline pollutant loads, the following three steps were used. First, published and available catchment modelling and other information on natural and total pollutant loads was collated and reviewed for each individual basin (largely based on Brodie *et al.* 2009b). Second, catchment water quality and flow information was collated and assessed (largely based on Brodie *et al.* 2009b), and used to estimate total pollutant loads with uncertainty bounds using the loads regression estimator (Kuhnert *et al.* 2009; Wang *et al.* 2009). Finally, baseline (i.e. anthropogenic) pollutant loads were estimated for each individual basin, based on the best available estimates of total and natural pollutant loads from the first two steps. These baseline pollutant loads provide estimates to monitor and evaluate progress against Reef Plan pollutant load targets and goals for 2013 and 2020.

In addition, Lewis and others (see Brodie *et al.* 2009c) have since established an improved method to estimate end-of-catchment pesticide loads for the GBR which incorporates a range of land uses and types of herbicides, resulting in considerable differences (increases) in the estimated PS-II herbicide loads for the GBR catchments. Runoff coefficients were established for the six key herbicides designed to inhibit photosystem II in plants and commonly detected in the GBR lagoon, including diuron, atrazine, hexazinone, ametryn, simazine and tebuthiuron (Brodie *et al.* 2009c). These coefficients were developed based on the loads calculated for the Haughton River, Barratta Creek, Pioneer River, Sandy Creek, O'Connell River and Fitzroy River and published in Lewis *et al.* (2009b) and Packett *et al.* (2009). The event mean concentrations (EMC) were calculated from these loads and an average EMC for each stream was calculated where multiple years were monitored. The 'average load' was then calculated using the 'average discharge' from each of the monitored streams determined by a SedNet model run (Brodie *et al.* 2003). The upstream land use (in hectares, using 1999 Queensland land use mapping data for the sampled point of each stream) was then established and major land uses included: forest, grazing, sugar, other crops and *other* (includes urban, water storages, etc.). The average herbicide runoff (kg/ha) was then calculated for sugar areas assuming that all loads of diuron, atrazine, hexazinone and ametryn from the Haughton River, Barratta Creek, Pioneer River, Sandy Creek and O'Connell River are derived from the sugar industry. This assumption is reasonable given that, (1) sugar is the predominant industry within these regions; and (2) these herbicides are widely used in sugar cultivation and studies have shown a direct relationship between sugar crop area and the concentration of these herbicides in streams (e.g. Bainbridge *et al.* 2009b; Lewis *et al.* 2009b).

The mean of the runoff coefficients for each stream was then taken to produce an average coefficient for sugar areas in the GBR catchments; this coefficient was then used to estimate the loads of these herbicides. Similarly, runoff coefficients for atrazine, diuron and simazine in cropping areas were generated using the load data from the Fitzroy River and assuming that these herbicides in this river are only derived from cropping area lands. This coefficient was then applied to the 'other crops' land use to estimate atrazine, diuron and simazine loads. Since tebuthiuron is typically only sourced to the grazing industry, a runoff coefficient for tebuthiuron in grazing lands was developed using the mean kilogram per hectare load data from the Fitzroy River, Haughton River and O'Connell River. As there were considerable differences in the individual kilogram per hectare calculations between the Fitzroy River and the Haughton and O'Connell Rivers, the calculation for the Fitzroy River was used exclusively for dryland grazing lands (including the Burdekin and Fitzroy Rivers). The tebuthiuron grazing coefficient was only applied for the catchments where it had been detected in either grab or passive samples.

These methods have been applied in establishing the baseline pesticide loads for the GBR catchments as part of the Paddock to Reef Program (Kroon *et al.* 2010), in guiding investment through the Reef Rescue Program and in the development of priority areas for the introduction of regulations for agricultural areas in Queensland (Brodie and Waterhouse, 2009; Brodie *et al.* 2009c).

Table 3.2: Summary of the current best estimates of priority pollutant loads and the modelled 'natural' loads discharged to the GBR. Source: Brodie *et al.* (2009b).

ID	Name	DIN natural	DIN current	DON natural	DON current	PN natural	PN current	DIP natural	DIP current	PP natural	PP current	DOP natural	DOP current	TSS natural	TSS current	Total PS-II nat	Total PS-II cur
	Unit	tonnes per year												'000 tonnes per year		kg per year	
1	Jacky Jacky Creek	133	250	149	200	10	400	12	10	14	60	14	10	17	100	0	0
2	Olive-Pascoe Rivers	236	500	268	400	27	1,000	10	10	38	200	25	20	57	330	0	0
3	Lockhart River	85	200	167	200	8	300	5	6	14	70	13	10	28	150	0	0
4	Stewart River	69	150	85	120	7	200	3	3	10	40	8	10	22	110	0	0
5	Normanby River	517	900	544	800	85	2,000	10	20	72	400	53	50	184	1,100	0	0
6	Jeannie River	122	250	140	150	23	500	5	6	19	70	13	10	66	240	0	0
7	Endeavour River	119	250	186	250	18	500	3	5	23	100	16	10	70	370	0	0
8	Daintree River	123	200	426	250	22	300	9	10	25	80	29	15	45	240	0	20
9	Mossman River	17	50	46	50	4	100	1	2	3	20	3	5	7	80	0	70
10	Barron River	59	200	152	150	13	150	3	5	12	40	11	25	25	100	0	180
11	Mulgrave-Russell Rivers	166	1,000	566	500	23	700	14	20	32	250	38	50	41	210	0	260
12	Johnstone River	243	850	825	400	26	1,000	26	20	38	300	56	60	41	260	0	440
13	Tully River	172	600	523	250	14	450	17	20	25	90	36	15	24	120	0	250
14	Murray River (QLD)	72	300	158	150	4	170	8	10	8	40	12	8	9	50	0	170
16	Herbert River	257	700	442	500	47	700	10	20	47	200	36	30	107	540	0	450
17	Black River	26	60	43	50	8	300	1	5	6	70	4	3	30	180	0	10
18	Ross River	16	70	17	50	6	200	0	8	3	50	2	4	20	190	0	0
19	Haughton River	42	150	42	100	7	400	2	15	6	120	4	7	29	200	0	400

Waterhouse and Brodie

ID	Name	DIN natural	DIN current	DON natural	DON current	PN natural	PN current	DIP natural	DIP current	PP natural	PP current	DOP natural	DOP current	TSS natural	TSS current	Total PS-II nat	Total PS-II cur
	Unit	tonnes per year												'000 tonnes per year		kg per year	
20	Burdekin River	979	1,300	1,020	1,800	165	9,000	16	180	165	1,800	100	50	478	4,600	0	100
21	Don River	33	60	33	100	9	500	1	10	6	150	3	6	39	590	0	0
22	Proserpine River	83	450	111	160	9	200	4	50	19	50	10	10	45	50	0	1,000
39	O'Connell River	125	700	152	250	18	400	4	50	31	150	14	15	99	150	0	250
40	Pioneer River	84	600	111	120	10	800	2	100	22	300	10	50	50	280	0	1,500
24	Plane Creek	95	250	103	200	11	200	4	50	20	100	10	15	54	60	0	800
25	Styx River	23	50	24	150	5	600	1	20	5	200	2	10	25	250	0	0
41	Shoalwater Creek	41	50	41	150	5	500	1	20	7	150	4	10	22	100	0	0
26	Waterpark Creek	41	80	41	130	4	400	3	20	6	100	4	10	10	100	0	0
27	Fitzroy River (QLD)	607	1,500	634	2,500	70	8,000	7	300	75	3,000	62	70	275	3,400	0	1,200
29	Calliope River	20	50	21	50	5	300	0	5	4	100	2	3	20	200	0	0
30	Boyne River	38	70	39	30	13	120	1	5	9	30	4	3	41	50	0	0
31	Baffle Creek	96	150	97	150	10	500	4	10	14	120	10	8	35	300	0	20
32	Kolan River	48	100	49	50	7	200	1	10	8	40	5	4	22	100	0	100
33	Burnett River	175	400	191	300	30	1,000	3	35	29	300	18	50	99	200	0	300
34	Burrum River	61	150	69	100	3	250	6	10	7	70	6	6	9	100	0	400
35	Mary River (Qld)	280	450	314	400	33	1,000	9	50	53	300	30	25	98	1,200	0	150
Total		5,303	13,090	7,829	11,210	759	33,340	206	1,120	875	9,160	667	687	2,243	16,300	0	8,070

4. Identification of priority areas for management

In a project funded by the Queensland Government (DERM) and supported by the MTSRF, Brodie and others (2009c) demonstrated that it is possible with current data to identify 'hot spots' of pollutant delivery to the GBR with a reasonable degree of certainty, and so facilitating management prioritisation. The MTSRF-funded research described in the previous sections of this report provided the primary input data to this assessment. This section provides an overview of two recent studies supported by the MTSRF that identified priority pollutants and priority areas for management within the regions, and permitted a relative risk assessment of priority pollutants across the regions of the GBR.

4.1 Regional assessment of pollutant loads

As part of the development of the Reef Protection Package, the DERM required the best available information on the priority pollutants and priority areas for the GBR catchment with respect to management of broadscale agriculture to help direct management activities to basins and pollutants of most concern. This task was completed by Brodie and others for the Department with support of the MTSRF in July 2009. The outcomes of the study are summarised below and are detailed in Brodie *et al.* (2009c).

In consideration of the risks from anthropogenic loading of runoff into GBR waters, various measures of current and anthropogenic exports of suspended sediments, dissolved inorganic nitrogen and PS-II herbicides were compared for the river-creek basins from the Daintree basin south to the Calliope basin. These three key categories of pollutants were considered to be the most important pollutants derived from anthropogenic land uses, mainly cropping and grazing, that may pose threats to the quality of runoff water entering the GBR ecosystem. Note that some statements have also been added about particulate nitrogen where new information has become available since the study was completed.

The approach used to complete the study was based on a series of questions within each region for each of the priority pollutants:

Suspended sediment

- Which basin of the region delivers the most suspended sediment (current) on an annual basis to the GBR?
- Which basin of the region delivers the most anthropogenic suspended sediment on an annual basis to the GBR?
- Within the basins, which land use contributes the majority of the suspended sediment?
- Within all of the basins what is the erosion type that generates the most suspended sediment?

Dissolved inorganic nitrogen

- Which basin of the region delivers the most DIN on an annual basis to the GBR?
- Within the basins, which land use contributes the majority of the DIN?
- Within the primary source land use, which basins deliver the most DIN per hectare?

PS-II herbicides

- Which basins of the region deliver the most herbicides on an annual basis to the GBR?
- What kind of herbicide is delivered from which basins?

Hence, within each region, the measures and major contributing factors estimated for each basin are shown in Table 4.1.

Table 4.1: Measures and major contributing factors for the risk assessment. Source: Brodie *et al.* (2009c).

Pollutant	Measure	Most relevant land use	Dominant erosion
TSS	Current load Anthropogenic load Current load per area Anthropogenic load per area	Grazing	Hillslope Gully Bank
DIN	Current load Anthropogenic load Current load per area Anthropogenic load per area	Sugarcane	
Herbicides	Current load Current load per area	Sugarcane and/or grazing and other crops	

The study did not include the rivers in the Cape York and Burnett Mary NRM regions, and it should be highlighted that the conclusions are relevant to each region only and do not include a cross regional comparison.

There were some differences in the assessment processes used for each region due to differences in data availability and catchment geographic characteristics. In particular, the assessment approach in the Wet Tropics and Mackay Whitsunday is not the same as the Burdekin and Fitzroy assessments, since the latter regions are mostly one large catchment with large basins all dominated by grazing. In the Wet Tropics and Mackay Whitsunday, there are individual major basins and the dominant land use for water quality purposes is sugarcane. In some cases, the basin consisted of one catchment or sub-catchment, while in other cases the basin is an aggregation of several catchments or sub-catchments.

Major land uses which potentially contribute to GBR water quality issues were included in the study, including 'forest', 'grazing', 'sugarcane', 'other crops' and 'other' (e.g. urban, water bodies). The fact that specific land uses such as urban, dairy or grains and their incorporation into categories such as 'other' or 'other crops' are absent as a specific discussion point under any section does not mean that they do not have a contributory effect, but does mean that the contribution is known to be small at a GBR-wide scale as is the case for dairy, or only important in one region, such as grains in the Fitzroy. Land use contributions were based on the calculations presented in Brodie *et al.* (2003) and then these proportions were applied to the revised load estimates to provide an updated load estimate for each land use.

All loads were an estimate of average annual loads, generally averaged over the last twenty years. This is complicated by the difference in approaches used in modelling and monitoring; modelled data is generally based on much longer time frames compared to monitoring data, which is only available for less than ten years in most cases. Current load was based on the current best estimates, mostly derived from Brodie *et al.* (2009b), Brodie *et al.* (2003) and recent WQIP reports. Natural load was estimated mostly from Brodie *et al.* (2003) or specific estimates for DIN as explained below. The approach for calculating anthropogenic load for each parameter is outlined below.

- **Suspended sediment (SS):** The anthropogenic loads of suspended sediment for major basins are derived from Brodie *et al.* (2009b). The natural loads for the sub-catchment of the Burdekin referred to here as basins (e.g. Lower Burdekin) were calculated using a proportional allocation, i.e. using the same proportion of natural:current (~1:10) for the Burdekin basin as a whole.
- **Dissolved inorganic nitrogen (DIN):** The anthropogenic loads of DIN for major basins are derived from Brodie *et al.* (2009b). The anthropogenic load for land uses was based on assumptions about natural dynamics of nutrient generation in natural areas and grazing lands. The assumption is that no anthropogenic DIN is generated in these land uses. For sugarcane, other crops and other land uses, the natural DIN load is calculated from a natural DIN generation rate, derived from current regional natural DIN generation, multiplied by the land use area. Examples of these calculations are provided in grey text boxes within the report.

Because different techniques were used to estimate anthropogenic loads in different parts of the report, i.e. anthropogenic load by basin (Brodie *et al.* 2009b), and then anthropogenic load by land use, the total anthropogenic load for the region by the sum of the basins and the sum of the land use contributions may not match. The differences are partly because in Brodie *et al.* (2009b), the natural loads are ultimately derived from Brodie *et al.* (2003) where it was assumed that grazed savannah generated more DIN than ungrazed savannah. The current understanding however is that there is no documented difference in DIN generation rate between grazed and ungrazed savannah, and that is the assumption in the DIN land use contributions in this report.

- **PS-II herbicides:** The natural load is zero; hence the current load is all anthropogenic. There is no comprehensive modelling of herbicide loads and limited monitoring data exist for only a few GBR rivers, thus the herbicide load estimates are derived from a simple model initially developed by Maughan, Brodie and Waterhouse (Maughan *et al.* 2008) and subsequently extended by Lewis (unpub.).

In the analysis, the total herbicide load is assumed to consist of atrazine, ametryn, hexazinone, simazine, tebuthiuron and diuron, and called 'Total PS-II Herbicides', as all six herbicides work in a similar way by suppressing photosynthesis. Lewis used available pesticide study data from the Pioneer, Barratta, Haughton, Sandy, O'Connell and Fitzroy Rivers to predict the load and eventual concentration of herbicides in other GBR catchments. For each of the known loads, the land area of sugarcane, dryland cropping and dryland grazing was determined, and the loss per hectare calculated. The herbicide load using land area for other GBR river catchments was then calculated and used to estimate the presumed loss per river basin.

All herbicide loading is related to human activities with:

- Tebuthiuron associated with grazing land management; and
- Other PS-II herbicides, which include diuron, atrazine, ametryn and hexazinone, associated with sugarcane cultivation and, to a lesser extent, grains; the sources of simazine are not well known at this stage. Atrazine also comes from dryland cropping but mostly from the headwaters of the Burdekin and Fitzroy Rivers.

The highlights from the study from each region are summarised below.

Wet Tropics region

The basins for the Wet Tropics region in the study are shown in Figure 4.1 with the basin boundaries for the Wet Tropics as defined in Brodie *et al.* (2003).

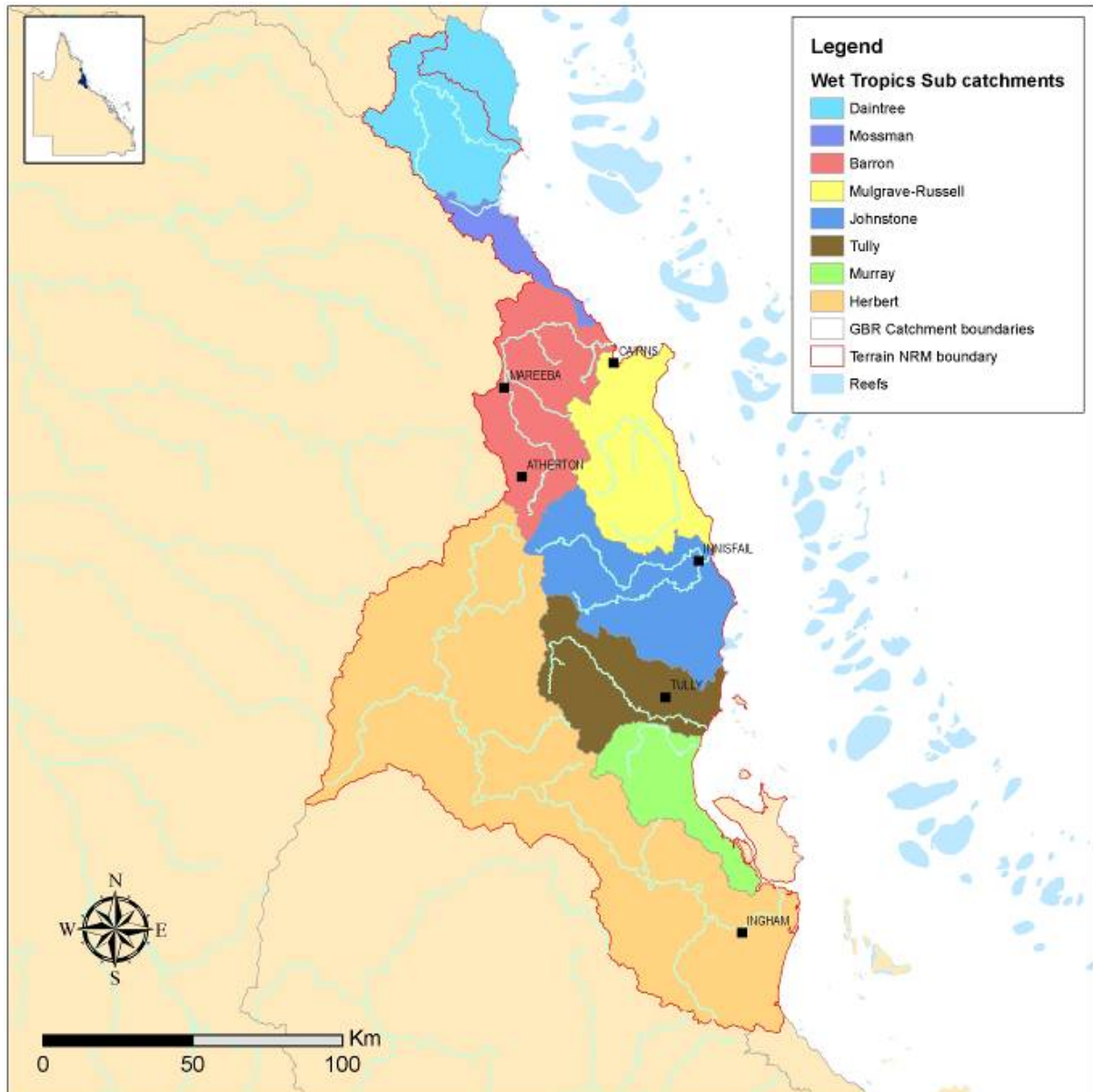


Figure 4.1: Basins in the Wet Tropics region. Source: Brodie *et al.* (2009c).

It is important to note that the Trinity Inlet drainage area is included in the Russell Mulgrave basin and not the Barron basin. This area contains large areas of sugarcane. This differs from the Barron WQIP boundary but is consistent with the Australian Water Resource Commission basin boundaries (utilised by DERM for river gauging).

Dissolved inorganic nitrogen (DIN) / Particulate nitrogen (PN)

- The Russell Mulgrave basin generates the most total DIN on an annual basis, followed by the Johnstone, Herbert and Tully basins.
- The key contributing land use to DIN loads is sugarcane and associated fertiliser application.
- The largest proportion of total anthropogenic DIN load from sugarcane is from the Johnstone basin, with high contributions also from the Russell Mulgrave, Herbert, Tully and Murray basins.
- In terms of DIN load from sugarcane per unit area of sugarcane cultivation, the highest loads per unit area are from the Russell Mulgrave, Tully, Murray and Johnstone basins.
- In the Wet Tropics region it is estimated that the source of DIN is approximately 75% sugar and 5% bananas, 12% grazing and forest, and 8% other crops / dairy and urban.
- PN is likely to be a priority in grazing lands in the upper Herbert basin and poorly managed non-sugar cropping lands in the Atherton and Evelyn Tablelands (Brodie, pers. comm.).

PS-II herbicides

- The Herbert basin delivers the greatest load of PS-II herbicide followed by the Johnstone, Russell Mulgrave and Tully basins. The loads from remaining basins are comparatively lower.
- The greatest proportion of PS-II herbicides is generated from sugarcane areas in all Wet Tropics basins.
- Diuron is the PS-II herbicide discharged in the highest amounts from the region, followed by atrazine and hexazinone. The Herbert, Russell Mulgrave, Johnstone and Tully basins deliver substantial exports of diuron.
- It is believed that tebuthiuron is derived from grazing but there is little monitoring data for tebuthiuron in the Wet Tropics and all conclusions about tebuthiuron need to be treated with caution. The other PS-II herbicides are known to be derived from sugarcane with high certainty (with the exception of simazine). The sources of simazine are not widely known but it is known to be used in plantation forestry.

Total suspended sediment (TSS)

- Generally TSS contamination is no longer seen to be a major issue in the Wet Tropics region (Drewry *et al.* 2008). This is largely due to improved management practices in sugarcane (e.g. minimum tillage and green cane harvesting) and, to some extent, grazing in the region over the last twenty years (Rayment, 2003).
- The Herbert basin generates the most current and anthropogenic suspended sediment load on an annual basis, followed by the Johnstone, Daintree and Russell Mulgrave basins. However, the Mossman basin generates the most suspended sediment per basin area on an annual basis, followed by the Russell Mulgrave, Daintree and Johnstone basins.
- The greatest anthropogenic load of suspended sediment to the GBR per unit area of land use is from sugarcane in most Wet Tropics basins (except the Murray, where 'other crops' are higher). Grazing is also an important bulk source in the Herbert, Daintree and Mossman basins.
- Loading reductions of suspended sediment could be achieved through managing hillslope erosion across the region.

Burdekin region

The Burdekin region consists of one large catchment and three smaller coastal basins (Cape, Suttor and Belyando). The Burdekin catchment is divided into seven basins as shown in Figure 4.2.

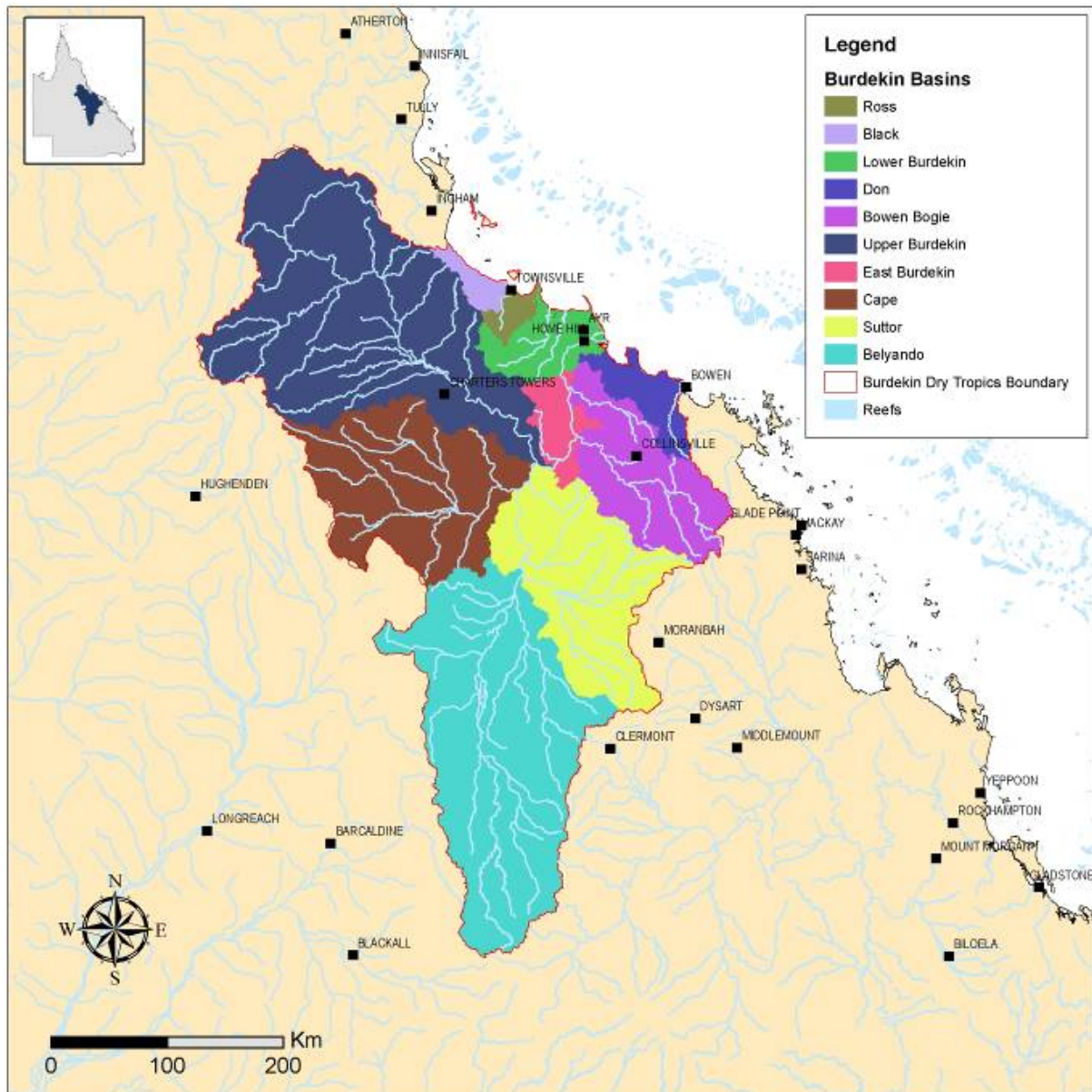


Figure 4.2: Basins in the Burdekin region. Source: Brodie *et al.* (2009c).

Total suspended sediment (TSS)

- The overall suspended sediment load to the GBR from the Bowen-Bogie basin is the highest in the region, partly due to the trapping in the Burdekin Falls Dam of sediment derived from above catchments, followed by the Upper Burdekin basin and the Don basin.

- Hillslope erosion across the region contributes the most suspended sediments in comparison to other erosion types like bank or gully erosion (refer to limitations to TSS calculations discussed above).
- The key land use requiring management of suspended sediment is grazing.

Dissolved inorganic nitrogen (DIN) / Particulate nitrogen (PN)

- The total DIN load to the GBR from the Lower Burdekin basin is the highest in the region. The other coastal basins in the Burdekin Region also contribute minor anthropogenic DIN loadings but in total are substantially less than that of the Lower Burdekin basin.
- The key contributing land use to DIN delivery to the GBR is sugarcane and associated fertiliser application.
- In the Burdekin region it is estimated that the overall total annual load estimate of DIN delivery to the GBR is 4,480 t (Brodie and Bainbridge, 2008). Surface and sub-surface annual losses are estimated to be 3,000 t (2,000 t and 1,000 t loss to GBR waters by surface and groundwater pathways respectively) in the Lower Burdekin sugarcane area and 1,480 t from the rest of the catchment. It is assumed that the majority of the DIN generated by sugarcane production is within the Lower Burdekin, therefore contributing approximately 67% (3,000 t / 4,480 t) of the overall DIN load. The estimated contribution from grazing to the regional DIN load has been reduced substantially from previous estimates of approximately 80% to 18% to account for the above findings related to sugar (Kroon *et al.* 2010). The remaining contributions are likely to be derived from forest (12% – Brodie *et al.* 2003) and other land uses including urban and other crops (3%) (not including point source sewage discharges of DIN from Townsville).

PS-II herbicides

- The Lower Burdekin basin delivers most PS-II herbicides to the GBR from the Burdekin region.
- The overall load of tebuthiuron to the GBR is estimated to be highest from the Belyando, Cape and Suttor basins, whilst the largest contribution of other PS-II herbicides is in the Lower Burdekin basin. The confidence in the load estimates for the Cape, Belyando and Bowen Bogie basins, where tebuthiuron has only been detected in a limited number of samples, is considered low. As tebuthiuron has never been detected in the Upper, East Burdekin, Don, Black and Ross basins the load has been given as 0.
- The PS-II herbicides delivered from basins in the region are believed to be from two land uses: sugarcane is the primary source of PS-II herbicides other than tebuthiuron (mainly diuron but also atrazine, ametryn, hexazinone). The sources of simazine are not widely known but it is known to be used in plantation forestry.
- Grazing lands are the primary source of tebuthiuron.

Mackay Whitsunday region

The basins for the Mackay Whitsunday region used in the study are shown in Figure 4.3, as defined in Brodie *et al.* (2003).

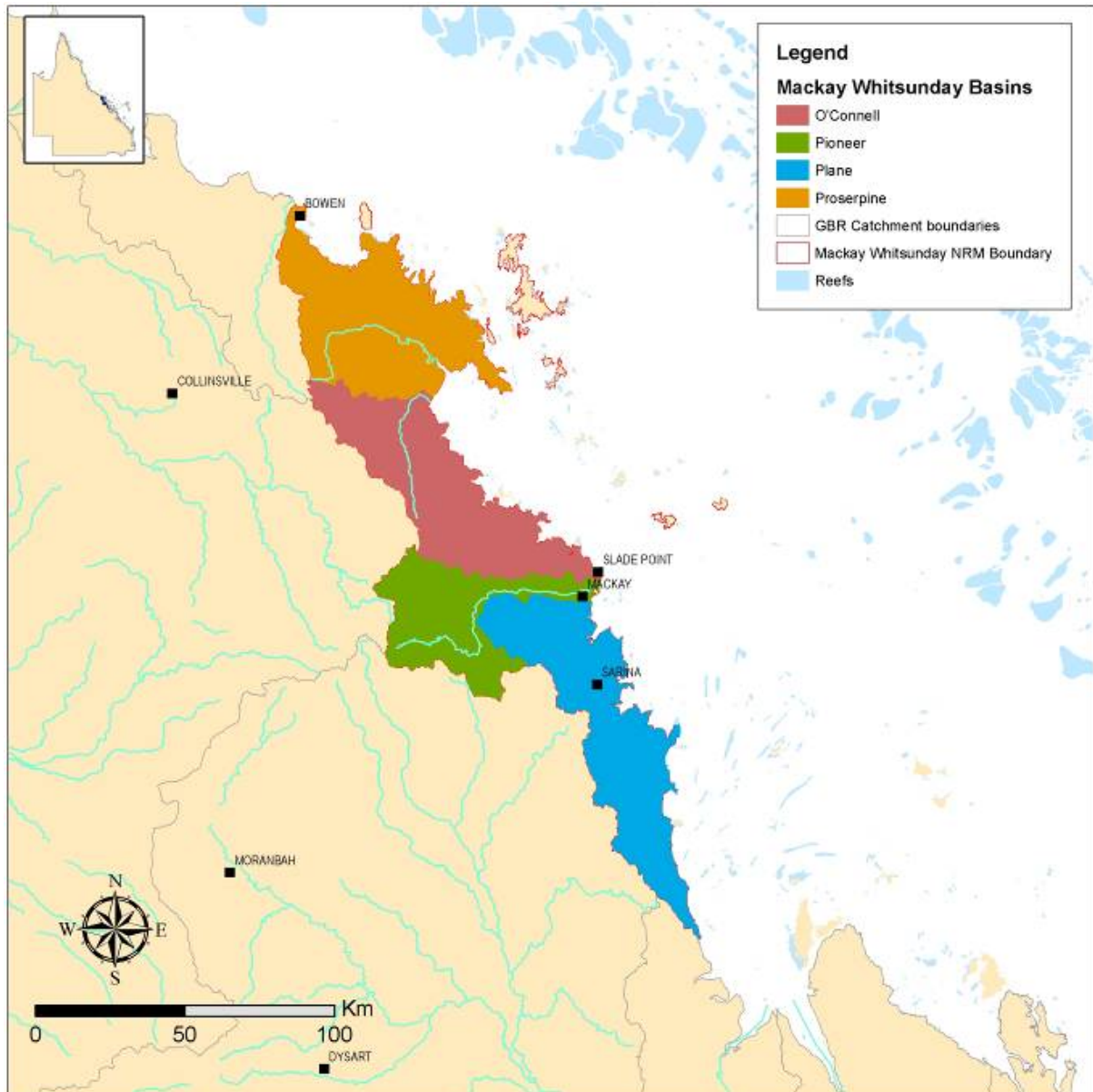


Figure 4.3: Basins in the Mackay Whitsunday region. Source: Brodie *et al.* (2009c).

Dissolved inorganic nitrogen (DIN) / Particulate nitrogen (PN)

- The O'Connell basin generates the most total DIN load on an annual basis, followed by the Pioneer basin.
- The greatest proportion of anthropogenic DIN load is derived from sugarcane areas, particularly in the Pioneer basin.
- The largest proportion of total anthropogenic DIN load from sugarcane is from the Pioneer basin, followed by the O'Connell basin.

- In terms of DIN load from sugarcane per unit area of sugarcane cultivation, the highest loads are from the Pioneer and O'Connell basins.
- In the Mackay Whitsunday region it is estimated that the source of total DIN is approximately 77% sugar, 12% grazing and 10% forest, other crops, intensive uses and urban (Drewry *et al.* 2008).

PS-II herbicides

- The Plane basin has the greatest load of PS-II herbicide delivery followed by the Pioneer and O'Connell basins.
- The greatest proportion of PS-II herbicides in the Plane basin is generated from sugarcane areas, accounting for 88% of the total PS-II herbicide load.
- Diuron is the PS-II herbicide discharged in the highest amounts and is discharged in high amounts from all basins. The use of diuron in the region is associated with sugarcane cultivation.
- It is believed that tebuthiuron is derived from grazing, while the other PS-II herbicides are known to be derived from sugarcane. Simazine detection in the region is minor and the sources of simazine are not widely known.

Total suspended sediment (TSS)

- Generally TSS contamination is no longer seen to be a major issue in the Mackay Whitsunday Region (Drewry *et al.* 2008). This is largely due to improved management practices in sugarcane (e.g. minimum tillage and green cane harvesting) and, to some extent, grazing in the region over the last twenty years (Rayment, 2003).
- The Pioneer basin delivers the most current and anthropogenic suspended sediment load on an annual basis, followed by the O'Connell basin. The Pioneer basin also delivers the most suspended sediment per basin area on an annual basis in the Mackay Whitsunday Region, followed by the O'Connell basin.
- The land use that generates the most anthropogenic suspended sediment load to the GBR is sugarcane in the Pioneer basin and grazing in the Pioneer and O'Connell basins.
- The greatest anthropogenic load of suspended sediment to the GBR per unit area of land use is from sugarcane in the Pioneer, O'Connell and Proserpine basins. Grazing is also an important source in the Pioneer and O'Connell basins.
- Hillslope erosion across the region contributes the most suspended sediments in comparison to other erosion types like bank or gully erosion.

Fitzroy region

The basins of the Fitzroy region in the study were defined as including the Styx, Shoalwater, Waterpark, Fitzroy and Calliope basins (Figure 4.4). The area of the Fitzroy River basin is so much larger than the other basins that it dominates the region. It would have been preferable to separately consider the major basins of the Fitzroy basin (Dawson, Comet, Nogoa, Theresa Creek, Isaac, Connors, Mackenzie and Lower Fitzroy), but there was insufficient information at the time of the study to report the outputs from these different basins.

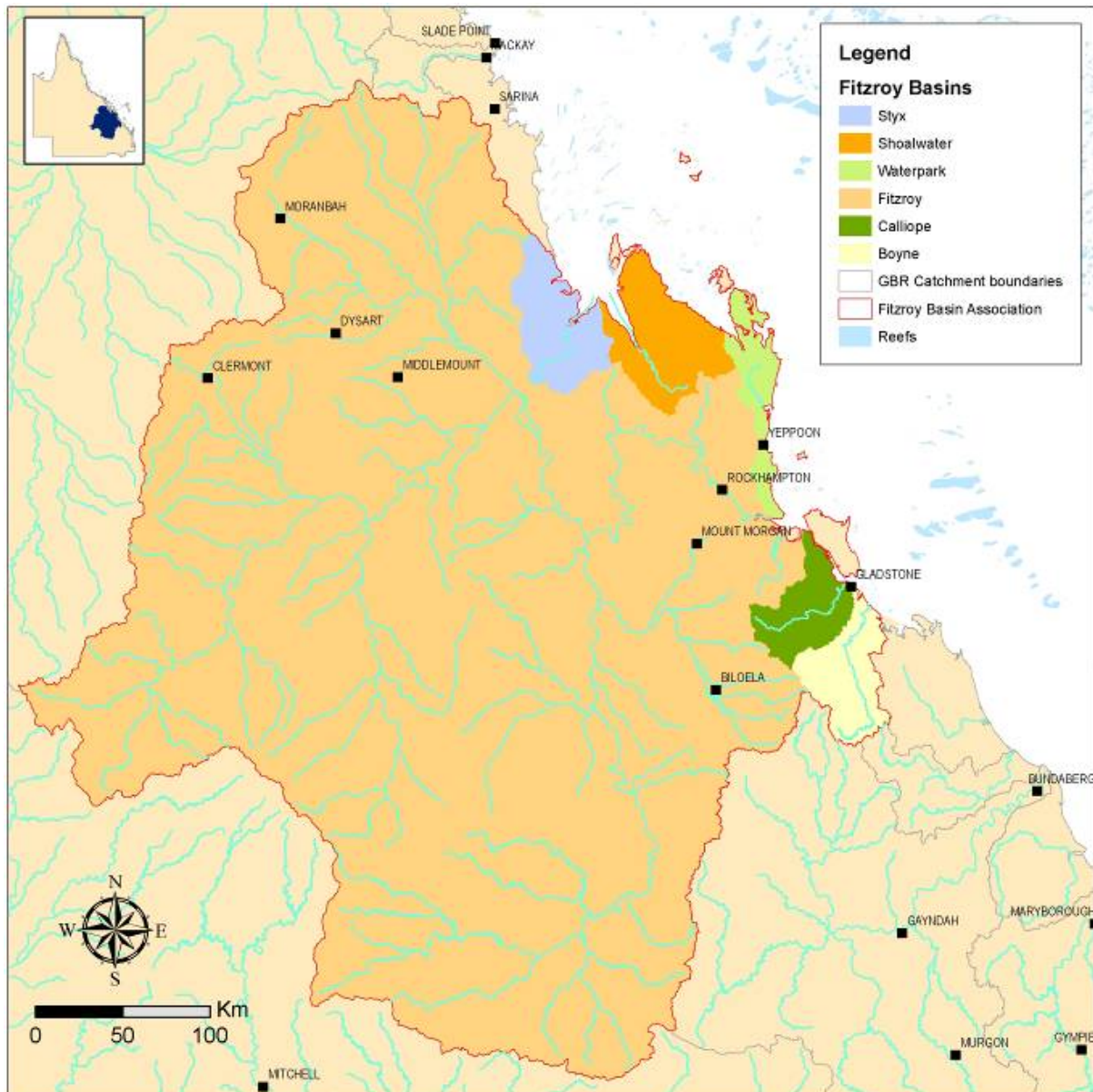


Figure 4.4: Basins in the Fitzroy region. Source: Brodie *et al.* (2009c).

Total suspended sediment (TSS)

- The overall suspended sediment load to the GBR from the Fitzroy basin is by far the highest in the Fitzroy Region, linked to the large size of this basin.
- The key land use requiring management of suspended sediment in the Fitzroy Region is grazing.
- Loading reductions of suspended sediment could be achieved through managing hillslope erosion across the region.
- Highest erosion inputs are seen from hillslope erosion in the Connors, Lower Fitzroy, Comet and Nogoia sub-basins of the Fitzroy basin (Dougall *et al.* 2008).

Dissolved inorganic nitrogen (DIN) / Particulate nitrogen (PN)

- The total DIN load to the GBR from the Fitzroy basin is the highest in the Fitzroy Region, in part a reflection of the large size of this basin.
- The other coastal basins in the Fitzroy Region also contribute minor anthropogenic DIN loadings, but in total this is substantially less than that of the Fitzroy basin.
- The key contributing land use to anthropogenic DIN delivery to the GBR is 'other crops', mainly grains and cotton. While the fertiliser application rates for grain crops are relatively low compared to sugarcane activity in other GBR catchments, the area of grain crops is large (approximately 700,000 ha). Cotton has comparable fertiliser rates to sugarcane but the area in the Fitzroy Region is smaller (approximately 30,000 ha).

PS-II herbicides

- The Fitzroy basin delivers more tebuthiuron than any of the basins considered here in the four regions, largely due to its very large size and area of grazing. An approximately equal amount of Other PS-II herbicides, mostly atrazine, derives from the large grain crops in the Fitzroy basin.
- All of the basins in the region deliver low PS-II herbicide loads per basin area.
- The PS-II herbicides delivered from basins in the region are from two land uses: other crops, specifically grains, are the primary source of PS-II herbicides (primarily atrazine and diuron) other than tebuthiuron. Grazing lands are the primary source of tebuthiuron (Packett *et al.* 2009).
- The largest loads of tebuthiuron (associated with grazing land management) are from the Fitzroy basin. The largest loads of other PS-II herbicides (associated with 'other crops' cultivation) are also from the Fitzroy basin.

Summary and conclusions

Measures of the current suspended sediment, anthropogenic suspended sediment, current and anthropogenic DIN and current PS-II herbicide loads for the four NRM regions (Burdekin, Wet Tropics, Mackay Whitsunday and Fitzroy) are summarised in Figures 4.5-4.8 respectively. In each of these figures (except for suspended sediment), the areas of each basin are plotted in the left-hand graph, with the most relevant land uses shown by a colour key for the DIN and PS-II herbicide export figures. Conclusions across the four regions are presented below.

Suspended sediment

For current and anthropogenic suspended sediment loads, there is a clear, increasing relationship with basin area (Figures 4.5 and 4.6). Large basins such as the Fitzroy and most sub-basins of the Burdekin have large suspended sediment loads, while small basins generally have relatively small loads (Figure 4.9). Hence, suspended sediment load among basins is primarily determined by basin area. However, this relationship is crude and the reasonable correlation coefficient is largely driven by the points from the Fitzroy and Upper Burdekin basins. The Bowen-Bogie sub-basin, with the second-largest current suspended sediment load, has only a moderate-sized basin area, much smaller than those of the Upper Burdekin and Belyando sub-basins with lower current suspended sediment loads. In a similar vein, some relatively small basins have moderately large suspended sediment loads (e.g. Daintree, Johnstone, Pioneer and Styx). For anthropogenic suspended sediment loads, the relationship becomes slightly stronger because of the greater similarity between the Burdekin and Fitzroy anthropogenic loads. When suspended sediment loads are expressed on a per area basis, a poor, inverse relationship with basin area becomes apparent (Figure 4.10). This is consistent with studies of suspended sediment load versus catchment area worldwide.

Dissolved inorganic nitrogen

Measures of the current and anthropogenic DIN loads are clearly unrelated to basin area (Figure 4.7a and b), except in a very poor inverse relationship. Rather, DIN loads are likely determined by the area of fertiliser-additive land use in each basin and subsequent leakage from fertiliser application. Hence, the higher DIN exports are typically observed in basins with sugarcane and other crops as the most important land use (Figure 4.7b). The plot of anthropogenic DIN per land use area (Figure 4.7d) is probably more relevant than the plot of anthropogenic DIN per basin area (Figure 4.7c).

The high DIN rate in the Lower Burdekin basin is highlighted in Figure 4.7d. There are a number of explanations for high rates in this basin. Aside from errors in the estimates, the recommended fertiliser-application rates in the Lower Burdekin (Burdekin River Irrigation Area) are up to twice as high as other areas due to its high yield. The actual fertiliser rates may also be considerably higher than recommended for a significant fraction of farmers, up to 600 kg N/ha (Brodie and Bainbridge, 2008), taking into account all inputs (direct fertiliser, mill mud, groundwater-derived N). In contrast to the Lower Burdekin basin, the DIN load per sugarcane area for the Mackay Whitsunday basins appears to be reduced relative to the basins in the Wet Tropics (Figure 4.7d). No explanation is offered for this, except that there may be regional differences in the treatment/measurement of similar land uses. Also, while the scale of Queensland land use mapping is relatively fine, there may be considerable amalgamation of roads, runoff, drains and other areas – perhaps up to 30% – into that which is designated as ‘sugarcane’.

The relationship between land use area and DIN load is also given here (Figure 4.11), but only for sugarcane (Daintree south to Plane), since there is a large variation in both the application rates of fertiliser and the runoff of DIN from different crops. Even with just this single crop, there is considerable variation in the relationship. Some of this variation is

understandable; for example the relatively high DIN load from the Lower Burdekin basin may be partially explained by the higher fertiliser application rates noted in this basin. When DIN loads expressed on a per sugarcane area basis are compared to sugarcane area, the overall pattern is less clear. There is no second derivative relationship between anthropogenic DIN load per area and the area of sugarcane, indicating that the delivery of DIN is efficient and little trapping occurs. Note that despite the very large area of cropping in the Fitzroy basin, the DIN export load is only moderate and the rate of DIN load per land use area is small, suggesting that fertiliser application rates used on grains and cotton cropping are low compared to sugarcane.

Herbicides

Measures of PS-II herbicide loads are divided at least into 'Tebuthiuron' and 'Other PS-II Herbicides' (Figure 4.8). The significance of this separation is that tebuthiuron is used almost exclusively in grazing land use, albeit at low levels, while other PS-II herbicides, mainly diuron and/or atrazine, are used in the land uses of sugarcane and other crops at considerably higher application rates. The data were obtained from monitoring and modelling studies (Lewis *et al.* 2009b; Lewis, unpub.; Packett *et al.* 2009). On these estimates, tebuthiuron is a relatively minor component in most basins, only equivalent to other PS-II herbicides in the Fitzroy basin (Figure 4.8). Exports of other PS-II herbicides are mostly delivered from basins in which sugarcane is the most relevant land use. The rate of total PS-II herbicide loads per basin area varies somewhat between different sugarcane cultivation basins, with the highest rates seen in the Plane and Pioneer basins.

Overall, this study has shown that it is possible with current data to identify 'hot-spots' of pollutant delivery to the GBR with a reasonable degree of certainty. This then allows management prioritisation. However, the results also show that in some areas data are scarce and that quantitative uncertainty estimates are still beyond current methods to measure.

The sources of data for the study mainly relied on Brodie *et al.* (2009b) and Brodie *et al.* (2003), although a number of recent WQIP reports have also been used. In an ideal comparison, identically-derived, consistent data would be used for each of the 27 basins. The reality is that data across these many basins are inconsistent in terms of different model runs, better modelling in more recent runs and very different time periods of monitoring as the observational baseline. To emphasise the latter point, the data sets range from one year to around twenty years. Hence, data consistency between the basins is low. Also, since a number of parameters (e.g. anthropogenic loads) are estimated by differences, this introduces a much larger error. Thus, because we use anthropogenic loads as a basis for comparison between basins, there is an inherent, high degree of inconsistency and uncertainty. However, these are the only data we have available. Despite all these caveats, we consider that confidence in these estimates should be considered fair or better.

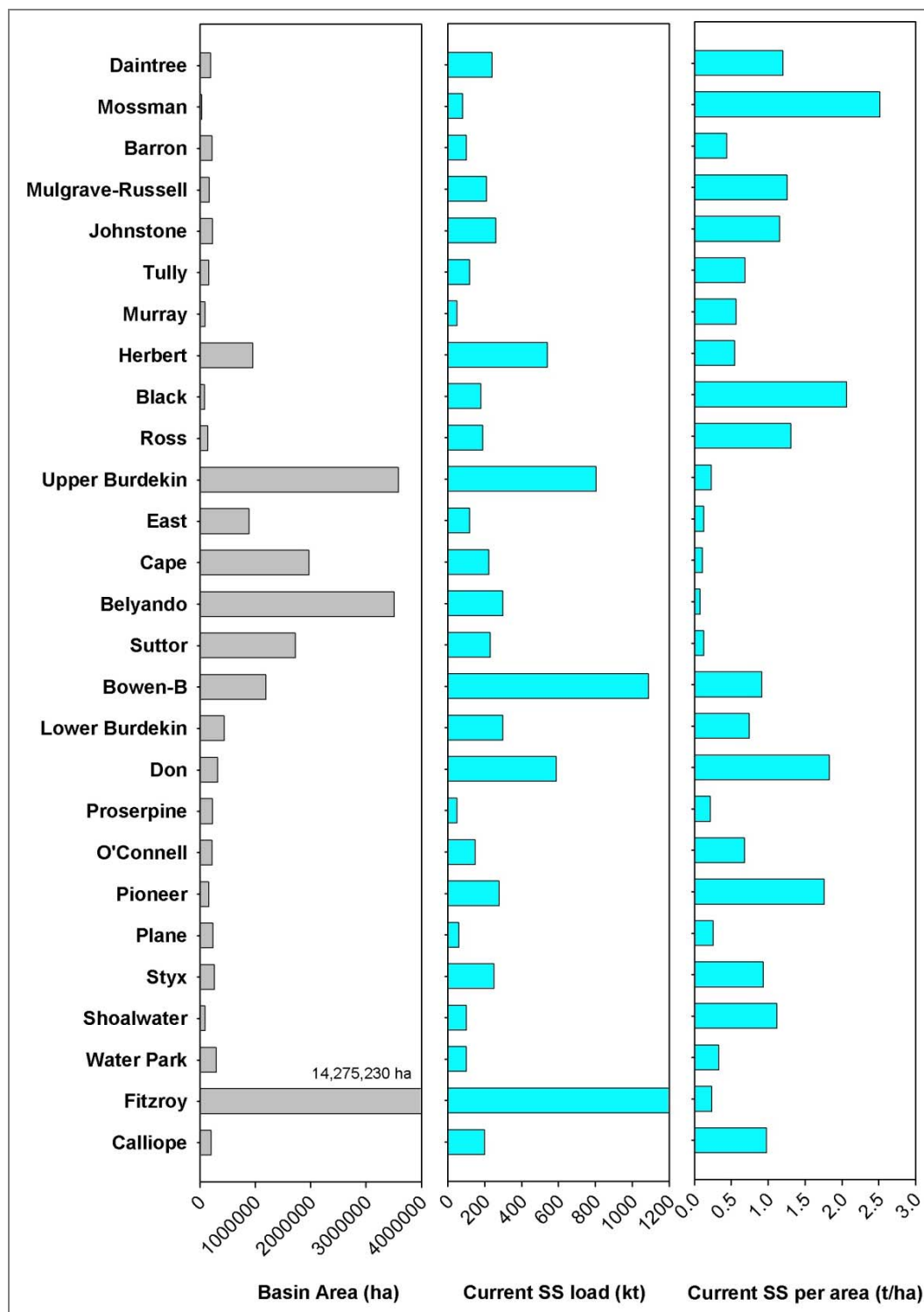


Figure 4.5: Summary of current suspended sediment exports for GBR catchments. Source: Brodie *et al.* (2009c).

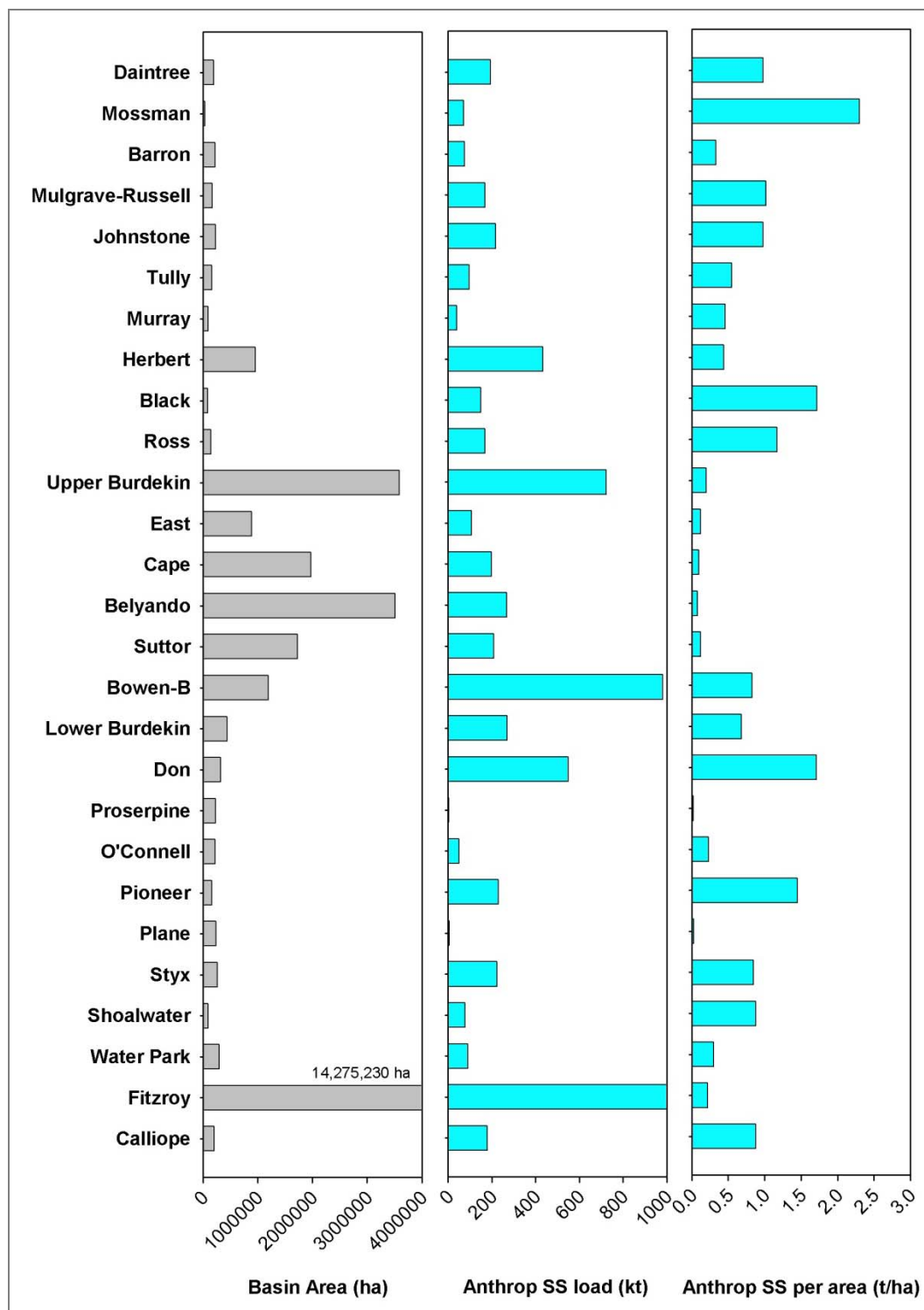


Figure 4.6: Summary of anthropogenic suspended sediment exports for the GBR catchments. Source: Brodie *et al.* (2009c).

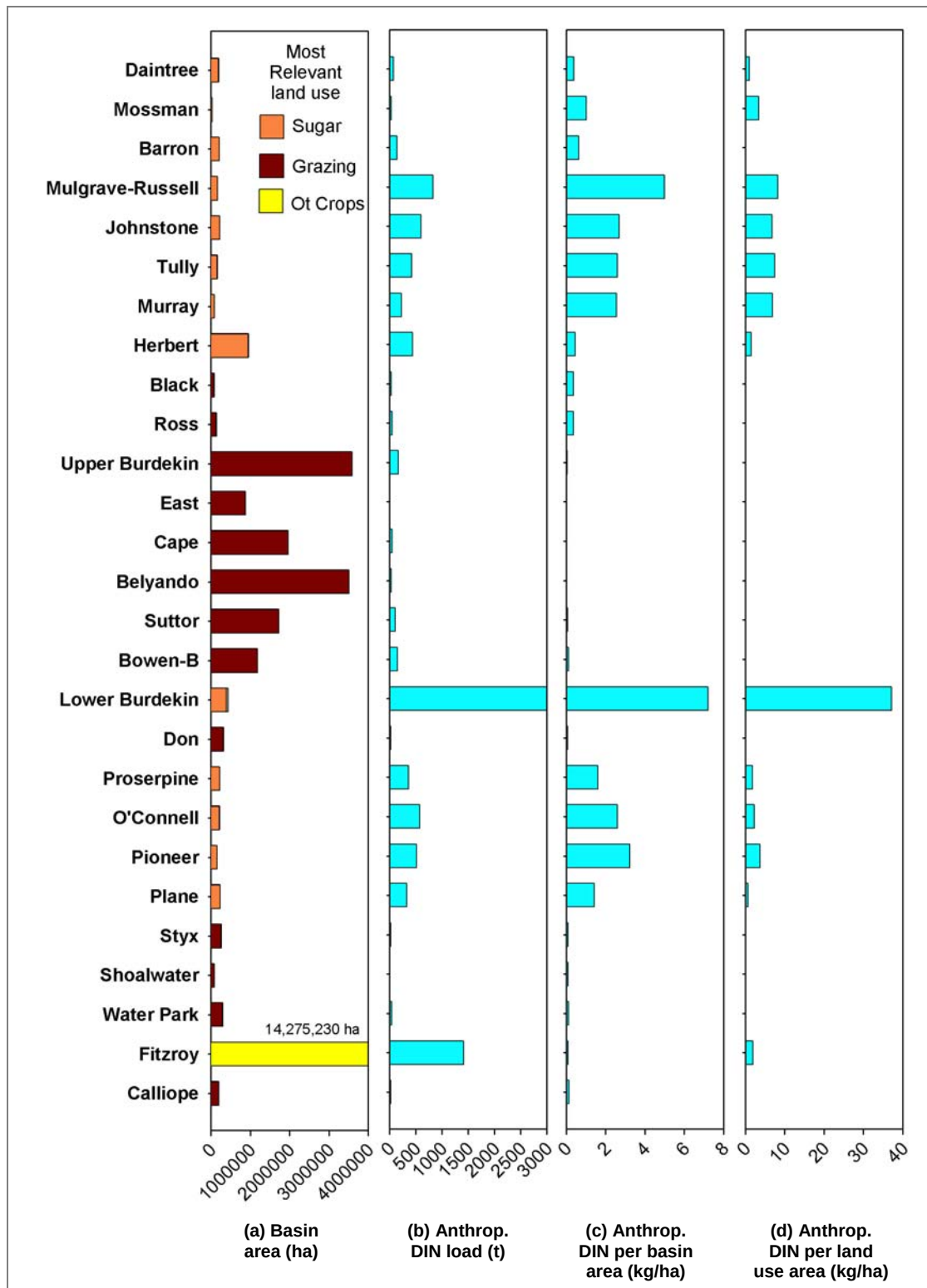


Figure 4.7: Summary of DIN exports for GBR catchments. Source: Brodie *et al.* (2009c).

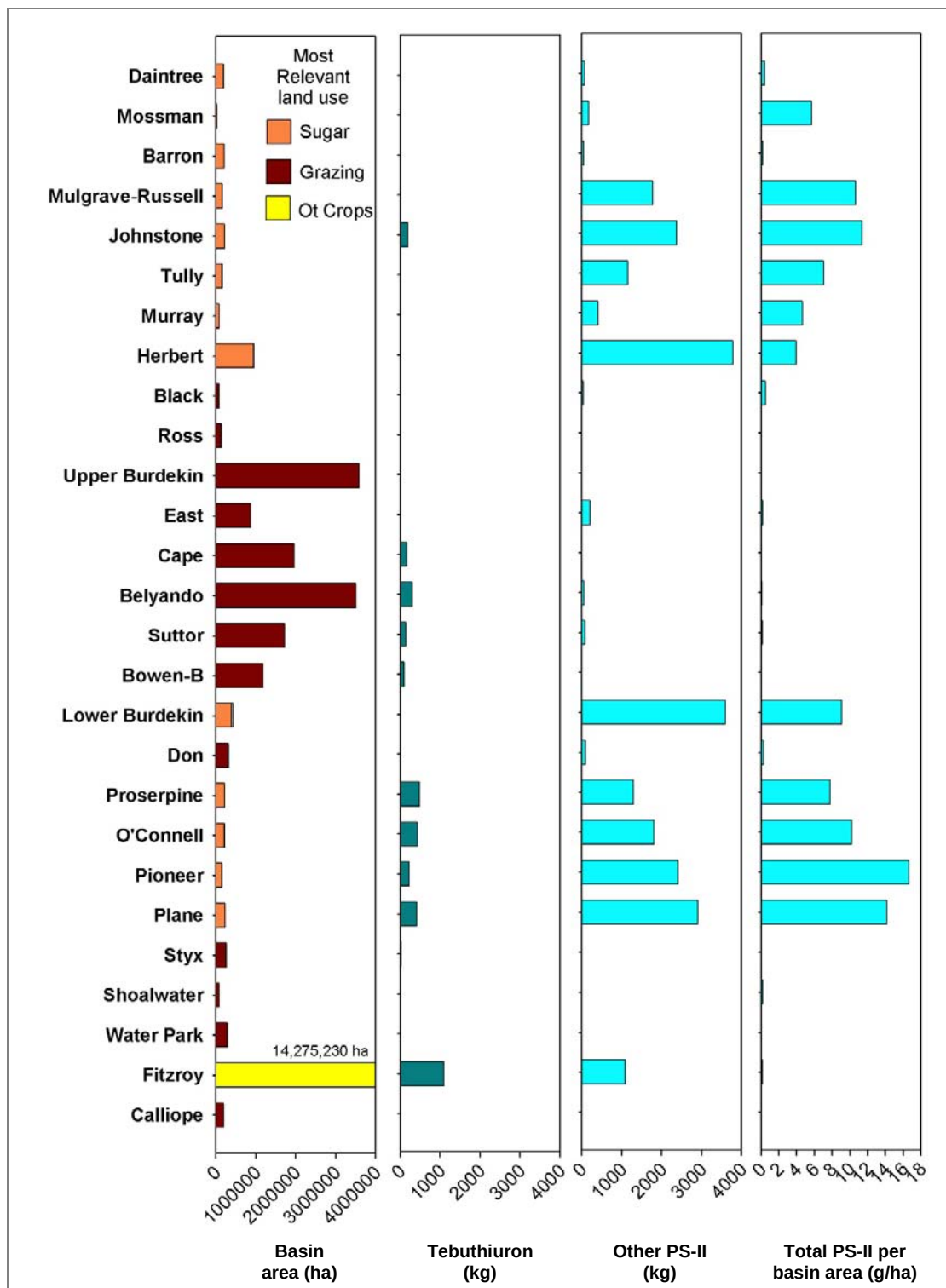


Figure 4.8: Summary of PS-II herbicide exports for GBR catchments. Source: Brodie *et al.* (2009c).

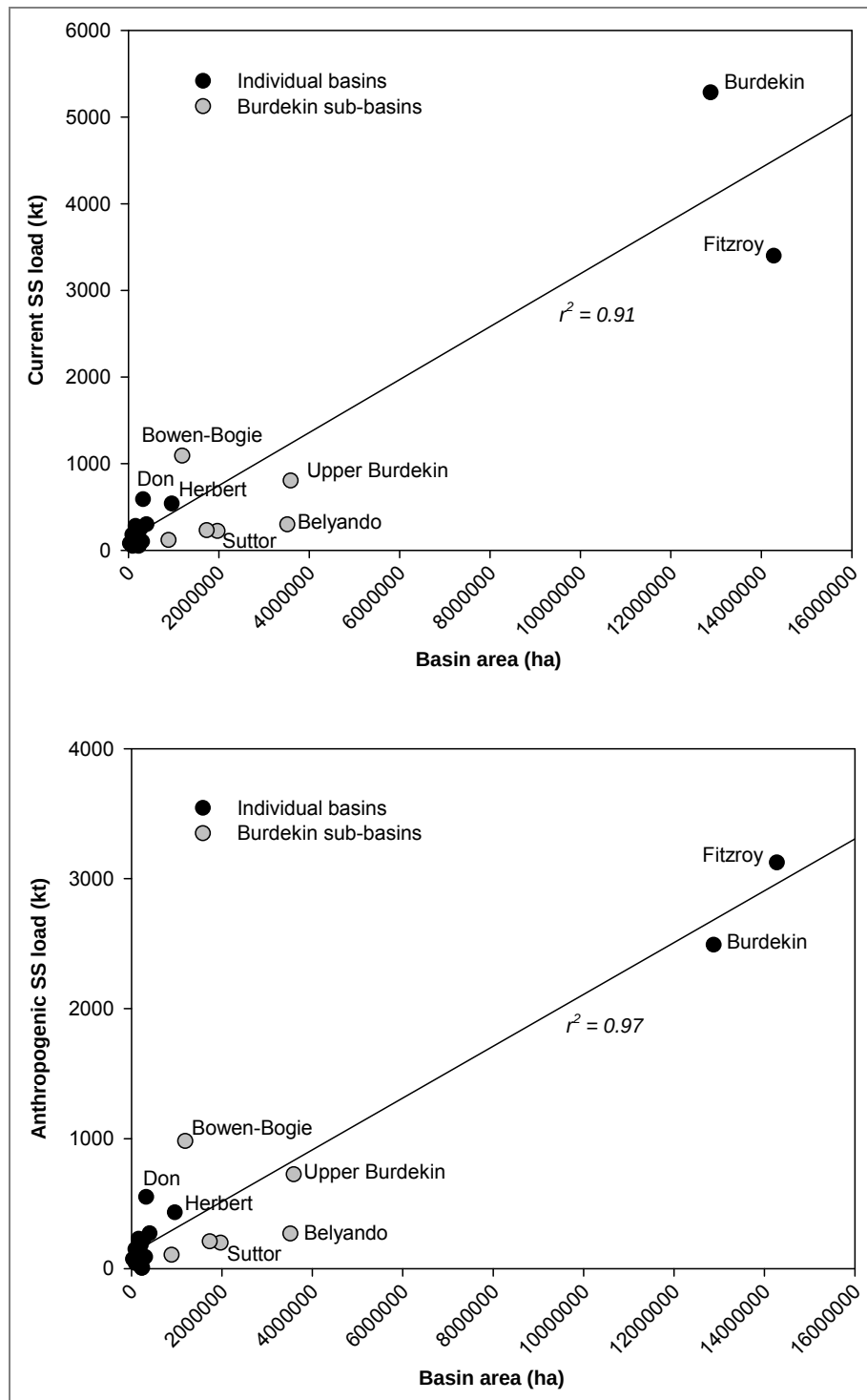


Figure 4.9: Current and anthropogenic suspended sediment loads ('000s tonnes) versus basin area. Source: Brodie *et al.* (2009c).

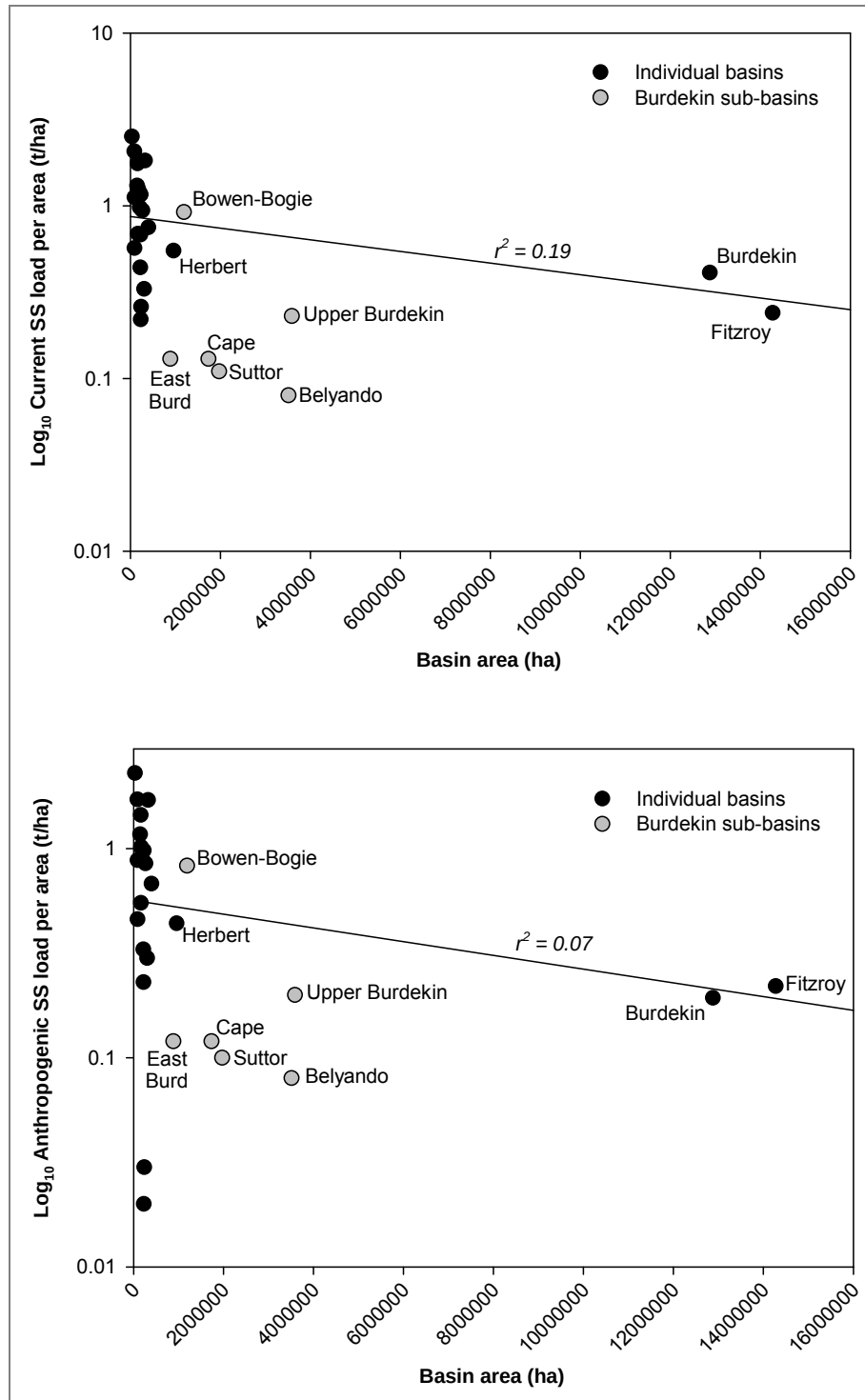


Figure 4.10: Current and anthropogenic suspended sediment loads per basin area (tonnes per hectare) versus basin area. Source: Brodie *et al.* (2009c).

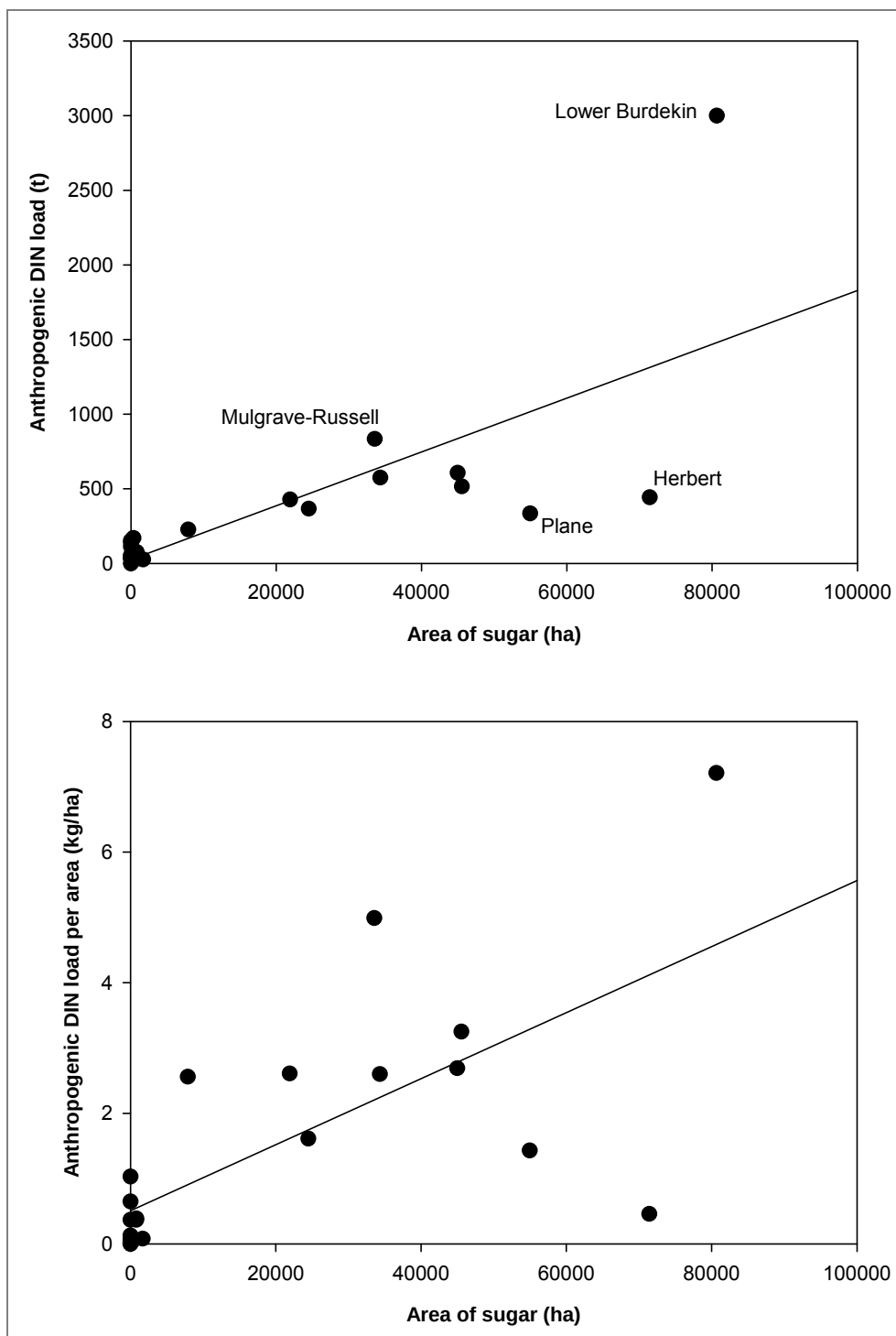


Figure 4.11: Area of sugarcane (ha) versus anthropogenic DIN load. Source: Brodie *et al.* (2009c).

4.2 Assessment of risk to the GBR

Managers of the GBR and its catchments need to know which areas are priorities for management in terms of risk to valuable ecosystems. Given the connection between the catchments and the health of the GBR, the first important step is to identify areas of high pollutant generation in the catchment and to determine which pollutants are of greatest concern. The study described above (Brodie *et al.* 2009c) and the supporting information provides this assessment based on the best available knowledge. At the same time, the values of the GBR need to be clearly defined at a relatively fine spatial scale, and the pressures on these areas need to be well understood. This exercise was a major part of the basis for the rezoning of the GBR in 2004 (Day *et al.* 2004). Connecting the two sets of information to undertake a risk assessment of the GBR has proven to be more challenging. However, mapping of risk and exposure of the GBR to pollutants has been undertaken by a number of MTSRF-funded researchers (e.g. De'ath, 2006; Delean and De'ath, 2008; Wooldridge, 2009; Maughan and Brodie, 2009; Devlin and Schaffelke, 2009; Brodie and Waterhouse, 2009; De'ath and Fabricius, 2010; Devlin *et al.* 2010). Two examples of this research are presented in this report.

The first example is a simple assessment of relative risk between the NRM regions in the GBR completed by Brodie and Waterhouse to inform the Reef Protection Package. The second example is a more sophisticated approach undertaken by Devlin and others with an emphasis on exposure of the GBR to plume waters and, hence, assessment of ecosystems in these areas of high exposure.

Note that much of the following information is extracted from Brodie and Waterhouse (2009) and Devlin *et al.* (2010) with permission from the authors.

Relative risk assessment of regions in the GBR

In a collaborative project between the MTSRF and DERM, Brodie and Waterhouse (2009) provided a relative risk assessment of pollutants for the NRM regions in the GBR catchments. To identify the relative risk for each region, a relative risk score was calculated using the following formula:

Relative Risk = Anthropogenic Load Score The sum of scores for TSS, DIN, and PS-II herbicide anthropogenic loads (Source: Brodie <i>et al.</i> 2009a) + Reef Condition Score The sum of scores for Coastal and inner shelf macroalgal cover, Coastal and inner shelf hard coral richness, Coastal and inner shelf secchi depth, and Coastal and inner shelf chlorophyll (Source: De'ath and Fabricius, 2010). + Reef Exposure Score The sum of scores for TSS exposure, DIN exposure, and PS-II herbicide exposure (Source: Maughan <i>et al.</i> 2008)
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Anthropogenic Load Score: Calculated as the sum of categorised scores of anthropogenic sediment, DIN and PS-II herbicide loads derived from Brodie *et al.* (2009b), with some improvements in DIN load estimations. The data were categorised into five groups across the full range of load values and were different for each parameter (see Appendix 2 in Brodie

and Waterhouse, 2009). High loads received a high score. The scores for each region were summed to give an overall Anthropogenic Load Score.

Reef Condition Score: Calculated using the data analysed by De'ath and Fabricius (2008) to support the development of the Water Quality Guidelines for the Great Barrier Reef Marine Park (GBRMPA, 2009). Current reef condition coupled with water quality data can provide an indication of the previous exposure of an ecosystem to declining water quality. It could also be considered a useful indicator of the resilience of a reef to future contaminant exposure. However, it is difficult to make assumptions about the likelihood of the impact of ongoing or increased pollutant exposure without considering more detailed data on a baseline or reference condition (generalised on a regional basis). Whilst this would produce a more robust assessment of the risk of pollutant exposure to particular reef assemblages, the effort involved was considered to be beyond the scope of the project. Therefore, the current condition of coastal and inshore reefs and water quality reported in De'ath and Fabricius (2008) were used, acknowledging these limitations.

The parameters used for assessment of **Reef Condition** were:

- **Macroalgal cover:** Macroalgal cover, reported as percent cover, can be used as an indicator of exposure of reefs to poor water quality and reduced grazing (particularly fish) pressure. Research has shown that high levels of nutrients and sediments lead to high macroalgal cover, low coral biodiversity and low rates of coral recruitment on inshore reefs, slowing rates of coral recovery after disturbances, and increasing frequency of outbreaks of crown-of-thorns starfish. High cover received a high score.
- **Hard coral richness:** Coral richness is the number of coral species present in a survey area. While hard coral cover is predominantly determined by disturbance history, the species richness of hard corals appears to be a sensitive indicator of the physico-chemical environmental conditions of a site. Data are based on surveys conducted on 110 reefs (599 transects) of the GBR between 1994 and 2001 (see Figure 3 in Devantier *et al.* 2006). The analyses presented here are based on reef averaged data. Low hard coral richness received a high score.
- **Secchi depth:** Reported in metres (m), secchi depth provides a useful indicator of suspended sediment and particulate matter in the water column which is enhanced from land based runoff. High secchi depth generally reflects a light climate suitable for benthic coral growth, whilst low secchi depth reflects turbid water and a poorer light climate. The Water Quality Guideline for secchi depth is defined as >10 metres (GBRMPA, 2009). Low secchi depth received a high score.
- **Chlorophyll:** Reported as micrograms per litre ($\mu\text{g/L}$), concentrations of the plant pigment 'chlorophyll a' (which occurs in all marine phytoplankton) provide a useful proxy indicator of the amount of nutrients incorporated into phytoplankton biomass, because phytoplankton have predictable nutrient-to-chlorophyll ratios. Chlorophyll a is the most commonly used parameter for monitoring phytoplankton biomass and nutrient status, as an index of water quality (Brodie *et al.* 2007). The Water Quality Guideline for chlorophyll is defined as <0.45 $\mu\text{g/L}$ (GBRMPA, 2009). High chlorophyll concentrations received a high score.

The GBR mean of each of these parameters for the 'Inner Shelf' and 'Coastal' data from De'ath and Fabricius (2008) was reported to provide reference for categorising the Reef Condition values as low, medium or high. These were summed for each region to give an overall score for Reef Condition for each one.

It should also be noted that the Burnett Mary region does not include any data for Inner Shelf Macroalgal Cover or Hard Coral Richness. This is true for the marine areas within the Great Barrier Reef Marine Park boundary which is the scope of the assessment completed by

Death and Fabricius (2008), but it is probable that datasets for reefs south of the Marine Park boundary and still relevant to the Burnett Mary catchments are available (Maria Zann, EPA, pers. comm.). Sourcing these datasets was not considered to be within the scope of the assessment and was recommended for any future work.

Reef Exposure Score: An estimate of the exposure of individual reefs to various contaminants provides the basis of a vulnerability assessment of GBR condition from water quality influences. Ideally, an exposure criterion would factor parameters such as the proximity of the reef to the source of the contaminant, the likelihood and frequency of exposure of the reef to river plumes, and the amount of contaminant within the plumes at a range of distances. The best attempt of this kind of assessment for the GBR to date is the reef exposure model developed by Maughan *et al.* (2008). The model provides a relatively simple way of combining contaminant load estimates, river flow and variability characteristics with plume and contaminant behaviour, and the distance of every reef to each river mouth to give an estimated reef exposure class. The classes range from Low to Very High for each contaminant, and the classes are defined arbitrarily. There are some limitations with the model that should be acknowledged for the incorporation of the results in this assessment. In particular, the River Variability Index is currently given a higher weighting in the model than what is now considered to be appropriate. Essentially, the low variable rivers like those of the Wet Tropics are given a high weighting which substantially over emphasises this index against other more variable rivers such as those of the Mackay Whitsunday catchments. A revised version of the model that addresses this has been undertaken for the Fitzroy region (Maughan and Brodie, 2009). However, this same adjustment needs to be made to the model for the rest of the GBR.

A number of ways of applying Reef Exposure as a criterion in this assessment were considered with a final decision to calculate the number of reefs in the exposure categories 'Medium', 'High' or 'Very High' from Maughan *et al.* (2008) for TSS, DIN and PS-II herbicides. These values were then categorised and summed to give a 'Reef Exposure Score'.

The final criteria contained the parameters listed in Table 4.2.

Table 4.2: Summary of criteria and parameters used in the Relative Risk Assessment.
Source: Brodie and Waterhouse (2009).

Criteria	Parameter
Anthropogenic load	Total Suspended Sediment (TSS) (tonnes)
	Dissolved Inorganic Nitrogen (DIN) (tonnes)
	PS-II Herbicides (tonnes)
Reef Condition	Macroalgal cover (%)
	Coastal Macroalgal cover
	Inner Shelf Macroalgal cover
	Hard Coral Richness (Number)
	Coastal Hard Coral Richness
	Inner Shelf Hard Coral Richness
	Secchi Depth (m)
	Coastal Secchi depth
	Inner Shelf Secchi depth
	Chlorophyll (ug/L)

Criteria	Parameter
Reef Exposure	Coastal Chlorophyll
	Inner Shelf Chlorophyll
	TSS Exposure (No. of reefs in medium to very high exposure)
Reef Condition	DIN Exposure (No. of reefs in medium to very high exposure)
	PS-II Herbicide Exposure (No. of reefs in medium to very high exposure)

Each parameter was given a score between 1 and 5. The upper and lower boundaries of the classes were defined by the range of the parameter values and were then (arbitrarily) equally divided into five classes depending on the relationship between the parameter, and impact or risk. The range and classes for each parameter are detailed in the project report. The scores for the parameters in each factor were summed, and the score for each of the three factors was used to calculate the overall score. Scores were categorised into five classes of Relative Risk, where 1 = 'Low', 2 = 'Medium-Low', 3 = 'Medium', 4 = 'Medium-High' and 5 = 'High'. The boundaries for the classes were (arbitrarily) equally divided within the range from the minimum overall score to the top of the range of the overall score.

It should be noted that it is the order of the scores across the regions that is of most interest in the context of undertaking a **relative risk assessment** between the regions, and that the final classes may be useful for communicating the results. However, a more sophisticated assessment should incorporate further investigation of regional differences and the relative importance of different pollutants to better inform future management priorities.

The comparison of relative risk scores across the NRM regions is shown in Figure 4.12 with further information on land uses and priority pollutants presented in Table 4.3. From these results it is possible to develop a risk ranking between the NRM regions, indicating highest management priority to the Wet Tropics and Mackay Whitsunday regions.

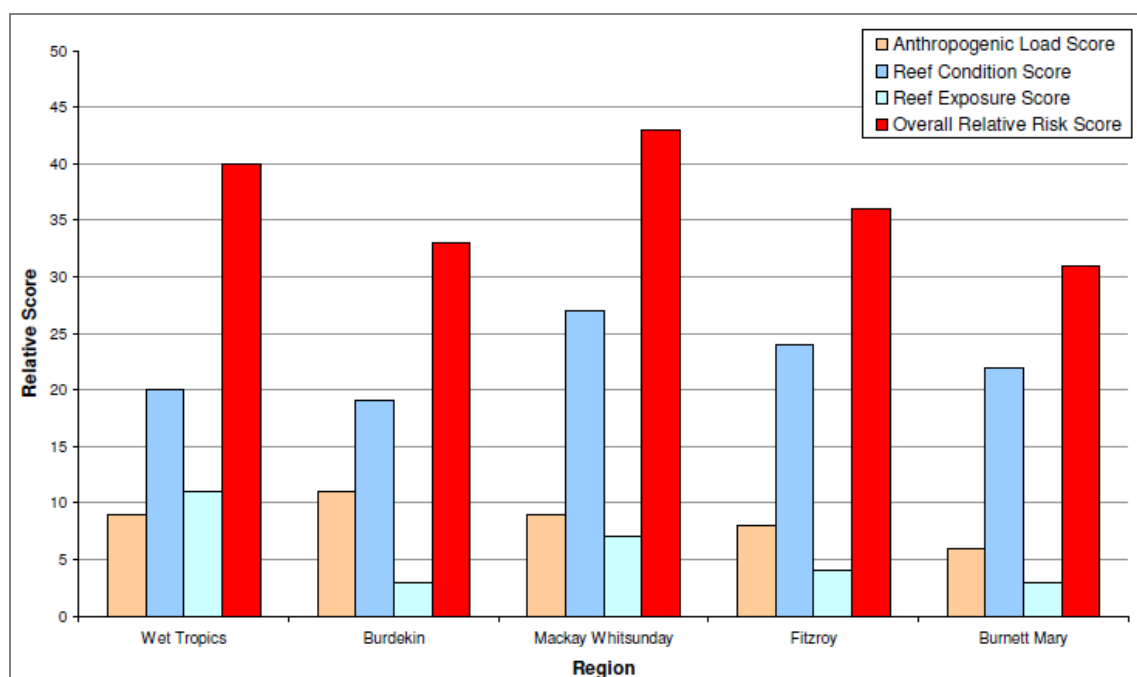


Figure 4.12: Comparison of the relative risk scores for the GBR catchments.
Source: Brodie and Waterhouse (2009).

Table 4.3: Results of the relative risk assessment of priority contaminants in the GBR catchments. Source: Brodie and Waterhouse (2009).

Region	Relative Risk	Dominant agricultural land use	Priority pollutants
Wet Tropics	High	Sugarcane	DIN, PS-II Herbicides
Burdekin	Medium-High	Grazing with sugarcane in the lower Burdekin	TSS, DIN, PS-II Herbicides
Mackay Whitsunday	High	Sugarcane	DIN, PS-II Herbicides
Fitzroy	Medium-High	Grazing	TSS, PS-II Herbicides
Burnett Mary	Medium	Grazing with sugarcane in the coastal areas	DIN, PS-II Herbicides

The assessment indicates that the Wet Tropics and Mackay Whitsunday regions rank the highest priority (ranked High), with Burdekin and Fitzroy catchments relatively high priority (Medium-High) and the Burnett Mary catchments of moderate priority in terms of the contribution and influence of land-based contaminants. This concurs with several principles of the current understanding of priority pollutants and land uses in the GBR:

1. Sugarcane and horticultural land uses that generate large quantities of DIN and PS-II herbicide runoff per unit area are dominant in the coastal areas of the Wet Tropics, Burdekin, Mackay Whitsunday and Burnett Mary catchments.
2. The predominantly coastal location of intensive agricultural land uses in the GBR catchment results in efficient delivery of contaminants to the GBR.
3. A high number of reefs are located close to the coast in the northern area of the GBR, particularly in the Wet Tropics, whereas reefs in the southern area tend to be located further offshore.
4. The assessment reflects the importance of Dry Tropics grazing activities and the contribution of sediment by erosion to receiving waters. A large proportion of the reefs in the dominant grazing areas of the Fitzroy and particularly the Burdekin region are located further offshore and thus may present a lower risk to reef habitats. However, suspended sediment risk to other important GBR ecosystems such as seagrass beds has not been included in this assessment and if this was done the importance of the Burdekin and Fitzroy regions could be enhanced.
5. Also considered in this relative risk assessment is the likely speed at which improvements can be achieved from applied management in the different land uses and the quantity of the contaminant load. In general, improvements in PS-II herbicide loads will be the quickest to eventuate, followed by improvements in DIN due to fertiliser management, with considerably longer times required to reduce suspended sediment due to erosion management.

The overall relative risk assessment is as follows (note that this list has been slightly amended from the original published by Brodie and Waterhouse (2009) following further consideration by the authors):

- Priority 1: Sugarcane in the Wet Tropics, Burdekin and Mackay Whitsunday regions
- Priority 2: Grazing in the Burdekin and Fitzroy regions
- Priority 3: Sugarcane and grazing in the Burnett Mary region and cotton and grains in the Fitzroy region
- Priority 4: Bananas in the Wet Tropics region

- Priority 5: Horticulture (except Wet Tropics bananas) and other cropping across all of the regions
- Priority 6: Intensive dairy and wet coastal grazing (Wet Tropics, Mackay Whitsunday, Burnett)

Risk of exposure to plume waters

The above study provides useful information for managers to determine investment priorities for land management in the GBR catchments; however, it was not intended to provide a risk assessment of the GBR to water quality. An example of a recent project that does attempt to identify exposure and risk of GBR ecosystems to priority pollutants is a collaborative project between the GBRMPA and the Australian Centre for Tropical Freshwater Research (ACTFR) that aimed to identify areas of high frequency exposure to plume waters in the GBR, and the probability of water quality parameters exceeding the GBR Water Quality Guidelines.

A majority of the input data to this project was derived from MTSRF research and the Reef Rescue Marine Monitoring Program, including the pollutant load information presented above (Brodie and Waterhouse, 2009; Brodie *et al.* 2009c), data that supported the development of the Water Quality Guidelines (De'ath and Fabricius, 2008, 2010), and understanding of the movement, extent and duration of flood plumes (Devlin *et al.* 2009; Devlin and Schaffelke, 2009; Brando *et al.* 2010). The project estimated the number of inshore marine ecosystems (coral reefs, seagrass meadows and seabed) in areas of high exposure to flood plume waters carrying high concentrations of pollutants (suspended sediments, DIN and PS-II herbicides) (Devlin *et al.* 2010).

Using pollutant load estimations from Brodie *et al.* (2009b), regional areas were ranked according to the volume of pollutant loading for dissolved nutrients (DIN), TSS and PS-II herbicides. Exposure to contaminants was then identified by combining information from the ranked catchment loads and the frequency at which these contaminants can reach and impact on GBR ecosystems. The frequency of exposure was determined using remote sensing images of plume extent and categorised in a range between 'high' and 'low'. High exposure areas are those which receive plume waters 'at least' two to five times per year from land use activities specific to that pollutant (i.e. grazing/TSS in the Burdekin). Moderately exposed areas receive plume waters 'at least' once or twice per year. It is important to recognise that plume periods can vary between catchments, but generally Wet Tropics systems receive high-flow periods from a period of days to weeks intermittently. Dry Tropics systems are usually associated with much longer flow periods, and recent events in both Burdekin and Fitzroy have sustained high flow for periods of four to six weeks.

The exposure mapping was then used to identify the number of seagrass and coral reef systems that are located in the High to Moderate exposure areas using spatial analysis. Comparison of the number of seagrass and reef ecosystems within the High to Moderate category for each pollutant is shown in Figure 4.13. The number of reefs and seagrass beds located within each exposure category depends on the proximity of the ecological systems to the riverine influence gradient. For example, the Mackay Whitsunday region has a large number of reefs within the High exposure category due to the close proximity of the reefs to the Whitsunday River, and the large extent measured from flood plume imagery in the region. The Fitzroy region has the highest number of seagrass beds within the High to Medium exposure categories for all pollutants.

Exposure mapping focuses on the movement, extent and frequency of individual pollutants. However, during high flow periods, these pollutants move together and have different pressures from combined exposure. The actual movement, dispersion and uptake of the individual pollutants would vary dependent on the mixing properties; however, it is likely that

the areas regularly exposed to plume waters may receive exposures to all three pollutants at the same time. In response to this concern, Devlin and others have also identified the spatial extent of combined exposure for the three pollutants. The combination rules identify High exposure as both TSS/DIN or TSS/PS-II or DIN/PS-II scoring High exposure, and the third pollutant scoring at least Medium exposure. This exposure score then identifies different combinations of exposure rankings, down to the three pollutants all being Low exposure (Figure 4.14).

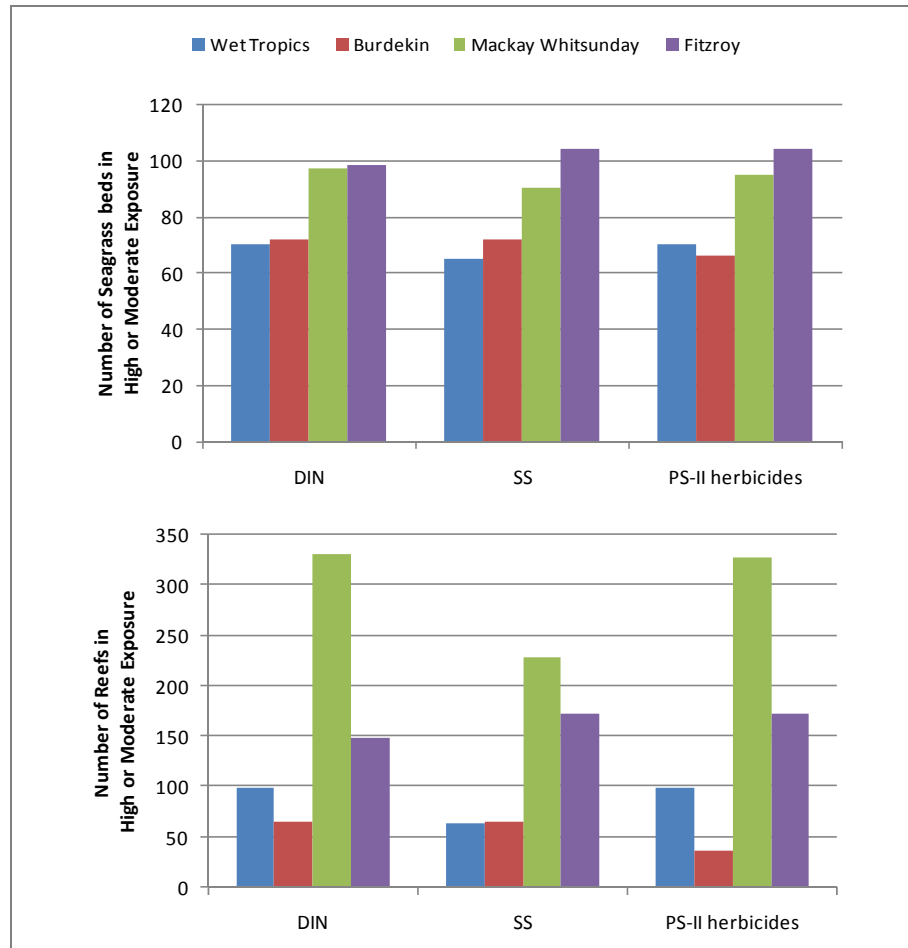


Figure 4.13: Number of seagrass (*top*) and coral reef (*bottom*) ecosystems located within areas of High to Medium exposure to specific pollutants in flood plume waters (calculated by spatial mapping of plume extent and catchment loads). Source: Derived from Devlin *et al.* (2010).

In considering these results, it is important to recognise that exposure does not indicate certainty of an ecological effect on the plants and animals present within the plume. The probability of actually exceeding the Water Quality Guidelines is limited to a smaller area contained within the high to moderate exposure area. The areas identified as high to moderate exposure will receive plume waters which contain elevated concentrations of pollutants (the pollutant dependent on the adjacent landscape) which may potentially impact on the ecology. In particular, the potential PS-II herbicide exposure indicates that detectable concentrations are sometimes at levels that can cause measurable effects on marine organisms. Despite elevated concentrations being measured across these exposure areas in periods of high flow, it is not sufficient to ascribe certainty that water quality values will exceed thresholds based on water quality guidelines and/or be linked to a measurable

ecological impact. These exposure areas could be identified as potential areas for impact relative to terrestrial discharge. Continuing research, monitoring and mapping could be used to resolve the extent of probable impact over these exposure areas.

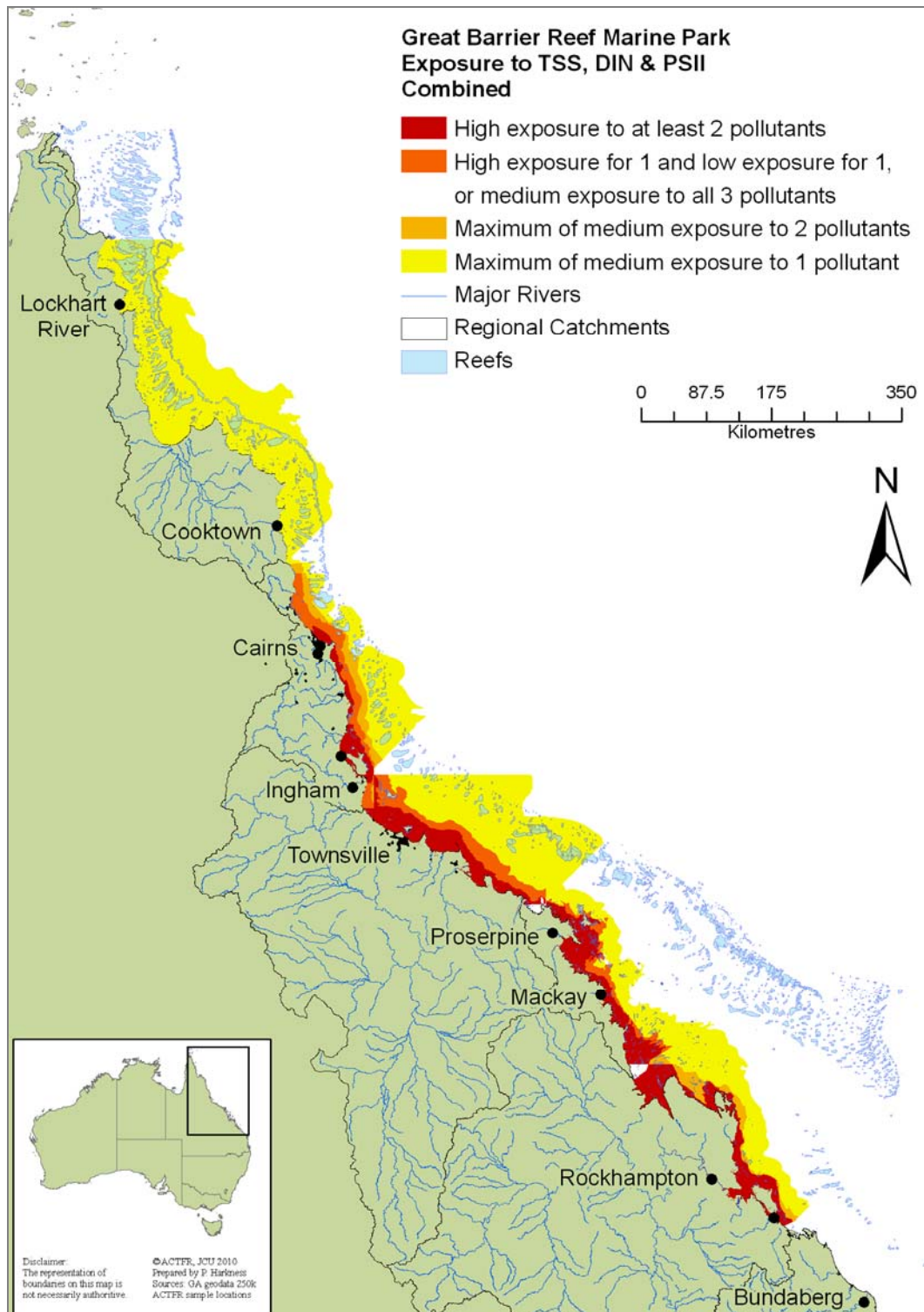


Figure 4.14: Spatial extent of the exposure categories for TSS, DIN and PS-II herbicides. Exposure categories are based on the combination of the exposure rankings for the three pollutants, highest exposure is identified by two out of the three pollutants being at high exposure. Source: Devlin *et al.* (2010).

5. Management practices in priority areas

The success of the Reef Plan requires identified primary industries in the GBR catchments to embrace change in specific management practices. In order to achieve change, the complexity and socio-economic influences of these management practices must be taken into account and they must be realistic, affordable and have demonstrable environmental benefits. This requires an understanding of what is needed to be achieved and involves individual landholders and their support networks (suppliers, advisory groups, NRM groups), in addition to robust knowledge of the water quality and economic outcomes of recommended management practices.

Through the MTSRF, van Grieken and others (2010a) identified the priority management actions for each identified production system (sugarcane, grazing and horticulture) and prioritised the management actions according to water quality improvement potential. They have also identified the most important agricultural production systems in the GBR catchment from a profit point of view, more specifically their gross direct economic value (Access Economics, 2005).

Management practices targeted, based on the findings with regard to priority pollutants, include nutrient, pesticide and soil management and actions to reduce soil erosion (Table 5.1). Fertiliser and herbicide management in sugarcane includes '6 Easy Steps' training, application rate recording and reporting, adoption of proven practices to manage contaminants in bananas and promotion of grazing land management principles in the Burdekin and Fitzroy regions.

In collaboration with a range of stakeholders, MTSRF-funded researchers have also assisted in defining a classification of management practices according to water quality benefit and cost effectiveness (Table 5.2). There is a system of practices which are structured from 'Best' (B – practices which currently hold the highest potential for improving water quality) to 'Dated' (D – the lowest potential). 'Aspirational' (A) management practices may further improve water quality but are currently under research and commercially not proven (therefore these practices are difficult to accurately model because data on their water quality improvement is not yet available). A detailed description of management practices that are identified according to the classification described can be found in van Grieken *et al.* (2010a).

Table 5.1: Key industries and priority management actions for each identified industry to address the issue of water pollution by nutrients, pesticides and sedimentation. Source: van Grieken *et al.* (2010a).

Production system	Dominant region	Priority actions
Sugarcane	Wet Tropics (WT), Burdekin Dry Tropics (BDT), Mackay Whitsundays	Nutrient, pesticide and soil management
Grazing	Rangelands (BDT), Wet coastal grazing (WT)	Pasture (reduced stocking rates), riparian (frontage) and gully management
Horticulture (bananas)	Wet Tropics	Nutrient, soil management, insect/disease and irrigation management

Table 5.2: Types of management practices undertaken by farmers.
Source: van Grieken *et al.* (2010a).

Practice class	Description
Aspirational – commercial viability not yet proven (A)	Aspirational / Proof of concept, practice / farming system under research / scientifically sound but unproven
Best practice (B)	Best practice / farming system currently available
Common practice (C)	Currently code of practice level of farming system
Dated practice (D)	Dated and likely degrading practice / farming system

Further analysis of identified priority actions is required to ensure best management practices that are promoted are cost-effective and do in fact improve downstream water quality. An example of such an analysis is presented in van Grieken *et al.* (2010b). Figure 5.1 refers to the costs and benefits of moving to 'improved' farming systems (grouping of management practices) in the Wet Tropics (represented by the Tully region) and the Burdekin basin (represented by the Delta region). In other words, farming systems with the potential to reduce DIN available (from runoff and deep drainage leaching) to enter the waterways from the paddock in the corresponding regions.

For each farming system (A, B, C and D, described in Table 5.2) the corresponding information is given on DIN (kg/ha/yr) available to enter the (hydrological) system, farm gross margins (AU\$/ha/yr) and the investments (e.g. machinery) required to move from one farming system to the other. It must be noted that transaction costs (or hidden costs of change) are not incorporated hence total costs of change are likely to be underestimated.

In the Tully catchment, moving from a 'C' farming system to a 'B' farming system will require the investment of approximately AU\$43,000 (e.g. the purchase and modification of machinery) (Figure 5.1, *top*). It will potentially reduce DIN pollution from the paddock, with more than 10% but increasing (steady state) farm gross margins greater than 25%. A few examples of the changes that farmers face in moving from a 'C' to a 'B' farming system are the use of GPS for planting, a reduction of tillage operations, fertiliser application rates based on soil tests, the use of legume crops in half of the fallow area, the development of a soil management plan, improved record keeping and the use of climate and weather forecasts.

In conclusion, for the Tully catchment, change in (dominant) agricultural practices can be summarised as below:

- **Sugarcane:** Improved practices may lead to increased productivity benefits but show significant investment costs. It must be noted that costs and benefits associated with a transition between practices will be different for each individual grower and therefore each circumstance needs to be carefully considered before making a change in management practice.
- **Bananas:** Overall, there are expected to be benefits to growers in the Tully region through transitions towards water quality improvement management practices, although the benefits will vary for each individual grower depending on their starting point and their individual property scenario. Further education regarding the expected benefits of transition to improved cane management practices may encourage some growers in the region to begin the transition. However, the costs and benefits associated with a transition will be different for each individual grower and, therefore, each circumstance needs to be carefully considered before making a change in management practice.
- **Grazing:** In wet coastal grazing, matching stocking rates to pasture carrying capacity leads to a small reduction in sediment delivery as well as an increase in profitability. In

general, gross margins are lower for pastures with a lower carrying capacity, i.e. in particular for pastures on soils where pasture growth is affected by water logging.

In the Burdekin Dry Tropics example (Figure 5.1, *bottom*; a 120 ha sugarcane farm operating in the Delta area on a relatively coarser texture soil and where groundwater is used for irrigation), moving from a 'C' farming system to a 'B' farming system will require the investment of approximately AU\$45,000 (e.g. the purchase and modification of machinery). It will potentially reduce DIN pollution from the paddock by more than 15% while increasing (steady state) farm gross margins by 17%.

In conclusion, for the Burdekin catchment, change in (dominant) agricultural practices can be summarised as below:

- **Sugarcane:** Improved practices may lead to increased productivity benefits but show significant investment costs. It must be noted that costs and benefits associated with a transition between practices will be different for each individual grower and so each circumstance needs to be carefully considered before making a change in management practice.
- **Grazing:** In general, improved practices (reduced stocking rates) come at a productivity loss. However, in some cases, reducing stocking rates may lead to benefits (increased gross margins).

These results emphasise the importance of further research to quantify the benefits of management practices for water quality improvement and cost effectiveness to ensure that investors are provided with confidence of a return on investment through initiatives such as Reef Rescue. The Paddock to Reef Program incorporates a number of monitoring and modelling activities at the paddock/plot scale that will assist in better selection of management practices in the priority industries of sugarcane, grazing, horticulture and grains; however, specific research and development investment is required in the coming years to quantify the outcomes of management practices, particularly in the 'A' class described above. Continuation of the efforts of van Grieken and other MTSRF-funded research on the cost effectiveness of management practices is essential for informing these programs. This information also provides critical input data for assessing the performance of pollutant load targets for the Reef Plan and Reef Rescue programs in the GBR and, therefore, is a priority for managers of the GBR.

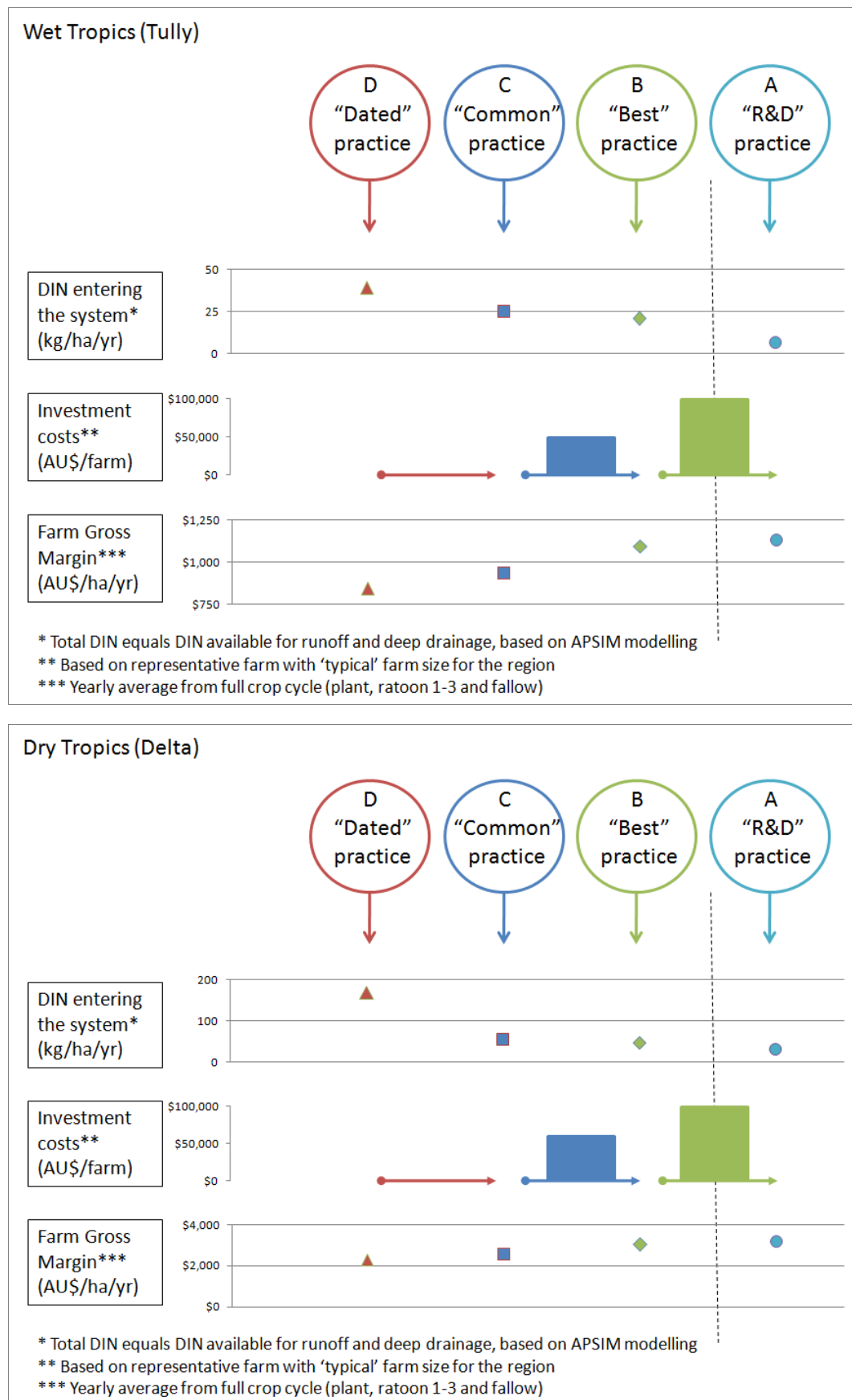


Figure 5.1: Investment costs of moving from one agricultural system to another for sugarcane activity in the Wet Tropics (Tully) (top) and the Dry Tropics (Burdekin Delta) (bottom). Source: M. van Grieken.

6. Conclusions, management applications and future directions

6.1 Conclusions

MTSRF-funded research has generated significant outcomes in identifying the priority pollutants in the GBR and its catchments, estimating pollutant loads and determining the priority areas for management. The key findings are summarised in Figure 6.1. The priority pollutants derived from anthropogenic land uses considered most likely to pose a threat to the quality of runoff water entering the GBR ecosystem are suspended sediment, dissolved inorganic nitrogen and PS-II herbicides. Through the MTSRF, current estimates and sources of each priority pollutant and the anthropogenic component of the load have been estimated (e.g. Brodie and Waterhouse, 2009; Brodie *et al.* 2009b, 2009c). However, it must be acknowledged that there are many uncertainties and limitations associated with current load estimations and the methods used continue to be refined (e.g. Kuhnert and Henderson, 2010). Further information on future research priorities is provided in Section 6.2. The impact of pollutants on the reef ecosystems is reasonably well understood (e.g. Fabricius, 2011b), particularly in comparison to understanding the impact of priority pollutants at a localised scale throughout the GBR catchment, or their impact on catchment waterways (wetlands, creeks, rivers and estuaries), mangroves, seagrasses and pelagic and inter-reefal ecosystems. Despite these gaps, considerable progress has been made through the MTSRF to better understand these relationships (e.g. Pearson *et al.* 2010a; Wallace *et al.* 2010a, 2010b; Karim *et al.* 2010a; Sheaves *et al.* 2010).

The current load estimates do enable 'hot spots' of pollutant delivery to the GBR to be identified with a reasonable degree of certainty and, to date, management prioritisation is based on these estimates (see Brodie *et al.* 2009c). The assessment by Brodie and Waterhouse (2009), presented in this report, indicates that the Wet Tropics and Mackay Whitsunday regions rank the highest priority (ranked High), with Burdekin and Fitzroy catchments relatively high priority (Medium-High) and the Burnett Mary catchments of moderate priority in terms of the contribution and influence of land-based pollutants. The relative risk of priority pollutants has been assessed at a sub-regional scale; however conclusions are relative to each region only and do not include a cross-regional comparison (Brodie *et al.* 2009c). In some areas the data are scarce and, consequently, quantitative uncertainty estimates are still beyond our current methods to measure. The overall relative risk assessment developed for broadscale agriculture in the GBR is:

- Priority 1: Sugarcane in the Wet Tropics, Burdekin and Mackay Whitsunday regions
- Priority 2: Grazing in the Burdekin and Fitzroy regions
- Priority 3: Sugarcane and grazing in the Burnett Mary region and cotton and grains in the Fitzroy region
- Priority 4: Bananas in the Wet Tropics region
- Priority 5: Horticulture (except Wet Tropics bananas) and other cropping across all of the regions
- Priority 6: Intensive dairy and wet coastal grazing (Wet Tropics, Mackay Whitsunday, Burnett)

The regional results of pollutant load assessments indicate that:

- The areas of the highest generation of pollutant loads are: DIN – sugarcane in the Burdekin and Wet Tropics regions; suspended sediments – grazing lands in the Burdekin and Fitzroy regions; and PS-II herbicides – sugarcane in the Wet Tropics and Mackay Whitsunday regions.
- A large proportion of the anthropogenic load of DIN (approximately 80%) is derived from sugarcane fertiliser losses (Wet Tropics 84%, lower Burdekin 80%, Mackay Whitsunday 88%), except in the Fitzroy region where almost all of the DIN load is from cereal grains and cotton.
- Hillslope erosion contributes the most suspended sediment to the overall load across the GBR catchments in comparison to bank and gully erosion.
- Diuron is the dominant herbicide found in the Wet Tropics, lower Burdekin and Mackay Whitsunday regions. It is generally associated with areas of sugarcane but is also found in other cropping areas.
- Tebuthiuron is the dominant herbicide in the Burdekin and Fitzroy regions associated with grazing lands. Atrazine is associated with other crops in the Fitzroy region.

The priority pollutants are mainly derived from grazing, cropping and urban use and, as such, promotion of best practice regarding their use is included in the Reef Protection Package and Reef Rescue priorities. MTSRF-funded research has substantially progressed our understanding of priority management actions (e.g. see van Grieken *et al.* 2010a), particularly from the perspective of cost-effectiveness (e.g. van Grieken *et al.* 2010b). Further analysis of identified priority actions is required to ensure that the best management practices promoted are cost-effective and do, in fact, improve downstream water quality. Continual integration of research results (environmental, social and agricultural) by scientists, landholders and relevant agencies will further improve GBR catchment management and water quality. The capacity of different regions, areas within each region and different industries within different regions to respond to these priorities depends on many factors and is an important consideration.

In general, improvements in PS-II herbicide loads will be the quickest to eventuate, followed by improvements in DIN loads due to improved fertiliser management and considerable times to reduce suspended sediment due to erosion management. In some regions further prioritisation of different catchments is necessary, particularly in the Wet Tropics region, to ensure the most effective investment is made.

The management applications of these findings are outlined further below.

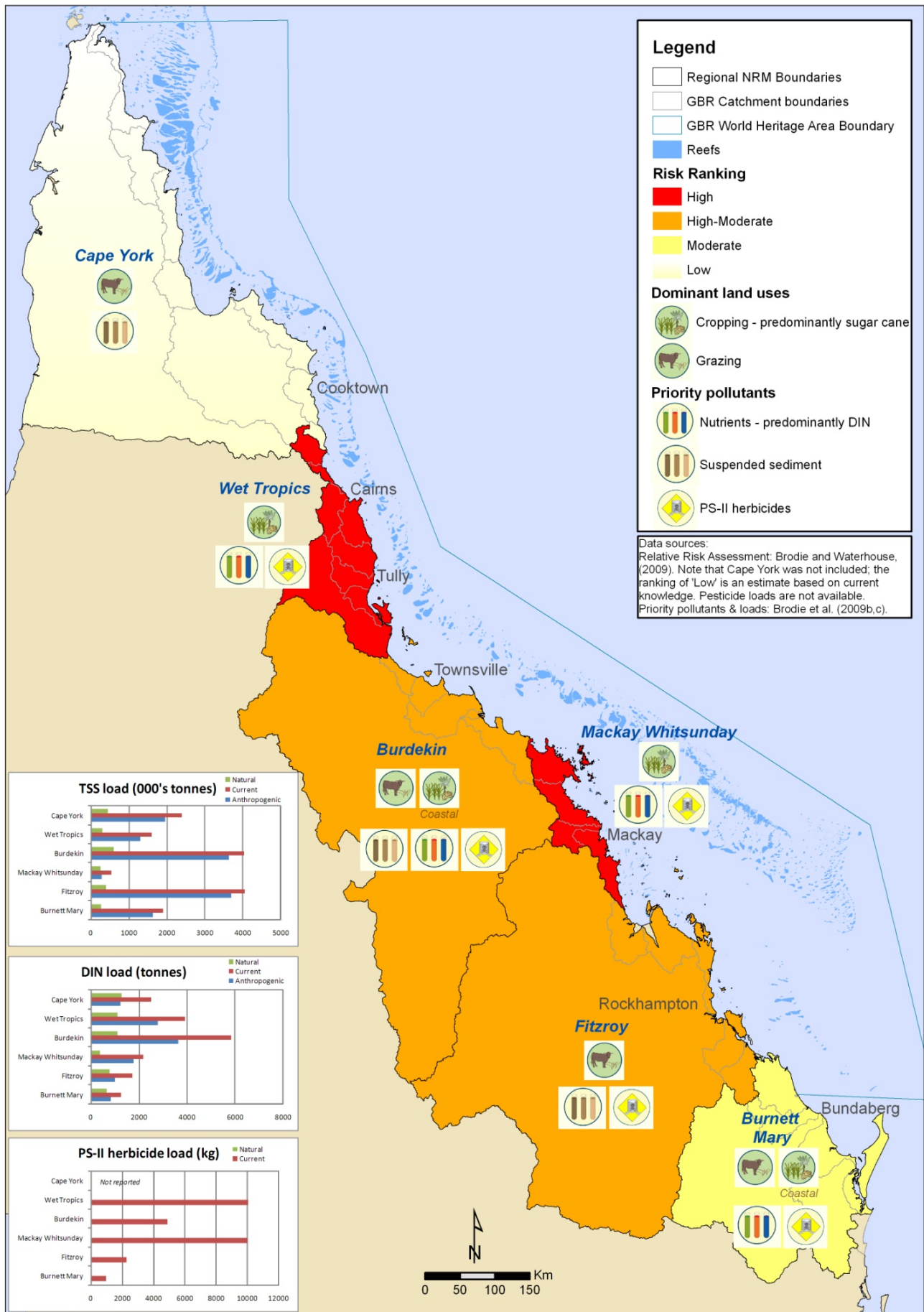


Figure 6.1: Summary of priority pollutants, pollutant loads and priority areas for water quality management in the GBR catchments.

6.2 Management applications

The findings of MTSRF-funded research presented in this report are directly relevant to managers of the Great Barrier Reef World Heritage Area and its catchment. Some examples of the management applications of the outcomes are provided below. In addition, important limitations of the research and areas which require further research are highlighted.

Of considerable significance, the management responses presently being assisted through Reef Rescue initiatives and the *Great Barrier Reef Protection Amendment Act 2009* (Reef Protection Package) are focused on the prioritised areas and industries identified in the overall risk assessment of priority pollutants and priority areas presented in this report.

For example, the development of the best estimate of pollutant loads for all of the GBR catchment undertaken by Brodie and others (Brodie *et al.* 2009b) informed the prioritisation of Reef Rescue expenditure across and within regions (across land uses and industries) of the GBR. The load estimations were incorporated into the multi-criteria analysis undertaken by the Australian Government in the selection of investment areas for the Reef Rescue program. The data used in this assessment were also used as the basis for the improvement of baseline pollutant loads for the Paddock to Reef Program (in Kroon *et al.* 2010).

Building on best estimates of pollutant loads, Brodie and Waterhouse (2009) conducted a relative risk assessment of the impacts of broadscale agriculture on the GBR and identified priorities for application of the Reef Protection Package introduced by the Queensland Government in 2009. This was completed using the pollutant loads referred to above, and using a number of regionally based measurements and literature to develop a ranking of catchment risk relative to anthropogenic load, potential exposure and ecosystem status. Subsequently, pollutant loads were calculated at finer resolution (sub-catchment scale) within the priority regions to refine the priority areas for management intervention.

The capacity of different regions, areas within each region and different industries within different regions to respond to these priorities is an important consideration. In some regions further prioritisation of different catchments is necessary, particularly in the Wet Tropics region where a regional prioritisation has not yet been completed, to ensure that the most effective investment is made.

Finally, many of the most significant influences of the research on management decisions have been through the participation of MTSRF-funded researchers in steering committees and technical groups coordinated by management agencies. These researchers were able to contribute their knowledge and synthesis of the research findings directly into the management processes; in many cases their contributions to discussion instigated interest which was subsequently supported through the provision of written evidence. Examples of these activities include the range of technical groups and forums coordinated for the regional Water Quality Improvement Plans, design workshops for the Paddock to Reef Program and ongoing participation in the associated Technical Advisory Group, the expert workshops convened for the Multi-Criteria Analysis for prioritising Reef Rescue investment, and involvement in several research prioritisation workshops which have informed the Reef Plan and Reef Rescue R&D strategies. Knowledge gained through the MTSRF and other research was also fed by participants involved in MTSRF research who contributed to the 2008 Scientific Consensus Statement for Water Quality Management in the GBR (Brodie *et al.* 2008a, 2008b) (with contributions from J. Brodie, K. Fabricius, R. Pearson, I. Gordon and J. Waterhouse).

6.3 Data limitations and future research needs

Given the importance of the application of the findings of the MTSRF-funded research outlined in this report, it would be remiss not to highlight some of the limitations of the studies and the areas where further research is required.

Despite the advances achieved through the MTSRF in estimating end-of-catchment pollutant loads, there are still several uncertainties and limitations associated with current load estimations (Brodie *et al.* 2009b) that managers need to be aware of. These include:

- Insufficient or ad hoc monitoring data to validate the models.
- Significant underestimation of the marine load during floods in areas outside of the Tully catchment.
- Broad underlying assumptions about pre-European conditions are made to differentiate natural loads from anthropogenic loads to give a more realistic estimate of the change in loads associated with human activities; this contributes to uncertainty in the estimates of improvements that may be achieved through changed land management practices.
- Limited modelling capability of erosion processes in closed-forests, and of material trapping. In recent model runs these parameters are generally calibrated to match monitoring data in that environment.
- Specific land use pollutant contributions on a regional basis are difficult to estimate and are based on broad assumptions based on proportional estimates of area. In addition, land use mapping in some catchments is dated.
- Many studies do not include the whole catchment source area and, as a result, large components of the total load may be overlooked.
- Limited pesticide monitoring data are available across the GBR catchment, hindering the development of more accurate regionally-specific and land use specific pesticide load estimations. Lewis and others are developing an improved technique to address this.
- A consistent technique needs to be developed and agreed to integrate or fuse together models with monitoring data to facilitate robust estimation of pollutant loads with uncertainties in a repeatable framework.

Ongoing research in these areas, directed by specific management questions, will help to address these gaps. There are also several other aspects of priority pollutants and priority areas for management in the GBR where further investigation would be beneficial for managers. Some of these gaps are highlighted below.

There are many outstanding questions with regard to water quality targets and target setting in the GBR. For example, how much do pollutant levels need to be reduced in order to achieve the desired outcomes of ecosystem health? What are the socio-economic implications of achieving water quality targets? Can water quality targets be achieved just through changed land management practices, or will changes in land use be required? These questions require long-term research efforts and should be a priority for any future research and development programs for the GBR.

The effect of dams on downstream water quality and the associated investment in priority catchment activities are important considerations which have not been studied across the GBR. Dams can trap significant quantities of contaminants from the upper catchment, as shown in the work of Lewis and others in the Burdekin catchment (Lewis *et al.* 2009a), but the effect of this depends on a number of factors including the retention time, percentage overflow and distance of the dam from the coast. For example, it is estimated that the Burdekin Falls Dam traps 60% of incoming suspended sediment during wet seasons,

whereas the Peter Faust Dam at Proserpine has never overflowed and thus sediment trapping in this dam would effectively be 100% (Lewis *et al.* 2009a). Dams in upper catchments, such as Fairbairn Dam in the Fitzroy region and Tinaroo Dam in the Wet Tropics region, are likely to have little impact on downstream water quality, whereas those closer to the coast will be very relevant (J. Brodie, pers. comm.). For example, in the Burnett Mary region, Reef Rescue funds have been primarily spent in areas below Paradise Dam as it is considered to trap 95% of sediment (Henry and Marsh, 2006), and as a result limited funds have been spent above the dam to date. These important considerations require further investigation for guiding future investment in the GBR catchments.

With regard to management practices, ongoing and proposed research building on the work already undertaken by van Grieken and others will assist in the estimation of the relative cost and effectiveness of improved management practices via better representation of the diversity of farm enterprises across land types and/or operating structures. However, improved quantification of the water quality benefits of a range of management practices across the GBR is required.

Researchers working in the GBR will continue to improve the approaches used to assess the risk of the GBR to external pressures including water quality and climate change and, ultimately, the combined impacts of these pressures. Understanding the linkage (synergistic/additive/dampening) between multiple stressors, in particular ocean acidification, temperature and nutrients, is a priority for future research. Recent work (Wagner *et al.* 2010) shows that DIN enrichment enhances bleaching susceptibility in reef ecosystems in the Florida Keys, USA. This confirms recent analysis/predictions from the GBR (Wooldridge and Done, 2009; Wooldridge, 2009). It is also known that DIN enrichment exacerbates the negative impact of increasing ocean acidification on coral growth (Renegar and Riegl, 2005). In addition, obtaining first-order approximations of local and regional residency times for dissolved and particulate materials is essential for these assessments. A receiving waters hydrodynamic model (currently under development with the support of MTSRF; Brinkman *et al.* 2010) will improve estimates of flood plume dilution and dispersal, deposition and re-suspension of sediments and help identify areas of greatest risk (e.g. exposure to highest loads, highest concentrations or greatest retention).

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Note: All references generated through MTSRF Program research are indicated by an asterisk (*).

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