2013 Scientific Consensus Statement

Chapter 3
Relative risks to the Great Barrier Reef from degraded water quality

Jon Brodie, Jane Waterhouse, Britta Schaffelke, Miles Furnas, Jeffrey Maynard, Catherine Collier, Stephen Lewis, Michael Warne, Katharina Fabricius, Michelle Devlin, Len McKenzie, Hugh Yorkston, Lucy Randall, John Bennett, Vittorio Brando

Image credits: TropWATER James Cook University, Tourism Queensland.

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

Table of Contents

Executive summary

A combination of qualitative and semi-quantitative assessments was used to estimate the relative risk of water quality constituents to Great Barrier Reef ecosystem health from major sources in the Great Barrier Reef catchments, focusing on agricultural land uses. In this assessment, the risk was defined simply as the area of coral reefs and seagrass within a range of assessment classes (very low to very high relative risk) for several water quality variables in each natural resource management region. The variables included ecologically relevant thresholds for concentrations of total suspended solids and chlorophyll *a* from daily remote sensing observations, and the distribution of key pollutants including total suspended solids, dissolved inorganic nitrogen and photosystem II inhibiting herbicides in the marine environment during flood conditions (based on end-of-catchment loads and plume loading estimates). A factor related to water quality influences on crown-of-thorns starfish outbreaks was included for coral reefs. The main finding was that increased loads of suspended sediments, nutrients (nitrogen and phosphorus) and pesticides all pose a high risk to some parts of the Great Barrier Reef. However, the risk differs between the individual pollutants, between the source catchments, and with distance from the coast.

Supporting points:

- Overall, nitrogen poses the greatest risk of pollution to coral reefs from catchments between the Daintree and Burdekin Rivers. Runoff from these rivers during extreme and early wet seasons is associated with outbreak cycles of the coral-eating crown-of-thorns starfish on the northern Great Barrier Reef shelf (15 to 17 degrees south) that subsequently generate secondary outbreaks throughout the central Great Barrier Reef. Great Barrier Reef-wide loss of coral cover due to crown-of-thorns starfish is estimated to be 1.4 per cent per year over the past 25 years, and a new outbreak is underway. It is estimated that crown-of-thorns starfish have affected more than 1000 of the approximately 3000 reefs within the Great Barrier Reef over the past 60 years.

- Of equal importance is the risk to seagrass from suspended sediments discharged from rivers in excess of natural erosion rates, especially the fine fractions (clays). Whether carried in flood plumes, or resuspended by waves, suspended solids create a turbid water column that reduces the light available to seagrass and corals. Increased sedimentation of fine particles interferes with many functions of benthic animal and plant communities. Runoff-associated risk decreases with increasing distance from rivers. High turbidity affects approximately 200 inshore reefs and most seagrass areas. On a regional basis, the Burdekin and Fitzroy regions present the greatest risk to the Great Barrier Reef in terms of sediment loads. Loss of seagrass habitat as a result of cyclones, floods and degraded water quality appears to be associated with higher mortality of dugong and turtles.

- At smaller scales, particularly in coastal seagrass habitats and freshwater and estuarine wetlands, pesticides can pose a high risk. Concentrations of a range of pesticides exceed water quality guidelines in many fresh and estuarine waterbodies downstream of cropping lands. Based on a risk assessment of the six commonly used photosystem II inhibiting herbicides, the Mackay Whitsunday and Burdekin region are considered to be at highest risk, followed by the Wet Tropics, Fitzroy and Burnett Mary regions. However, the risk of only a fraction of pesticides has been assessed, with only six of the 34 pesticides currently detected included in the assessment, and therefore the effect of pesticides is most likely to have been underestimated.

- The ranking of the relative risk of degraded water quality between the regions in the Great Barrier Reef is (from highest to lowest):

  - Wet Tropics
  - Fitzroy
  - Burdekin
  - Mackay Whitsunday
  - Burnett Mary
  - Cape York.

  Priority areas for management of degraded water quality in the Great Barrier Reef are Wet Tropics for nitrogen management; Mackay Whitsunday and the lower Burdekin for photosystem II inhibiting herbicide management; and Burdekin and Fitzroy for suspended sediment management.

- From a combined assessment of water quality variables in the Great Barrier Reef (using the total area of habitat affected in the areas identified to be of highest relative risk) and end-of-catchment anthropogenic loads of nutrients, sediments and photosystem II inhibiting herbicides, the regional ranking of water quality risk to coral reefs is (from highest risk to lowest):
  - Wet Tropics
  - Fitzroy
  - Mackay Whitsunday
  - Burdekin
  - Cape York
  - Burnett Mary.

  The regional ranking of water quality risk to seagrass is (from highest risk to lowest):
  - Burdekin
  - Wet Tropics
  - Fitzroy
  - Mackay Whitsunday
  - Burnett Mary
  - Cape York.

  Importantly in the Mackay Whitsunday region, 40 per cent of the seagrass area is in the highest relative risk class compared to less than 10 per cent for all other regions. The highly valuable seagrass meadows in Hervey Bay, and the importance to associated dugong and turtle populations in the Burnett Mary Region, were not included in the analysis as they are outside the Great Barrier Reef Marine Park boundaries.

- Both dissolved (inorganic and organic) and particulate forms of nutrients discharged into the Great Barrier Reef are important in driving ecological effects. Overall, increased nitrogen inputs are more important than phosphorus inputs. Dissolved inorganic forms of nitrogen and phosphorus are considered to be of greatest concern compared to dissolved organic and particulate forms as they are immediately bioavailable for supporting algal growth. Particulate forms of nitrogen and phosphorus mostly become bioavailable, but over longer time frames. Most dissolved organic nitrogen typically has limited and delayed bioavailability.

- Little is known about the types and concentrations of contaminants bound to sediment discharged by rivers into the Great Barrier Reef and the risk that these pose to marine ecosystems.

Introduction

The main water quality pollutants of concern for the Great Barrier Reef are identified in Chapter 4, Sources of sediment, nutrients, pesticides and other pollutants in the Great Barrier Reef catchment (Kroon *et al.,* 2013) and include enhanced levels of suspended sediments, excess nutrients and pesticides. Until recently, there has been insufficient knowledge about the relative exposure to and effects of these pollutants to guide effective prioritisation of the management of their sources. In this chapter, we will review current knowledge of the relative risk of pollutants, including different nutrient species, suspended sediment (including different size fractions) and pesticides. These issues were not specifically addressed in the 2008 Reef Plan Science Consensus Statement (Brodie *et al.,* 2008).

This chapter specifically addresses the overarching question: (**What are the relative risks to various parts of the Great Barrier Reef from *degraded* water quality?)** with the following sub questions:

a) What is current understanding of the ecological risk of individual pollutants to different components of the Great Barrier Reef marine ecosystems?
b) Where are the risks highest or the benefits of improved management greatest?
c) When are the risks highest or the benefits of improved management greatest?
d) What are the consequences of the water quality impact and which pollutants pose the greatest risk?

It is structured around these four questions. Questions a, b and c are largely supported by the most recent assessment of the relative risk of water quality to the Great Barrier Reef undertaken by Brodie *et al.,* (2013a).

Suspended (fine) sediments and nutrients (nitrogen, phosphorus) are referred to as 'pollutants' in this chapter. In this situation we explicitly mean enhanced concentrations of or exposures to these pollutants which are (directly or indirectly) derived from human activities in the Great Barrier Reef ecosystem or adjoining systems (e.g. river catchments). Fine sediments and nutrients naturally occur in the environment; all living things in ecosystems of the Great Barrier Reef require nutrients, and many have evolved to live in or on sediment. Pesticides do not naturally occur in the environment. The natural concentrations of these materials in Great Barrier Reef waters and inflowing rivers can vary, at least episodically, over considerable ranges. Pollution occurs when human activities raise ambient levels of these materials (time averages, or event-related) to concentrations that cause environmental harm and changes to the physical structure, biological communities and biological functions of the ecosystem.

This chapter was led by TropWATER James Cook University with contributions from several representatives from the Australian Institute of Marine Science (AIMS), the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES), the Great Barrier Reef Marine Park Authority (GBRMPA), the Commonwealth Science and Industrial Research Organisation (CSIRO), Queensland Department of Environment and Heritage Protection (DEHP), Queensland Department of Science, Information Technology, Innovation and the Arts (DSITIA) and independent researchers.

The chapter was prepared with the support of funding from the Australian Government's National Environmental Research Program. The authors would also like to acknowledge the funding provided by the Queensland Department of Environment and Heritage Protection for the associated project reported in Brodie *et al.*, (2013a).

Synthesis process

The preparation of this synthesis was undertaken with financial support from the Queensland Department of Environment and Heritage Protection under the Reef Protection Package Science Program. The funding supported the completion of the most recent assessment of the relative risk of pollutants in the Great Barrier Reef region to Great Barrier Reef ecosystem health (Brodie *et al.,* 2013a) which forms the basis of this chapter.

Ecological Risk Assessment (ERA) is a term used for a variety of methods to determine the risk posed by a stressor, for example a pollutant, to the health of an ecosystem (AS/NZS, 2004). Risk is usually defined as the probability that an adverse effect will occur as a result of ecosystem exposure to a certain concentration of the stressor. Risk is often quantified as the product of the *likelihood* of an event occurring (exposure) and the *consequences* (also measured as effects) of that event. Risk assessments are used as decision tools that rank risks to human values in order to prioritise management actions and investments (e.g. Burgman 2005; AS/NZS, 2004). A number of methodologies are available to carry out the analysis with Bayesian techniques now often favoured by decision makers (e.g. Hart *et al.,* 2005; Hart and Pollino, 2008).

In this assessment the relative risk of degraded water quality among regions was determined by combining information on the estimated ecological risk of water quality to coral reefs and seagrass in the Great Barrier Reef and end-of-catchment pollutant loads. This approach attempts to relate the water quality conditions in the Great Barrier Reef to catchment based influences, albeit in a relatively crude way.

Ecological risk is assessed using a relatively simple approach. The *likelihood of exposure* of a species or habitat to an impact is typically a function of the intensity of the impact (the concentration or load of a pollutant) and the length of time it is exposed to the impact. For example, a seagrass meadow may be exposed to a high intensity impact for a short period of time (acute), or to lower intensities for longer periods (chronic). When quantifying exposure, it is important to determine the threshold concentrations that lead to an effect on species or habitats, that is, the concentration that potentially leads to damage or mortality within hours or days, as well as understanding long-term average concentrations and the duration of exposure. This complicates the description of exposure thresholds given their values may change by one to two orders of magnitude between days, seasons and years. Hence, some key water quality variables such as suspended sediments are divided into different thresholds based on ecological responses and periods of exposure. To reflect this, each threshold is classified into several assessment classes to represent the potential differences between the duration and severity of the influence (from lowest to highest).

The *consequences* are the measured effects of the water quality exposure. Current knowledge of the effects of degraded water quality on the health of the Great Barrier Reef are summarised in the 2013 Scientific Consensus Statement. The Great Barrier Reef Water Quality Guidelines reflect our knowledge of ecological thresholds for water quality variables for coral reefs in the Great Barrier Reef (GBRMPA, 2009). However, only limited information is available to draw conclusions on the effects of the exposure of sediments, nutrients and pesticides on seagrass health. Evidence shows that one of the greatest drivers of seagrass health is the availability of light, which is reduced by increased suspended sediment and the secondary effects of increased nutrients such as increased phytoplankton production and growth of epiphytes (Collier *et al.,* 2012). However, in the absence of more regionally and species-specific knowledge of pollutant impacts on seagrass, the same threshold concentrations have been used for coral reefs and seagrass in this assessment. It is also recognised that the consequence of the exposure of species or habitats to a range of water quality conditions is complicated by the influence of multiple pressures, and many external influences including weather conditions, however it is difficult to factor this into the risk assessment in any quantitative way.

Given the above and recognising the inconsistencies in the spatial and temporal availability of the water quality data, our capacity to produce a true likelihood or true consequence estimate for this assessment is limited. It was therefore necessary to develop an effective, simple and standard methodology for the risk assessment that could be implemented with the available data, in a way that could be easily communicated and discussed with decision-makers and stakeholders. For this reason, ecological risk in the Great Barrier Reef is expressed simply as the area of coral reefs and seagrass within a range of assessment classes (very low to very high relative risk) for several water quality variables in each region in the GBR catchment. Our method for calculating risk essentially assesses the likelihood of exceedance of a selected threshold. This likelihood was set as one for a parameter and location if observations or modelled data indicate that the threshold was exceeded. Conversely, the likelihood was set as zero if observations or modelled data indicate that the threshold was not exceeded. As consequences are mostly unknown at a regional or species level, potential impact was calculated as the area of coral reef and seagrass (in square kilometres) within the highest assessment classes of the water quality variables (reflecting the highest severity of influence). The effects of multiplying the habitat area by one or zero for the likelihood mean that the *final assessment of risk in this assessment is only an indication of potential impact* - the area of coral reef and seagrass in which exceedance of an agreed threshold was modeled or observed. This becomes an assessment of 'relative risk' by comparing the areas of each habitat affected by the highest assessment classes of the variables among regions, and was used to generate a 'Marine Risk Index'.

Modelled end-of-catchment pollutant loads (generated from the Source Catchments model framework for the Reef Plan Paddock to Reef program) were obtained for each region for key pollutants, and only the anthropogenic portions were considered. The anthropogenic load is calculated as the difference between the long term average annual load, and the estimated average annual pre-European load. This information was used to define a 'Loads Index'.

Figure 1 illustrates the geographic boundaries of the assessment and the spatial distribution of the marine habitats in the assessment (coral reefs and seagrass), based on best available information. The area of Great Barrier Reef lagoon waters was also included as an ecological endpoint to represent the important pelagic ecosystems; however, the assessment was limited by associated knowledge of the likely impacts of water quality on these ecosystems and therefore not reported here. Qualitative conclusions were drawn about coastal and estuarine wetlands where information was available. The selection of the variables and methods used in the assessment were informed by several supporting studies reported in Brodie *et al.,* (2013a) and by the reviews of current knowledge presented in the other chapters. Unlike the risk assessment undertaken for Reef Plan in 2004 (Greiner *et al.,* 2005), this assessment did not take into account the social and economic significance of the ecological assets, for example the value of coastal industries such as tourism and fisheries.

A suite of water quality variables were chosen that represent the pollutants of greatest concern with regards to agricultural runoff and potential impacts on Great Barrier Reef ecosystems. Ecological impacts of terrestrial runoff on coral reefs and seagrass can be experienced as either acute, short term changes associated with formation of high-nutrient, high-sediment, low salinity flood plumes or the more chronic impacts associated with changes in long-term water quality concentration (Devlin *et al.,* 2012). The ecological impact of catchment pollutants varies not only with the type of pollutant, the magnitude and extent of the riverine influence but also with the ecosystems being affected and the frequency and duration of plume occurrence (e.g. Devlin *et al.,* 2013b). Long time series of pollutant concentration data provides a way of assessing chronic stress, while river plume models can help to develop risk maps by defining areas which may experience acute or chronic high exposure to pollutants or stressors (Alvarez-Romero *et al.,* 2013). Details of the pollutant movement and frequency of inundation can be key measurements in attributing water quality decline to ecosystem change. This assessment uses a combination of variables that represent chronic and acute stress on Great Barrier Reef ecosystems.

The selected variables are summarised in Table 2 and include ecologically relevant thresholds for concentrations of total suspended solids and chlorophyll *a* from daily remote sensing observations, and the distribution of key pollutants including total suspended solids, dissolved inorganic nitrogen and photosystem II inhibiting herbicides in the marine environment during flood conditions (based on end-of-catchment loads and surface water exposure estimates). A spatial variable was included that represents an area of the Great Barrier Reef lagoon where primary crown-of-thorns starfish outbreaks have most frequently been observed. Crown-of-thorns starfish outbreaks are an important cause of mid and outer shelf coral loss on the Great Barrier Reef (De'ath *et al.,* 2012) and are, based on current understanding, a response to excess nutrient runoff from certain catchments that reaches this 'crown-of-thorns starfish initiation zone' (Fabricius *et al.,* 2010). The relevance of each of these variables is described in further detail in Waterhouse *et al.,* (2013), and more detailed information on pollutant impacts on Great Barrier Reef ecosystems is provided in the Scientific Consensus Statement Chapter 1 (Schaffelke *et al.,* 2013).

For each variable, thresholds above which potential impacts have been observed were defined and classified into three to five classes (from lowest to highest), largely on the basis of the time (or probability) the ecosystem is likely to be exposed to concentrations above the threshold; these are defined as 'assessment classes'. The selected variables represent long term conditions (chronic exposure) and wet season pollutant loadings in flood plumes (acute exposure).

Additional variables were considered that have not been included here due to the current lack of data showing their temporal and spatial variability and ecological impacts. These include: phosphorus exposure, chronic exposure to photosystem II inhibiting herbicides and non-photosystem II inhibiting herbicides, and time series of pesticide concentration data. The decision to select dissolved inorganic nitrogen as primary nutrient variable within the assessment is supported by analysis of the relative importance of nutrient forms and of nitrogen and phosphorus in the Great Barrier Reef (Furnas *et al.,* 2013b). The analysis indicates that dissolved inorganic and particulate forms of nutrients discharged into the Great Barrier Reef are both important in driving ecological effects but increased nitrogen inputs are more important than phosphorus inputs. Dissolved inorganic forms of nitrogen and phosphorus are considered to be of greatest concern compared to dissolved organic and particulate forms of nutrients, as they are immediately and completely bioavailable for algal growth (see Furnas *et al.,* 2013b). Particulate forms mostly become bioavailable over longer time frames, and dissolved organic forms typically have limited and delayed bioavailability (see Furnas *et al.,* 2013b).

Figure 1. Assessment boundaries considered in the risk assessment for Reef Plan 2013 and Reef Rescue phase two. Consideration of ecosystems is confined to the areas inside the Great Barrier Reef Marine Park.

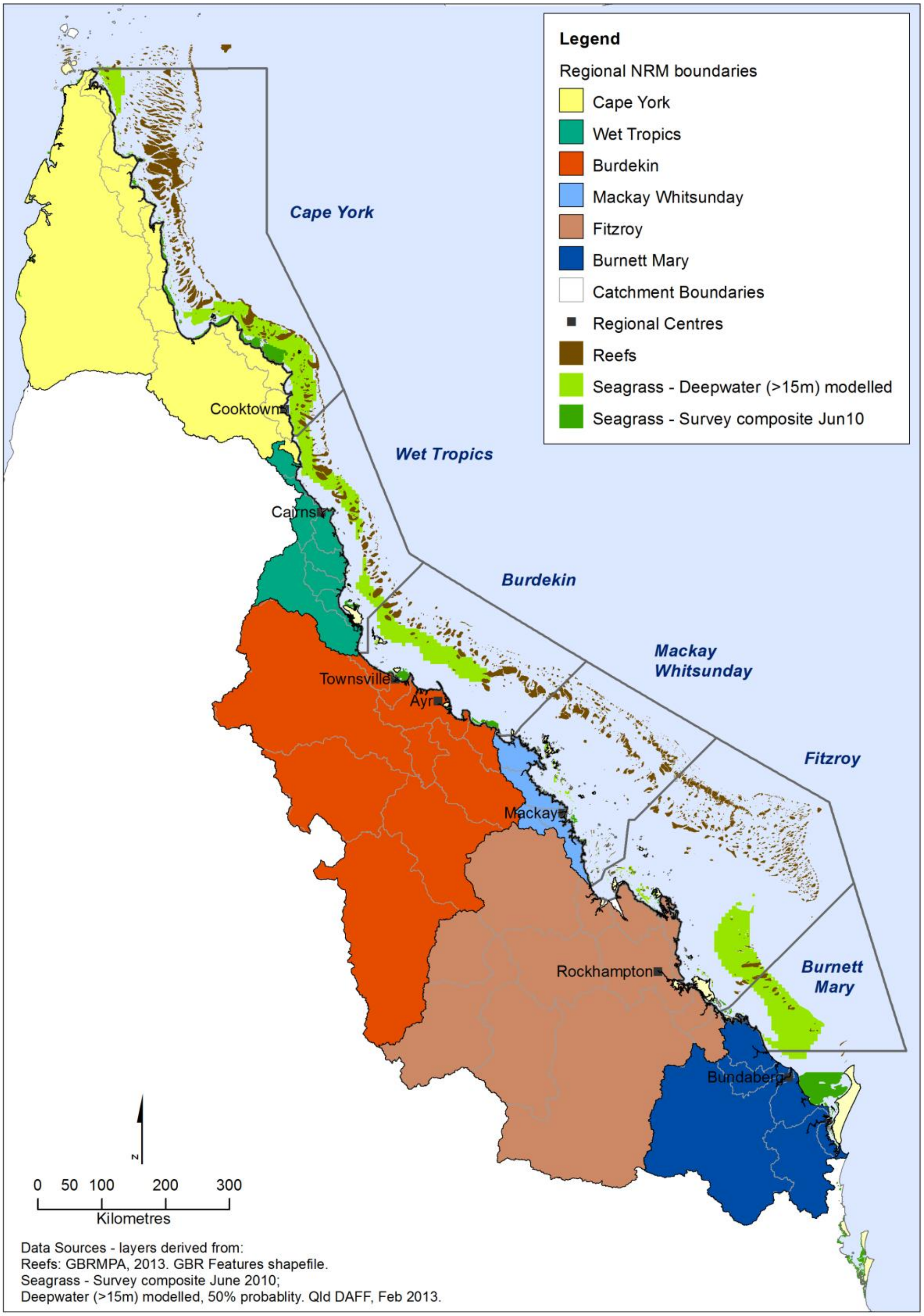


Table 1. Summary of water quality variables, assessment classes and data sources considered in the marine risk assessment. Refer to Waterhouse *et al.,* (2013) for further explanation of the selected variables.

Variables	Assessment Class					Data source/methodology
	Very Low 1	**Low 2**	**Medium 3**	**High 4**	**Very High 5**	*Refer to Waterhouse et al., (2013) for a more detailed description of the methods.*
Sediments						
TSS concentration (mg/L) *Frequency of exceedance %*						Based on daily observations of TSS in the period 1 November 2002 to 30 April 2012. Data has been interpolated across reefs (which are masked during image processing) using Euclidean Allocation in ArcGIS. Classification of frequency of exceedance is based on the number of valid observations in the full observation period. Method for extraction is described in Brando *et al.,* (2013).
Threshold a: 2 mg/L	<1	1-10	10-20	20-50	50-100	Threshold correlates strongly with declines in ecosystem condition such as increased macroalgal growth and declining diversity. Average annual threshold for TSS in the Great Barrier Reef Water Quality Guidelines.
Threshold b: 7mg/L	0	<1	1-10	10-20	20-100	Threshold is equivalent to a turbidity of 5 nephelometric turbidity units (NTU). Shown to have various ecosystem effects including coral reef stress, declines in seagrass cover (Collier *et al.,* 2012), fish habitat choice, home range movement (Wenger and McCormick, in press) and (above 7.5 nephelometric turbidity units) foraging and predator-prey relationships (Wenger *et al.,* in press).
TSS Plume Loading (mean 2007-2011)	Category 1		Category 2	Category 3		The frequency and extent of the influence of flood plumes containing differing concentrations of total suspended solids is used to provide an estimation of the extent of surface exposure of coral reefs and seagrass during wet season conditions. Modelled using an assessment of plume frequency from satellite imagery and monitored end of catchment loads in each wet season (November to May) from 2007 to 2011 (Devlin et al, 2013a). The mean of the five annual maps was selected as a way of factoring in inter-annual variability in river discharge, although it is recognised that this period was characterised by several extreme rainfall events.
Nutrients						
Chlorophyll concentration (µg/L) *Frequency of exceedance %*						Assessment classes were based on daily observations of Chlorophyll concentrations over the period 1 November 2002 to 30 April 2012. Data was interpolated across reefs (which are masked during image processing) using Euclidean Allocation in ArcGIS. Classification is based on the number of valid observations in the full observation period. Method for extraction described in Brando *et al.,* (2013).

Variables	Assessment Class					Data source/methodology
	Very Low 1	**Low 2**	**Medium 3**	**High 4**	**Very High 5**	*Refer to Waterhouse et al., (2013) for a more detailed description of the methods.*
0.45 µg/L	<1	1-10	10-20	20-50	50-100	Chlorophyll is an indicator of nutrient enrichment in marine waters. De'ath and Fabricius (2008) identified 0.45 µg/L as an important ecological threshold for macroalgal cover, hard coral species richness, octocoral species richness. Annual average threshold for chlorophyll in the Great Barrier Reef Water Quality Guidelines. Significant benefits for the ecological status of reefs in the region are likely if mean annual chlorophyll concentrations remain below this concentration.
DIN Plume Loading (mean 2007-2011)	Category 1		Category 2	Category 3		Elevated DIN is an indicator of nutrient enrichment. High concentrations of DIN can reduce coral recruitment (Babcock and Davies 1991; Loya *et al.,* 2004), enhance coral bleaching susceptibility (Wooldridge and Done, 2009) and change the relationship between coral and macroalgal abundance (De'ath and Fabricius, 2010). Elevated concentrations can also be deleterious to seagrass by lowering ambient light levels via the proliferation of local light absorbing algae thereby reducing the amount of photosynthesis in seagrass, particularly in deeper water (Collier, 2013). Modelled using an assessment of plume frequency from satellite imagery and monitored end of catchment loads in each wet season (November to May) from 2007 to 2011 (Devlin et al, 2013a). The mean of the five annual maps was selected as a way of factoring in inter-annual variability in river discharge, although it is recognised that this period was characterised by several extreme rainfall events.
COTS Initiation Zone	Out of the zone				In the zone	Shows an area defined to be highest risk in initiating COTS outbreaks, defined as the area between Latitude 14.5°S and 17°S and described in Furnas *et al.,* (2013a). Data from this area shows prolonged periods of high chlorophyll concentrations that exceed 0.8 µg/L, which is important for COTS larval survival.
Pesticides						
PSII Herbicide modelled concentration (µg/L)	0.025-0.1	0.1-0.5	0.5-2.3	2.3-10	>10	Based on an estimate of the relationship between Colour Dissolved Organic Matter (CDOM) and salinity, and then a salinity to PSII herbicide concentration relationship in a flood plume event in one river in each natural resource management region in 2009-2011. Data has been interpolated across reefs (which are masked during image processing) using Euclidean Allocation in ArcGIS. Risk posed was determined using a number of methods - some only assessed acute toxic effects, others both acute and chronic. Described in Lewis *et al.,* (2013).

Variables	Assessment Class					Data source/methodology
	Very Low 1	Low 2	Medium 3	High 4	Very High 5	*Refer to Waterhouse et al., (2013) for a more detailed description of the methods.*
						>0.025-0.1 µg/L: No observable effect; **0.1-0.5 µg/L**: Photosynthesis is reduced by up to 10% in corals (Negri *et al.,* 2011); seagrass (Haynes *et al.,* 2000; Chesworth *et al.,* 2004; Gao *et al.,* 2011; Flores *et al.*, in review) and microalgae (Magnusson *et al.,* 2008, 2010). The effect on primary production is minor. **0.5-2.3 µg/L**: Photosynthesis is reduced by between 10% and 50% in corals (Negri *et al.,* 2011); seagrass (Haynes *et al.,* 2000; Chesworth *et al.*, 2004; Gao *et al.,* 2011; Flores *et al.*, in review) and microalgae (Magnusson *et al.,* 2008, 2010). The community structure of tropical microalgae can be affected by concentrations of diuron as low as 1.6 µg/L (Magnusson *et al.,* 2012). The effect on primary production is moderate. **2.3-10 µg/L** Photosynthesis is reduced by between 50% and 90% in corals (Jones and Kerswell, 2003; Negri *et al.,* 2011); seagrass (Chesworth *et al.,*, 2004; Gao *et al.,* 2011; Flores *et al.,*, in review) and microalgae (Magnusson *et al.,* 2008, 2010). A 50% reduction of growth and biomass of tropical microalgae was also reported in this concentration range (Magnusson *et al.,* 2008). The community structure of tropical microalgae is significantly affected and this causes significant changes in the tolerance of microbial communities to herbicides (Magnusson *et al.,* 2012). The effect on primary production is major. **> 10 µg/L**: reduced growth and mortality in seagrass (Gao *et al.,* 2011) and loss of symbionts (bleaching) in corals (Jones *et al.,* 2003; Negri *et al.,* 2005).

TSS: total suspended solids; DIN: dissolved inorganic nitrogen; COTS: crown-of-thorns starfish; PSII: photosystem II inhibiting herbicides; CDOM: coloured dissolved organic matter

A three-step approach of estimating the relative risk of pollutants to the Great Barrier Reef at a regional level was applied (illustrated in Figure 2):

1. Assessment of the relative importance of different pollutants on Great Barrier Reef ecosystems (coral reefs and seagrass). This identifies the areas where each water quality variable is considered to pose the greatest relative risk to coral reefs and seagrass between the regions. The output can be used to guide priorities for management of individual pollutants between regions.
2. Combined risk of degraded water quality to Great Barrier Reef ecosystems. The combined assessment takes into account all assessment classes for each variable to generate a Marine Risk Index for coral reefs and seagrass. The areas within the Risk Index represent the areas of highest relative risk to degraded water quality in the Great Barrier Reef and identify the areas where coral reefs and seagrass are most likely to be under pressure from degraded water quality.
3. The relative risk of degraded water quality to Great Barrier Reef ecosystems. This relates the results of Part One and Part Two to land based influences using an assessment of end-of-catchment anthropogenic loads and river discharges (Loads Index and Crown-of-thorns starfish Influence Index). These results inform the regional management priorities required to address the risks identified in Part One and Part Two in terms of where to focus effort on which pollutants.

The detailed methods for the risk assessment are described in Waterhouse *et al.,* (2013), and are summarised here.

The relative importance of the three primary pollutants among regions was estimated by estimating the areas of coral reef and seagrass adjacent to each region for each of the 'assessment classes'. In comparing the risks from sediments and nutrients between regions, only the areas in the highest assessment class were considered as these were agreed (through expert judgment) to be the most relevant for assessing potential ecological impact. For photosystem II inhibiting herbicides, the two highest assessment classes were used in recognition of the level of toxicity associated with these classes. It should be noted that this assessment does not account for the potential synergistic or antagonistic effects that these multiple stressors may have on ecosystems when acting together.

The output is a map and a table showing the area (square kilometres) of coral reef and seagrass within each assessment class for all variables in all regions. The results were then anchored for comparison, i.e. the maximum area across all regions is set as an anchor point and given a value of 100, and all other area calculations are then expressed as a proportion of the maximum (values between zero and 100).

To estimate the combined risk of the selected water quality variables to marine ecosystems (Part 2), the results for the individual variables were summed at the one square kilometre pixel scale and normalised between zero and one using the Multi-Criteria Analysis Shell for Spatial Decision Support (MCAS-S). This essentially provides a weighting for each class of each variable, shown in Table Three. Pixels in the highest class category all received the maximum value of one. For example, for dissolved inorganic nitrogen and total suspended solids plume loading between 2007 and 2011, with three relative classes pixels received a score of 0.33 (Low), 0.66 (Medium) or a one (High). Anchoring and normalising the data to the uni-directional scale of zero to one ensures all variables are equally weighted and that the ranges in data values (very different among variables) can be justifiably averaged to produce a single index. Pixels with no data were not included in the final sum. A number of options were tested for combining the variables including grouping the variables into sediment, nutrient and pesticides and then summing them, or summing of the individual variables.

An important consideration of the assessment is the equivalency of the assessment classes for each variable. The classifications for this assessment were based on expert opinion and are shown in Table Three. Ideally the classes for each variable would be scaled so that they are equivalent in terms of potential ecological impacts to provide comparable weightings between variables. However, it is recognised that this may not be the case for all variables given the inconsistencies in the temporal and spatial characteristics of the datasets. As temporal and spatial resolution of data increases and the knowledge of the impacts of sediments, nutrients and photosystem II inhibiting herbicides on Great Barrier Reef ecosystems is advanced, this capability can be improved in future assessments.

Table 2. Summary of the weightings given to each assessment class and the overall weighting for the water quality variables used in the combined assessment. The variables are described in Table 2. The cells shaded in grey show the classes included in assessing the relative risk between variables (Part 1). Source: Waterhouse *et al.,* (2013).

Variables	**Overall weighting**	**Assessment Class**				
		Very Low 1	**Low 2**	**Medium 3**	**High 4**	**Very High 5**
Total suspended solids (TSS) exceedance 2 mg/L Frequency of exceedance (%)		<1	1-10	10-20	20-50	50-100
MCAS-S weighting	*1/7*	*0*	*0.25*	*0.5*	*0.75*	*1.0*
TSS exceedance 6.6 mg/L/ 5 NTU Frequency of exceedance (%)		0	<1	1-10	10-20	20-50 50-100
MCAS-S weighting	*1/7*	*0*	*0*	*0.33*	*0.66*	*1.0*
TSS plume loading (mean 2007-2011)		Category 1		Category 2	Category 3	
MCAS-S weighting	*1/7*	*0.33* [2]		*0.66*	*1.0* [3]	
Chlorophyll *a* exceedance (0.45 µg/L) Frequency of exceedance (%)		<1	1-10	10-20	20-50	50-100
MCAS-S weighting	*1/7*	*0*	*0.25*	*0.5*	*0.75*	*1.0*
DIN plume loading (mean 2007-2011)		Category 1		Category 2	Category 3	
MCAS-S weighting	*1/7*	*0.33* [1]		*0.66*	*1.0* [2]	
PSII herbicide modelled concentration (2009-2011) (µg/L)		0.025	0.1	0.5	2.3	10
MCAS-S weighting	*1/7*	*0*	*0.25*	*0.5*	*0.75*	*1.0*
COTS Initiation Zone		Outside COTS Initiation Zone				Within COTS Initiation Zone
MCAS-S weighting	*1/7*	*0*				*1.0*

[1] This class covers Very Low and Low; [2] This class covers High and Very High; TSS: total suspended solids; MCAS-S: Multi-Criteria Analysis Shell for Spatial Decision Support developed by ABARES, refer to http://www.daff.gov.au/abares/data/mcass; NTU: nephelometric turbidity units; DIN: dissolved inorganic nitrogen; PSII: photosystem II inhibiting; COTS: crown-of-thorns starfish.

To calculate the relative risk of water quality to ecosystems and regions in the Great Barrier Reef (Part 3 in Figure 2) the results of the marine risk assessment were linked to pollutant loads. Anthropogenic end-of-catchment loads were expressed as the proportion of total Great Barrier Reef load for each region to relate to the outcomes of the marine risk assessment (from Part 2 in Figure 2). Anthropogenic loads are calculated as the difference between modelled current long term annual average loads and modelled annual average pre-

European loads. This recognises that while the total Great Barrier Reef load is important in influencing the marine water quality conditions, it is only the anthropogenic proportion that can be factored into management. The regional proportional contributions of total suspended solids, dissolved inorganic nitrogen and photosystem II inhibiting herbicides anthropogenic loads were anchored (to normalise to a standard scale) and averaged to generate a Loads Index for each region. This assumes that the relative importance of each load is equal which may not be the case, although there is currently insufficient knowledge to weight the importance of the three pollutants relative to each other.

It is recognised that assessment of the input of pesticides from each region can be expressed in a number of ways, and while loads allow comparison between regions, it is the toxicity and therefore concentration that is most relevant to the receiving environment. However, pesticide concentration data is currently limited across the Great Barrier Reef. Therefore, in the final conclusions relating to pesticide risk in this assessment, additional evidence is drawn from a combination of load and concentration data from specific locations, assessed in Lewis *et al.,* (2013).

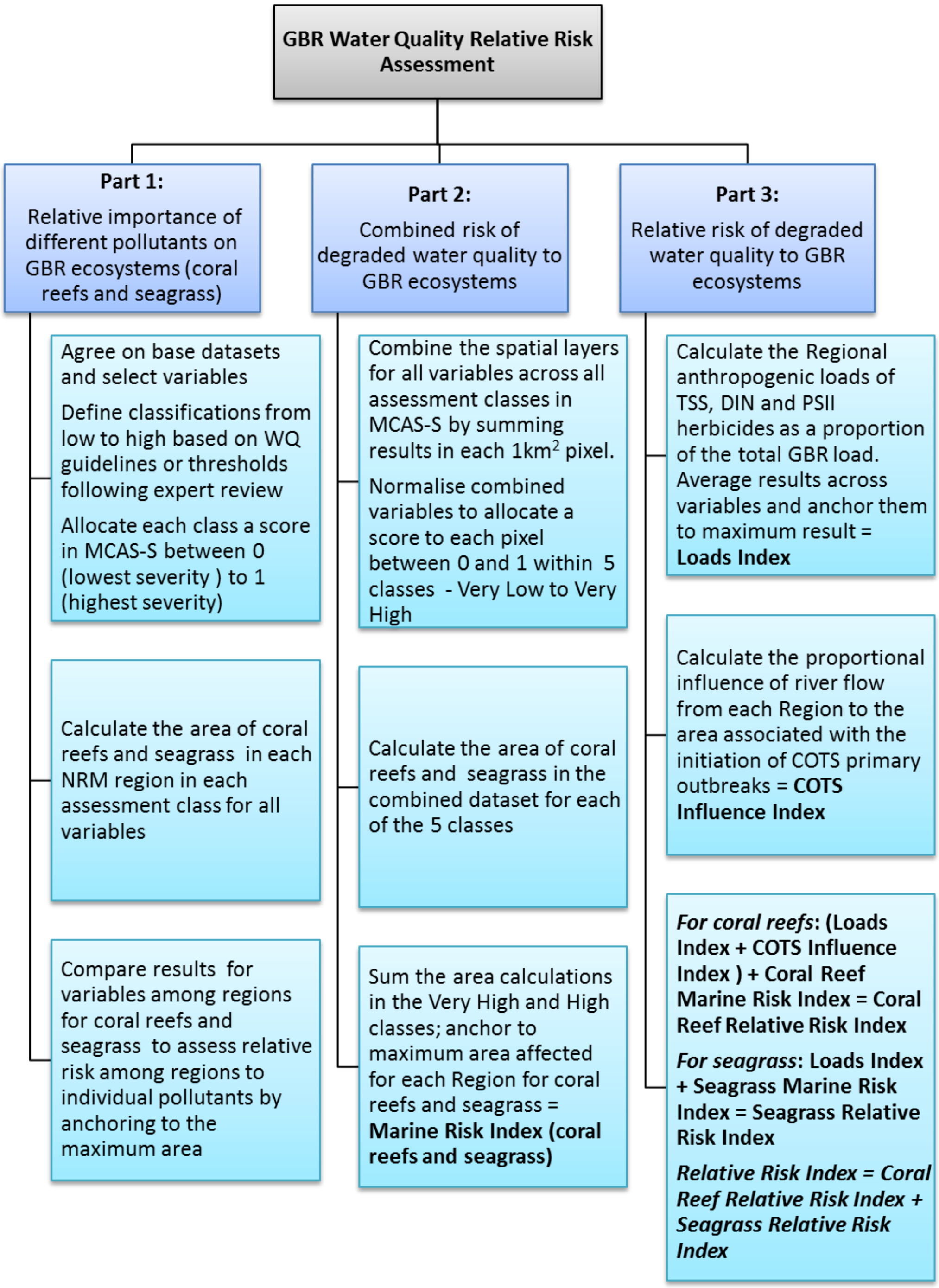
An index specific to the potential influence of river discharges on the initiation of crown-of-thorns starfish primary outbreaks in the Great Barrier Reef was added (see Furnas *et al.,* 2013a). Dissolved inorganic nitrogen runoff is considered to be an important factor as approximately 40 per cent of the loss of coral cover in the Great Barrier Reef since 1987 has been attributed to crown-of-thorns starfish predation (De'ath *et al.,* 2012). A crown-of-thorns starfish outbreak initiation zone has been defined between Lizard Island (14.5 degrees south) and Cairns (17 degrees south). On total volumetric basis, most (86 per cent) of the estimated freshwater input (direct and indirect) to the zone comes from Wet Tropics rivers, with the remaining 14 per cent from the Burdekin River (Furnas *et al.,* 2013a). These estimates were used to create a **Crown-of-thorns starfish Influence Index**. The normalised scores are 100 for Wet Tropics, 16 for Burdekin, and nil from all other regions.

To provide an overall water quality risk ranking between the regions, the Marine Risk Index for coral reefs and seagrass, Loads Index and Crown-of-thorns starfish Influence Index (for coral reefs) were combined. For coral reefs, the Crown-of-thorns starfish Influence Index was included by summing with the Loads Index, however, only the Loads Index and the Risk Index were used for seagrass. The final Indexes for coral reefs and seagrass were then summed and normalized to give an overall assessment of the relative risk of degraded water quality to coral reefs and seagrass to generate a **Relative Risk Index** for each region.

The distribution of coral reefs and seagrass in the Great Barrier Reef provide important context for the results of the risk assessment (see Figure 3; inset table shows the areas in each region). The Cape York region contains the greatest areas of coral reefs and seagrass in the Great Barrier Reef; it is also the largest area overall. The area coral reef and seagrass in all other regions are reasonably comparable, with the exception of Mackay Whitsunday and Burnett Mary. The area of seagrass in the Mackay Whitsunday region is relatively low compared to other regions with only approximately 430 square kilometres. Deepwater seagrasses are sparse in the Mackay Whitsunday region, particularly south of Mackay, where tidal velocities are high and no major deepwater seagrass meadows exist (Coles *et al.,* 2009). High current stress, low Secchi readings and coarse mobile sediments make this an unsuitable habitat for seagrass growth.

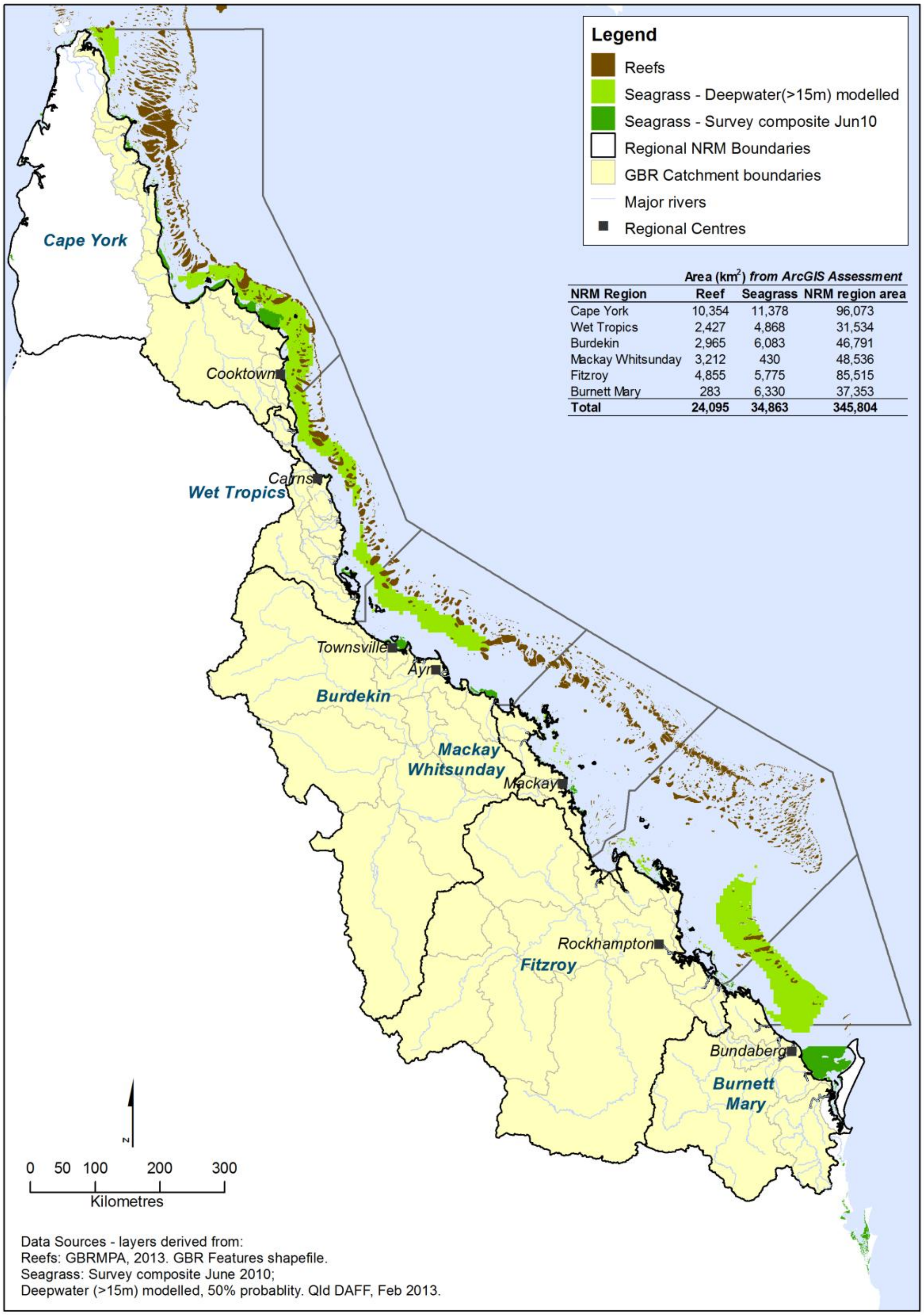
The habitats of the Burnett Mary region are under estimated in this assessment, as the Great Barrier Reef Marine Park and World Heritage Area boundary does not include all of the habitat areas that would be affected by the catchments of the Burnett Mary region. In particular, there is a large area of seagrass to the south of the boundary in Hervey Bay which is known to provide important habitat, and foraging grounds, for species that also inhabit the Great Barrier Reef Marine Park.

Figure 2. Illustration of the primary steps in the assessment of the relative risk of water quality to Great Barrier Reef ecosystems.



GBR: Great Barrier Reef; WQ: water quality; MCAS-S: Multi-Criteria Analysis Shell for Spatial Decision Support; TSS: total suspended solids; DIN: dissolved inorganic nitrogen; PSII: photosystem II inhibiting herbicides; NRM: natural resource management; COTS; crown-of-thorns starfish.

Figure 1. Locations of coral reefs and seagrass used for the risk assessment. Coral reef outlines used are per the Great Barrier Reef Marine Park Authority Spatial Data Centre official reefs spatial data layer 2013. Seagrass areas are observed (composite of surveyed data as at June 2010) and modelled deepwater seagrass habitat after Coles et al., (2009). Inset table shows the area of coral reef and seagrass for each marine region.



Previous Consensus Statement findings

The 2008 Scientific Consensus Statement did not specifically address the relative risk of specific water quality pollutants in the Great Barrier Reef. None of the water quality risk assessments to date have attempted to rank pollutants as a basis for prioritising management effort.

Exposure to land-sourced pollution has been identified as an important contributor to the world-wide decline in coral reef condition (Pandolfi *et al.,* 2003; Burke *et al.,* 2011). Different parts of the Great Barrier Reef World Heritage Area (GBRWHA) are exposed to very different levels of land-sourced pollutants. The degree of exposure is a function of factors such as the distance from the coast, the magnitude of river discharges, the distance from river mouths, physical forcing such as the strength and direction of wind and currents, and the mobility and persistence of different pollutant types. Differential exposure to land-sourced pollutants has important consequences for the likely degree of degradation that habitats such as coral reefs and seagrass may suffer and an assessment of exposure is required to prioritise management of such pollution on a regional basis.

To date, the prioritisation of potential management responses for different pollutants, land uses and industries, and regions has been supported by risk assessments using a Multiple Criteria Analysis (MCA) approach (Brodie and Waterhouse, 2009; Brodie *et al.,* 2009; Cotsell *et al.,* 2009; Greiner *et al.,* 2005; Waterhouse *et al.,* 2012). These assessments, although the best available at the time, are limited for reasons summarised in Table 1. While the analyses have proved useful for ongoing prioritisation of investment under Reef Plan (Queensland Department of the Premier and Cabinet, 2009), specifically as part of Reef Rescue and the selection of priority management areas under the Reef Protection Package, more sophisticated analyses are now needed to more confidently prioritise between pollutants and across catchments.

Table 3. Summary of the elements included in past and current assessments of the risk of degraded water quality to the Great Barrier Reef used to inform Reef Plan management prioritisation.

Element	Reef Plan *Greiner et al., (2005)*	Reef Rescue *Cotsell et al., (2009)*	Reef Protection package *Waterhouse et al., (2012)*	Reef Plan 2013 / Reef Rescue phase two *Brodie et al., (2013a)*
Method	Multiple Criteria Analysis	Multiple Criteria Analysis	Multiple Criteria Analysis	Multiple Criteria Analysis plus interpretive studies
Data availability	Very limited	Limited	Moderate	Good
Analysis end point	Coral reefs and seagrass	Coral reefs	Coral reefs, seagrass, water column	Coral reefs, seagrass, plus freshwater to marine ecosystems for pesticides
Relative importance of pollutants	No	No	No	Yes
Pesticide data	Very limited	Limited	Limited	Yes, with limitations
Marine exposure estimate	Limited – from Devlin *et al.,* 2003	Moderate – from Maughan and Brodie, 2009	Moderate – from Maughan and Brodie, 2009	Good – from recent work by Devlin *et al.,* 2013a; Alvarez Romero *et al.,* 2013
Socio and economic values included	Yes	Yes	No	No
Spatial coverage	All Great Barrier Reef, however Burnett Mary marine area outside of Great Barrier Reef Marine Park excluded	All Great Barrier Reef, however Burnett Mary marine area outside of Great Barrier Reef Marine Park excluded	Cape York and Burnett Mary excluded	All Great Barrier Reef however Burnett Mary marine area outside of Great Barrier Reef Marine Park excluded

The most recent risk assessment in this chapter (Brodie *et al.,* 2013a) still uses a Multi Criteria Analysis approach, however, with improved input data layers and more sophisticated spatial analyses. This reflects the current availability of long term water quality data for the Great Barrier Reef and recent studies of links between end-of-catchment pollutant loads and marine ecosystem health.

Current evidence on the relative risks of water quality pollutants to the Great Barrier Reef

Water quality within the Great Barrier Reef is influenced by many factors (see Chapters 1, 2 and 4 for detailed descriptions). The primary influences are the volume and timing of seasonal rainfall and subsequent runoff events which are determined by the monsoonal climate and extreme weather events (cyclones), tidal regimes and currents. These factors influence the relative risk of different pollutants at particular locations and to different habitats in the Great Barrier Reef.

What is the current relative risk of priority pollutants to Great Barrier Reef marine systems?

The conclusions herein draw primarily from the risk assessment process described above (Waterhouse *et al.,* 2013; Brodie *et al.,* 2013a).

Part 1: The relative importance of different pollutants to Great Barrier Reef ecosystems

The relative importance of the three primary pollutants to coral reefs and seagrass (Part 1 in Figure 2) was estimated by calculating the areas of coral reef and seagrass adjacent to each region for each of the assessment classes (Table 4). To compare sediment and nutrient risks between regions, only the areas in the highest assessment class were considered. For photosystem II inhibiting herbicides, the two highest assessment classes were used in recognition of the level of toxicity associated with these classes.

Table 4. Anchored scores for the area of coral reefs and seagrass for each region affected by the highest assessment classes for the water quality variables included in the risk analysis (final output of Part 1 in Figure 2). In the case of photosystem II inhibiting herbicides, the two highest assessment classes ware used. The region that had the largest area affected was given a score of 100; all other regions were expressed as a percentage based on the area affected in each region relative to the area in the region with the maximum area affected. To highlight differences between regions, cells with the greatest and second-greatest areas affected are shaded dark and light grey respectively. Refer to Table 2 for further explanation of the variables. Source: Waterhouse *et al.,* (2013).

	Sediments			**Nutrients**			**Pesticides**
Regions	TSS exceedance 2 mg/L	TSS exceedance 7mg/L	TSS plume loading 07-11	Chlorophyll *a* exceedance 0.45 µg/L	DIN plume loading 07-11	COTS Initiation Zone	PSII herbicide modelled concentration
Coral reefs							
Cape York	0	0	0	0	0	100	0
Wet Tropics	0	0	9	1	18	70	0
Burdekin	100	4	100	26	39	0	0
Mackay Whitsunday	14	0	6	22	6	0	100
Fitzroy	61	100	32	100	100	0	0
Burnett Mary	18	0	0	9	2	0	0
Seagrass						N/A	
Cape York	0	0	0	5	0		0
Wet Tropics	11	27	8	14	30		0
Burdekin	100	100	100	100	100		0
Mackay Whitsunday	2	0	1	7	8		100
Fitzroy	5	27	5	62	81		0
Burnett Mary	9	0	0	15	32		0

TSS: total suspended solids; DIN: Dissolved inorganic nitrogen; COTS: crown-of-thorns starfish; PSII: photosystem II inhibiting.

Key findings:

- The area of coral reefs at greatest risk from all of the sediment and nutrient variables (except for the crown-of-thorns starfish initiation zone) was highest in the Burdekin and Fitzroy regions (Table 4). The other regions (Cape York, Wet Tropics, Mackay Whitsunday and Burnett Mary) each had approximately 20 per cent or less of the coral reef area affected for each variable.

- The area of seagrass at greatest risk from all of the sediment and nutrient variables was highest in the Burdekin region. The area of seagrass within the Wet Tropics region is second greatest for all variables but the areas are less than one quarter of the areas affected in the Burdekin region in all cases. The area of seagrass within the highest assessment classes of the nutrient variables is greatest in the Burdekin region and then the Fitzroy.

- The crown-of-thorns starfish initiation zone straddles the boundary between the Cape York and Wet Tropics regions, with approximately 60 per cent of reefs within the zone located in the Cape York region.

- Of the regions examined in the assessment, the Mackay Whitsunday region presents by far the highest ecological risk of pesticides with the photosystem II inhibiting herbicide risk of 'High' and 'Medium' extending off the mouths of the Pioneer and O'Connell Rivers and Sandy Creek. This is followed by the Burdekin (due to the Barratta Creek and Haughton Rivers but not the Burdekin River itself), Wet Tropics, Fitzroy and Burnett Mary regions. It should be noted that the risk of 'pesticides' here is represented by photosystem II inhibiting herbicides as these are the dominant pesticides detected in catchments, however a total of 34 pesticides (herbicides, insecticides and fungicides) have been detected. In addition, the high risks of photosystem II inhibiting herbicides to wetland, estuarine and coastal habitats which provide important ecosystem services to the Great Barrier Reef including fish nursery habitats, were not included in this stage of the assessment but recognised as important and considered in the overall assessment of risk (Table 9).

An assessment of qualitative information on the potential risk of photosystem II inhibiting herbicides to other Great Barrier Reef ecosystems (Lewis *et al.,* 2013) showed that a variety of coastal habitats (e.g. wetlands, estuaries, mangroves and seagrass) which provide important ecological services (including nursery habitats, primary productivity and nutrient cycling) to Great Barrier Reef biota are at risk. The assessment was based on two methods: one that compares the equivalent toxicities of different photosystem II inhibiting herbicides to coral reef, seagrass and microalgae species (Toxic Equivalence Quotient, e.g. Kennedy *et al.,* 2012a; Smith *et al.,* 2012) and the second using the multiple substances potentially affected fraction (ms-PAF) method (Traas *et al.,* 2002) that assesses the toxicity of a mixture of substances to organisms that photosynthesise (phototrophs). Importantly both methods use the concentration addition model to determine the toxicity of mixtures of photosystem II inhibiting herbicides.

The assessment classified the risk of pesticides in the Great Barrier Reef into five groups ranging from Very Low to Very High.

- Within the freshwater reaches of rivers and freshwater/coastal wetlands, the risk of pesticides (photosystem II inhibiting herbicides and some non-photosystem II inhibiting pesticides) is rated in the Very High class (reduced growth and mortality in seagrass and loss of symbionts (bleaching) in corals; more than70 per cent of phototrophic species affected), High (reduction in photosynthesis by between 10 per cent and 50 per cent in corals, seagrass and microalgae; 5–40 per cent of phototrophic species affected) and Medium class (reduction in photosynthesis by between 10 per cent and 50 per cent in corals, seagrass and microalgae; 5–40 per cent of phototrophic species affected) (depending on the region and stream) particularly for the coastal stream networks that drain a relatively large area (more than 20 per cent) of intensive agriculture such as Barratta and Sandy Creeks.

- In the *estuarine reaches of the rivers*, the risk of pesticides is largely in the High to Low category (major reduction in photosynthesis by between 50 per cent and 90 per cent in corals, seagrass and microalgae (High) to up to 10 per cent photosynthesis reduction (Low); 1–70 per cent of phototrophic species affected). A similar risk occurs for the *coastal marine environment* including intertidal and subtidal seagrass.
- *Coral reefs and seagrass meadows on the inner shelf* (includes but not limited to areas extending up to 20 kilometres from the coast) generally fall into the Low (reduction in photosynthesis by between 10 per cent and 50 per cent in corals, seagrass and microalgae) to Very Low categories (no observed effect on corals, seagrass or microalgae; less than 40 per cent of phototrophic species affected) depending on the region and adjacent catchment(s).
- The risk to *coral reefs on the mid and outer shelf* is considered Very Low to no risk (less than one per cent phototrophic species affected).

Part 2: Combined risk of degraded water quality to Great Barrier Reef ecosystems

A combined assessment of all of the water quality variables takes into account all of the assessment classes to identify the areas of highest relative risk to degraded water quality in the Great Barrier Reef (Part 2 in Figure 2). The result of combining the variables is shown in the map in Figure 4 and the area of coral reefs and seagrass within each of those five classes is shown in Table 5. A Marine Risk Index was calculated by adding the areas of coral reefs and seagrass in the Very High and High classes and normalising those areas relative to the maximum areas. This shows relative differences in risk between regions (see final column in Table 4) by comparing the total area of habitat at risk among regions. However, the proportion of coral reefs and seagrass in each region that is within the Marine Risk Index is also presented as this is most relevant for determining management priorities within a region.

The risk was found to be greatest for coral reefs in the Fitzroy and Mackay Whitsunday regions, and for seagrass in the Burdekin and Fitzroy regions. The total areas within the Very High and High classes (forming the Marine Risk Index) are greatest in the Fitzroy, Mackay Whitsunday and Burdekin regions. In most cases, the proportion of the habitat area in each region within the High and Very High classes is less than 10 per cent, except in the case of seagrass in the Mackay Whitsunday region where 37 per cent of the area of seagrass in the region is within the Marine Risk Index area. It should be noted that this assessment does not account for the potential synergistic or antagonistic effects that these multiple stressors when acting together may have on ecosystems.

While the areas of coral reef and seagrass within the highest assessment classes for individual variables and the Marine Risk Index are relatively small, they often include highly valued tourism and recreation sites of the Great Barrier Reef. Examples include Fitzroy Island, Hinchinbrook Island, Magnetic Island, many of the islands in the Whitsunday Group and the Keppel Island group. In the case of seagrass, many of the highest risk areas overlap with dugong protection areas, which are assigned because of the large populations of dugongs feeding in the associated seagrass meadows.

Figure 2. Combined assessment (one square kilometre resolution) of the relative risk of water quality variables (output of Part 2 shown in Figure 2). The areas (in square kilometres) of habitat types within each class are shown in Table 4. The Marine Risk Index for coral reefs and seagrass is defined from the combined areas of the High and Very High relative risk classes. Inset bar chart shows reef and seagrass areas in the Marine Risk Index by Region; pie charts show affected coral reef and seagrass areas for each Region as a percentage of the total Great Barrier Reef coral reef and seagrass areas in the Marine Risk Index. Source: Waterhouse *et al.,* (2013).

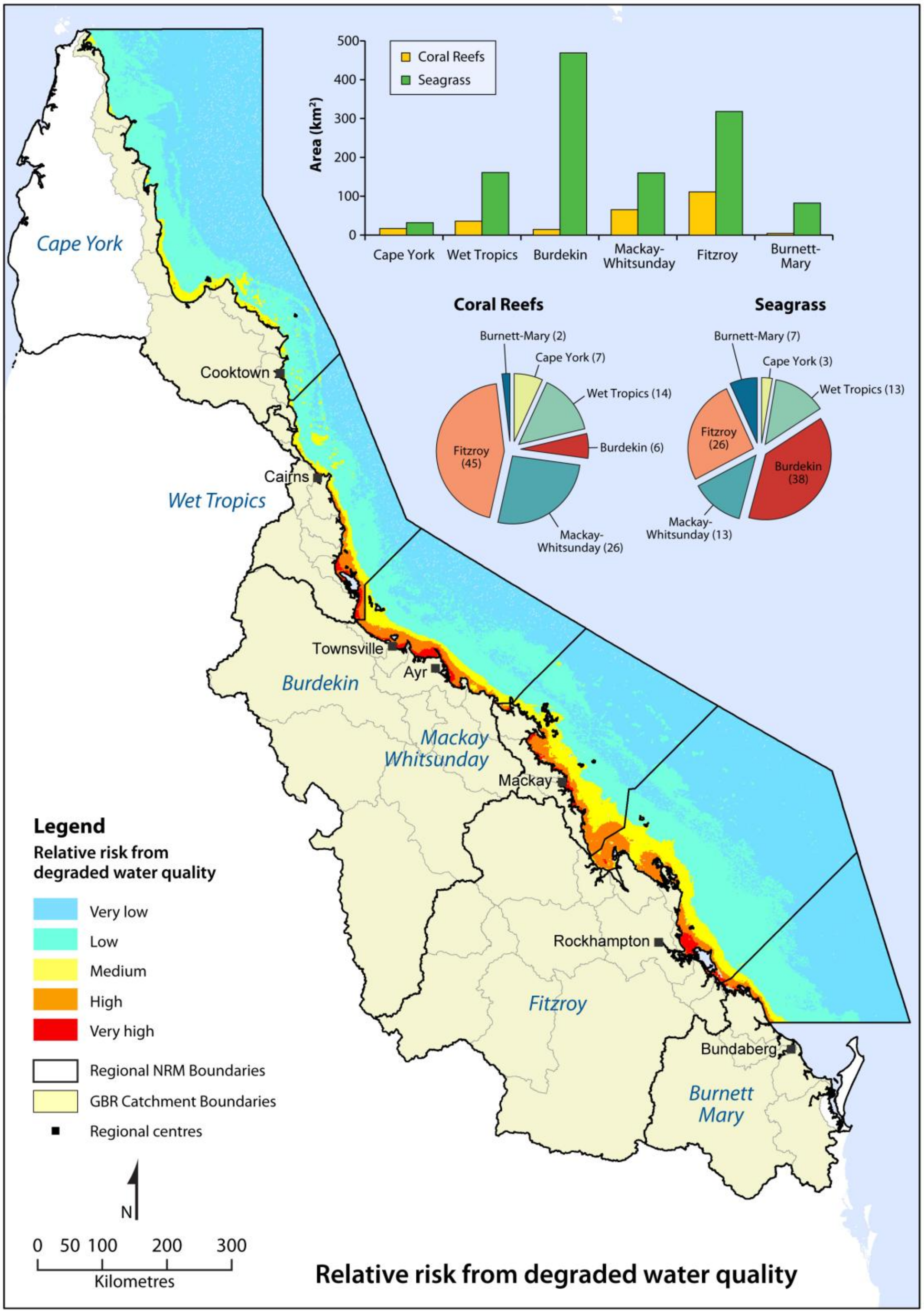


Table 5. Area of coral reefs and seagrass within the five relative risk classes (output of Part 2 in Figure 2). The sum of the area within the High and Very High classes form the Marine Risk Index. The region that had the largest area affected was given a score of 100; all other regions are expressed as a percentage based on the area affected in each region relative to the area in the region with the maximum area affected. To highlight relative differences the greatest area / highest scores are shaded dark grey, second is shaded light grey.

Habitat **Region**	**Very Low**	**Low**	**Medium**	**High**	**Very High**	**Total**	**Sum High and Very High**	**% of habitat in region (High & Very High)**	**Marine Risk Index**
	Area (km^2)								
Coral reefs									
Cape York	3585	6147	546	17	0	10,295	17	<1	15
Wet Tropics	121	1809	448	36	<1	2415	36	1	32
Burdekin	704	2206	24	14	<1	2948	15	<1	13
Mackay Whitsunday	2147	826	133	61	5	3171	66	2	59
Fitzroy	3726	964	38	103	8	4840	111	2	100
Burnett Mary	10	265	1	5	0	282	5	2	4
Seagrass									
Cape York	1258	8711	1329	32	0	11,330	32	<1	7
Wet Tropics	175	4240	278	102	59	4855	161	3	34
Burdekin	1281	4160	150	333	136	6060	470	8	100
Mackay Whitsunday	5	21	210	136	25	396	160	37	34
Fitzroy	201	5050	177	303	15	5746	319	6	68
Burnett Mary	458	5561	210	76	7	6313	83	1	18

Where are the risks highest or the benefits of improved management greatest?

Part 3: Relative risk of degraded water quality to Great Barrier Reef ecosystems

To inform management priorities to address the risks identified above (Part 3 of Figure 2), it is necessary to understand the influence of river discharge upon the individual regions, as river discharges carry most of the anthropogenic pollutant load into the Great Barrier Reef lagoon. Chapter 4 of the Scientific Consensus Statement (Kroon *et al.,* 2013) presents a current estimate of anthropogenic loads which were generated using a Source Catchments model (Waters *et al.,* in press) as part of the Reef Plan Paddock to Reef program. These estimates are long term average annual loads, calculated for the period 1986 to 2009. They represent inputs during an 'average' year of runoff rather than high-discharge years such as occurred between 2008 and the current (2012-2013) wet season.

The sources of pollutants make a significant difference to the ability to manage the water quality risk to habitats. When considering river discharges of sediment and nutrients to the Great Barrier Reef, the anthropogenic loads are the most relevant parameters. In the case of pesticides it is the (concentration-dependent) toxicity which is most important and, therefore, in situ concentration that is most relevant.

Unfortunately, such concentration data is limited for the Great Barrier Reef region. The final conclusions relating to pesticide risk are therefore drawn from a combination of load and concentration data.
To relate the results of the Marine Risk Index to catchment influences, estimated regional anthropogenic loads of total suspended solids, dissolved inorganic nitrogen and photosystem II inhibiting herbicides were expressed as the proportion of the total Great Barrier Reef load (Table 6). This recognises that while the total load is important in influencing marine water quality conditions, only the anthropogenic portion can be factored into management. The proportional regional contributions of total suspended solids, dissolved inorganic nitrogen and photosystem II inhibiting herbicides were then normalised to a standard scale (anchored) and averaged to generate a Loads Index. This assumes that the relative importance of each load is equal, which in reality is unlikely to be the case, although there is currently insufficient knowledge to weight the importance of the three pollutants relative to each other.

To generate a Loads Index, we averaged the regional anthropogenic load contributions as a proportion of the total Great Barrier Reef load for total suspended solids, dissolved inorganic nitrogen and photosystem II inhibiting herbicides (Table 6). These results were then anchored it to the maximum value to generate a relative assessment of load contributions to the Great Barrier Reef, forming a Loads Index for each region. The assessment shows the greatest relative contribution of combined end-of-catchment loads to the Great Barrier Reef is from the Wet Tropics region, followed by the Burdekin region. The contributions from the Mackay Whitsunday, Fitzroy and Burnett Mary regions are similar and are around one quarter of the contributions of the Wet Tropics. The load contributions from the Cape York region are minor compared to all other regions.

Table 6. Loads Index for total suspended solids, dissolved inorganic nitrogen and photosystem II inhibiting herbicides derived from the average of the regional anthropogenic load contributions to the total Great Barrier Reef load. The region that had the largest average load was given a score of 100; all other regions are expressed as a percentage based on the area affected in each region relative to the area in the region with the largest average. Source: Derived from Waters *et al.,* (in press).

Regional Anthropogenic Load as proportion of Total Great Barrier Reef Load						
Region	**Total Suspended Solids**	**Dissolved Inorganic Nitrogen**	**Photosystem II inhibiting herbicides**	**Average**	**Loads Index**	**Loads Index Rank**
Cape York	2.6	0.05	0.03	0.04	0	6
Wet Tropics	8.8	20.2	61.3	30.1	100	1
Burdekin	31.7	11.2	13.3	18.7	62	2
Mackay Whitsunday	4.1	6.3	12.2	7.5	25	4
Fitzroy	16.8	5	3.8	8.5	28	3
Burnett Mary	4.3	4.4	9.3	6.0	20	5
			Max	*30.1*		

An index specific to the potential influence of river discharge on the initiation of crown-of-thorns starfish primary outbreaks in the Great Barrier Reef was added (see Furnas *et al.,* 2013a). In particular, dissolved inorganic nitrogen runoff is considered to be an important factor as approximately 40 per cent of the loss of coral cover in the Great Barrier Reef since 1987 has been attributed to crown-of-thorns starfish predation (De'ath *et al.,* 2012). A crown-of-thorns starfish outbreak initiation zone has been defined between Lizard Island (15 degrees South) and Cairns (17 degrees South). Furnas *et al.,* (2013a) defined the volumetric contribution of river discharge and dissolved inorganic nitrogen loading from eight rivers to the crown-of-thorns starfish initiation zone between Lizard Island and Cairns. These included: the Normanby River in the Cape York region; the Daintree, Barron, Russell-Mulgrave, Johnstone, Tully and Herbert rivers in the Wet Tropics region; and the Burdekin River in the Burdekin region. The greatest contribution was identified from the Daintree River, and all other contributions were normalised against the Daintree to show relative contributions.

The proportion that each region contributes was then calculated by summing all values and presenting each region as a percentage of the total. The majority of the estimated influence (86 per cent) is from the Wet Tropics rivers and a small proportion (14 per cent) from the Burdekin River. This information was incorporated into an additional factor, the crown-of-thorns starfish influence index by anchoring these results which are then 100 per cent for the Wet Tropics region, 16 per cent for the Burdekin region and zero contribution from all other regions. While this assessment relies on many assumptions associated with dissolved inorganic nitrogen loads in river discharges and differences in inter annual variability it does provide a way of recognising the relative influence of the regional river discharges to the ecologically important initiation area of crown-of-thorns starfish primary outbreaks.

To provide an overall water quality risk ranking between the regions, the Loads Index, Crown-of-thorns starfish Influence Index (for coral reefs) and the Marine Risk Index for coral reefs and seagrass were combined (Table 7). For coral reefs, the Crown-of-thorns starfish Influence Index is included by summing with the Loads Index, however, only the Loads Index and the Marine Risk Index are used for seagrass. The final indexes for coral reefs and seagrass were then summed and normalised to provide an overall assessment of the relative risk of degraded water quality to coral reefs and seagrass – the Relative Risk Index (final output of Part 3 in Figure 2). These results are summarised in Figure 5.

Table 7. Results of the overall risk assessment from summing the Loads, Crown-of-thorns starfish Influence (for coral reefs only) and Marine Risk Index for coral reefs and seagrass. The region that had the maximum value was given a score of 100; all other regions are expressed as a percentage based on the value in each region relative to the area in the region with the maximum value. Source: Waterhouse *et al.,* (2013).

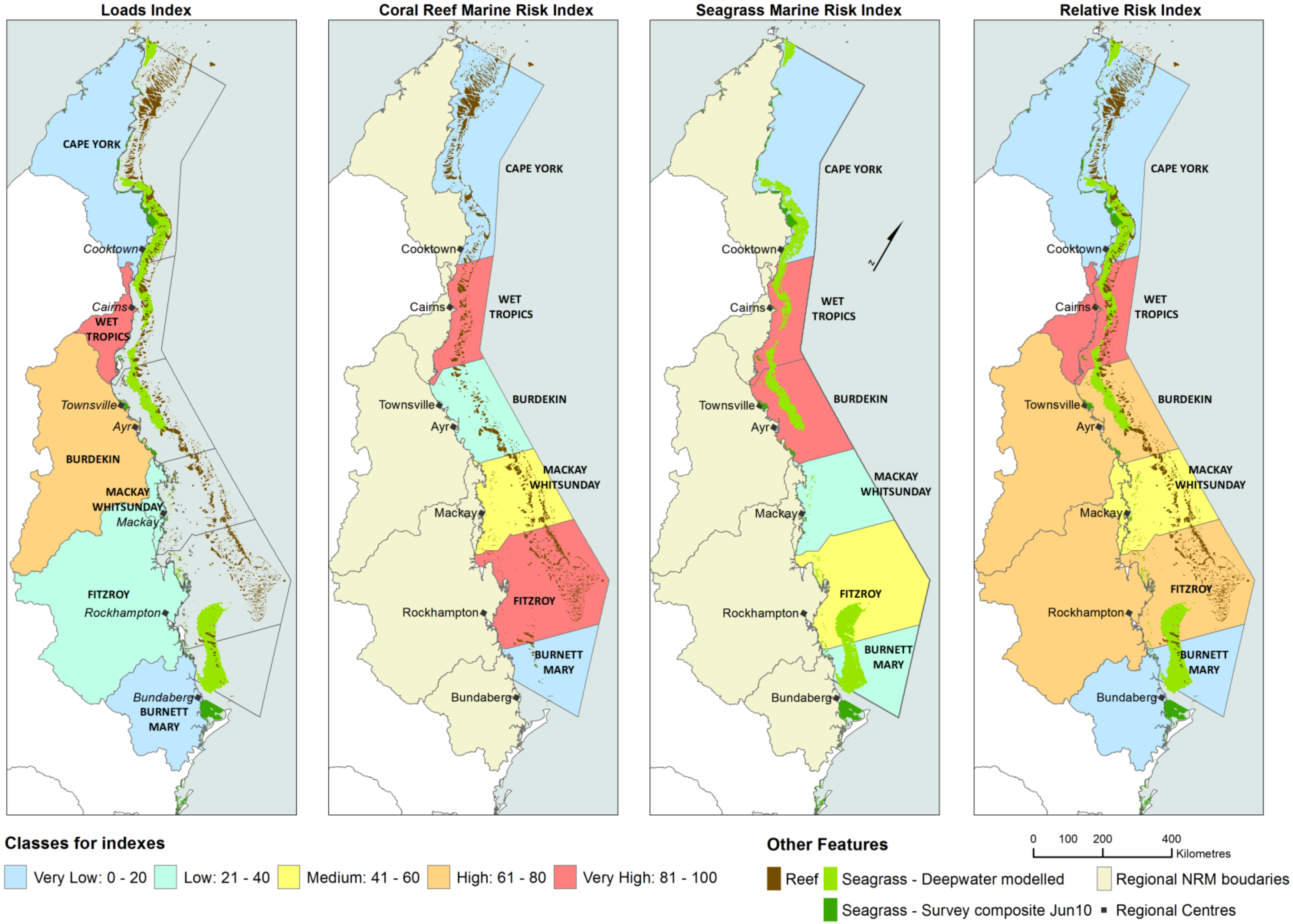
Coral reefs	Coral Reef Marine Risk Index	Loads & COTS Index	Sum of indexes	Coral reef Relative Risk Index (Anchored)	Rank
Cape York	15	0	15	12	5
Wet Tropics	32	100	132	100	1
Burdekin	13	39	52	40	4
Mackay Whitsunday	59	13	72	54	3
Fitzroy	100	14	114	86	2
Burnett Mary	4	10	14	11	6
		Max	*132*		
Seagrass	**Seagrass Marine Risk Index**	**Loads Index**	**Sum of Indexes**	**Seagrass Relative Risk Index (Anchored)**	**Rank**
Cape York	7	0	7	4	6
Wet Tropics	34	100	134	83	2
Burdekin	100	62	162	100	1
Mackay Whitsunday	34	25	59	37	4
Fitzroy	68	28	96	59	3
Burnett Mary	18	20	38	23	5
		Max	*162*		

COTS: crown-of-thorns starfish

Table 8. Results of the overall risk assessment using a sum of the anchored Indexes for coral reefs and seagrass (final output from Part 3 in Figure 2). The region that had the largest sum of indexes was given a score of 100; all other regions are expressed as a percentage based on sum of indexes in each region relative to the sum in the region with the maximum sum of indexes. Source: Waterhouse *et al.,* (2013).

Coral reef and seagrass	Coral Reef Relative Risk Index	Seagrass Relative Risk Index	Sum of indexes	Relative Risk Index (Anchored)	Rank
Cape York	12	4	16	9	6
Wet Tropics	100	83	183	100	1
Burdekin	40	100	140	76	3
Mackay Whitsunday	54	37	91	50	4
Fitzroy	86	59	145	80	2
Burnett Mary	11	23	34	19	5
		Max	*183*		

Figure 3. Map summarising the results of the Loads Index, Marine Risk Indexes (coral reefs and seagrass) and the Relative Risk Index. The assessment for coral reefs also includes the Crown-of-thorns starfish Influence Index associated with the extent of the influence of regional river discharge to the Crown-of-thorns starfish Initiation Zone; the scores are 100 for the Wet Tropics, and 16 for the Burdekin region. The method for deriving and combining the indexes is provided in Section (b).



These results show the greatest risk to each habitat in terms of the potential water quality impact from all of the assessment variables in the Great Barrier Reef and end-of-catchment anthropogenic loads of dissolved inorganic nitrogen, total suspended solids and photosystem II inhibiting herbicides. These are:

- **Coral reefs:** Wet Tropics region, followed by the Fitzroy region. The rank of the remaining regions is the Mackay Whitsunday, Burdekin, Cape York and Burnett Mary regions.
- **Seagrass**: Burdekin region, followed by the Wet Tropics. The rank of the remaining regions is the Fitzroy, Mackay Whitsunday, Burnett Mary and Cape York regions.
- **Coral reefs and seagrass combined:** Wet Tropics, followed by the Fitzroy and Burdekin (both approximately 80 per cent of the relative risk compared to the Wet Tropics). The relative risk to the Mackay Whitsunday region is half the greatest risk, followed by the Burnett Mary and Cape York regions.

These are relative assessments indicating that the risk posed to ecosystems from degraded water quality in the Burnett Mary and Cape York regions is low relative to the other regions. However, ecosystems in these regions may be exposed to a range of risks that still require improved pollutant management to recover or maintain ecosystem values.

Drawing on the results obtained from the risk assessment and additional evidence, an overall summary of the relative importance of different pollutants to Great Barrier Reef ecosystems, and the relative risk of degraded water quality to Great Barrier Reef ecosystems among regions is presented in Table 9. The table uses the individual assessments of each variable used in the ecological risk assessment to highlight where the variables dominate among the regions. The primary rank for each variable is listed, with an indication of whether it dominates in terms of coral reef or seagrass area, or both. The Marine Risk Index for coral reefs and seagrass is then shown for the results of the combined analysis of water quality variables. The regional anthropogenic loads as a proportion of the total Great Barrier Reef load for total suspended solids, dissolved inorganic nitrogen and photosystem II inhibiting herbicides are shown to identify the primary sources of anthropogenic loads delivered to the Great Barrier Reef, in addition to the Loads Index which combines this information. Additional information includes facts related to the influence of river discharges to the Crown-of-thorns starfish Initiation Zone and additional pesticide information. The Relative Risk Index in Section (b) is the critical underpinning for the overall conclusions. This is then informed by the management issues and associated land uses which were derived from published evidence and expert judgment of the assessment team (informed by the preceding columns). The overall ranking of relative risk was developed by the assessment on the basis of the overall content of the table. Importantly, while the Burnett Mary ranked relatively low in the Relative Risk Index, this result is considered to be highly uncertain due to the fact that most reefs and seagrass in this region (but outside of the Great Barrier Reef World Heritage Area) were not included formally in the analysis.

To relate these results to catchment management priorities, reference can be made to current knowledge of the pollutant contributions from different land uses in each region, which are presented in Chapter 4. In summary:

- Grazing lands contribute 75 per cent of the total suspended solids load. Land use, soil properties, the extensive area involved, river discharge flows and geomorphology all contribute to the loads. Provenance tracing shows that most sediment comes from a combination of gully and streambank erosion and subsoil erosion from hillslope rilling, rather than broad-scale hillslope sheetwash erosion.
- Eighty percent of dissolved inorganic nitrogen originates from the Wet Tropics, Burdekin and Mackay Whitsunday regions, primarily from fertilised land use and in particular, land used for sugarcane cultivation.
- Results from Source Catchments modelling suggest that over 90 per cent of the modelled photosystem II inhibiting herbicide load is from land used for sugarcane cultivation, with minor

contributions from cropping and grazing lands, in particular from the Fitzroy basin (Waters *et al.,* in press).

The summary in Table 9 has been coupled with the summary of pollutant sources from land uses in each region to generate the management priorities identified Table 10. However, cost effective solutions for all of these management issues are not necessarily currently available for all of these priorities. These issues are discussed further in *Chapter 5 The water quality and economic benefits of agricultural management practices* (Thorburn *et al.,* 2013) including outstanding information gaps in this field.

Even though the nutrient related variables of chlorophyll threshold exceedance and dissolved inorganic nitrogen plume loading were ranked highest in the Fitzroy region, there is insufficient knowledge of the sources of dissolved inorganic nitrogen in the region to make recommendations about management priorities for these. Further knowledge of the role of particulate nitrogen, which is largely derived from grazing lands, and the processing of this into dissolved inorganic nitrogen is important for making future management recommendations in the large grazing catchments of the Fitzroy region. Current research is showing differences in sediment and nutrient runoff from native brigalow scrub, newly planted legume based ley pastures and cropping lands which will be useful to guide management priorities in the future. Compared to the native brigalow scrub landscape, cropping exported more total suspended solids and dissolved inorganic nitrogen, while grazing exported less total nitrogen and dissolved inorganic nitrogen but more total suspended solids (Thornton and Elledge, 2012). The legume pastures do appear to pose a risk to water quality as they contribute higher nutrient loads than grass only pasture systems, established grass-leucaena pastures, and the native brigalow scrub landscape representative of the environment in its pre-European condition (Elledge and Thornton, 2012).

In the Burnett Mary region, all of the variables ranked relatively low, however, the assessment does not include large areas south of the Great Barrier Reef World Heritage Area boundary that contain coral reefs and large areas of seagrass (refer to Section 5). The end-of-catchment total suspended solids and anthropogenic annual average loads in the Mary River are the fourth highest of all Great Barrier Reef catchments. A majority of this is thought to be derived from grazing lands, although mixed cropping is also a potential contributor (Waters *et al.,* in press). The total suspended solids loads from the Burnett catchment and particularly the role of dams in sediment trapping requires further investigation. It is possible that a similar process of trapping of coarser sediments (greater than20 micrometres) that occurs in the Burdekin catchment (Lewis *et al.,* in press) may also occur in the Burnett catchment, resulting in the bulk of the material discharged to the marine environment being the finer fraction. It is the finer sediment fraction that is more harmful to coral reefs (Weber *et al.,* 2006, 2012) and seagrass (Collier *et al.,* 2012). For these reasons, sediment management in the Burnett Mary region is considered to be highest priority until a more thorough analysis is undertaken that includes all of the potential ecosystems at risk.

From this summary a number of conclusions can be made about priority areas for management of each pollutant, illustrated in Figure 6:

- Nitrogen management: Wet Tropics region
- Suspended solids management: Burdekin and Fitzroy regions
- Photosystem II inhibiting herbicide management: Burdekin (lower Burdekin) and Mackay Whitsunday regions.

Table 9. Summary of the outcomes of the overall assessment of the relative risk of water quality in the Great Barrier Reef. Note that the Burnett Mary region is shaded in grey to represent the fact that most reefs and seagrass in this region were not included formally in the analysis and thus the validity of the result has high uncertainty. Source: Brodie *et al.,* (2013a).

Region	Dominant variables in marine assessment *Variables where max area is in region*	Marine Risk Index		Regional Anthropogenic Load as a proportion of the Total Great Barrier Reef Load			Loads Index	Additional Factors	Relative Risk Index	Management Issues	Associated land uses	Overall Ranking of Relative Risk
		Coral reef	**Seagrass**	**TSS**	**DIN**	**PSII**						
Cape York	Crown-of-thorns starfish Initiation Zone (CR)	12	4	3	<1	<1	0	Influence from catchment runoff is predominantly from Wet Tropics Rivers	9	The data in this region are highly uncertain due to limited validation of marine datasets.		**LOW**
Wet Tropics		100	83	9	20	61	100	86% volumetric contribution to COTS Initiation Zone	100	Nutrients Pesticides	Sugarcane Bananas	**VERY HIGH**
Burdekin	TSS 2mg/L (SG, CR) TSS 7mg/L (SG) TSS Plume loading (CR, SG) Chlorophyll 0.45µg/L (SG) DIN Plume loading (SG)	40	100	32	11	13	62	14% volumetric contribution to COTS Initiation Zone High risk from PSII herbicides to Ramsar listed freshwater wetlands in the lower Burdekin catchments	76	Sediments Pesticides Nutrients	Grazing Sugarcane (coastal)	**HIGH**
Mackay Whitsunday	Pesticide exposure (CR, SG)	54	37	4	6	12	25	High risk from PSII herbicides in Sandy Creek	50	Pesticides Nutrients	Sugarcane	**MODERATE**
Fitzroy	TSS 7mg/L (CR) Chlorophyll 0.45µg/L (CR) DIN Plume loading (CR)	86	59	17	5	4	28	Monitored loads of PSII herbicides were high in 2011 (not reflected in modelled baseline)	80	Sediments Pesticides *Nutrients*[1]	Grazing Cropping	**HIGH**
Burnett Mary	All variables rank relatively low	11	23	4	4	9	20	The Mary River has the fourth highest total and	19	Sediments	Grazing	**UNCERTAIN**

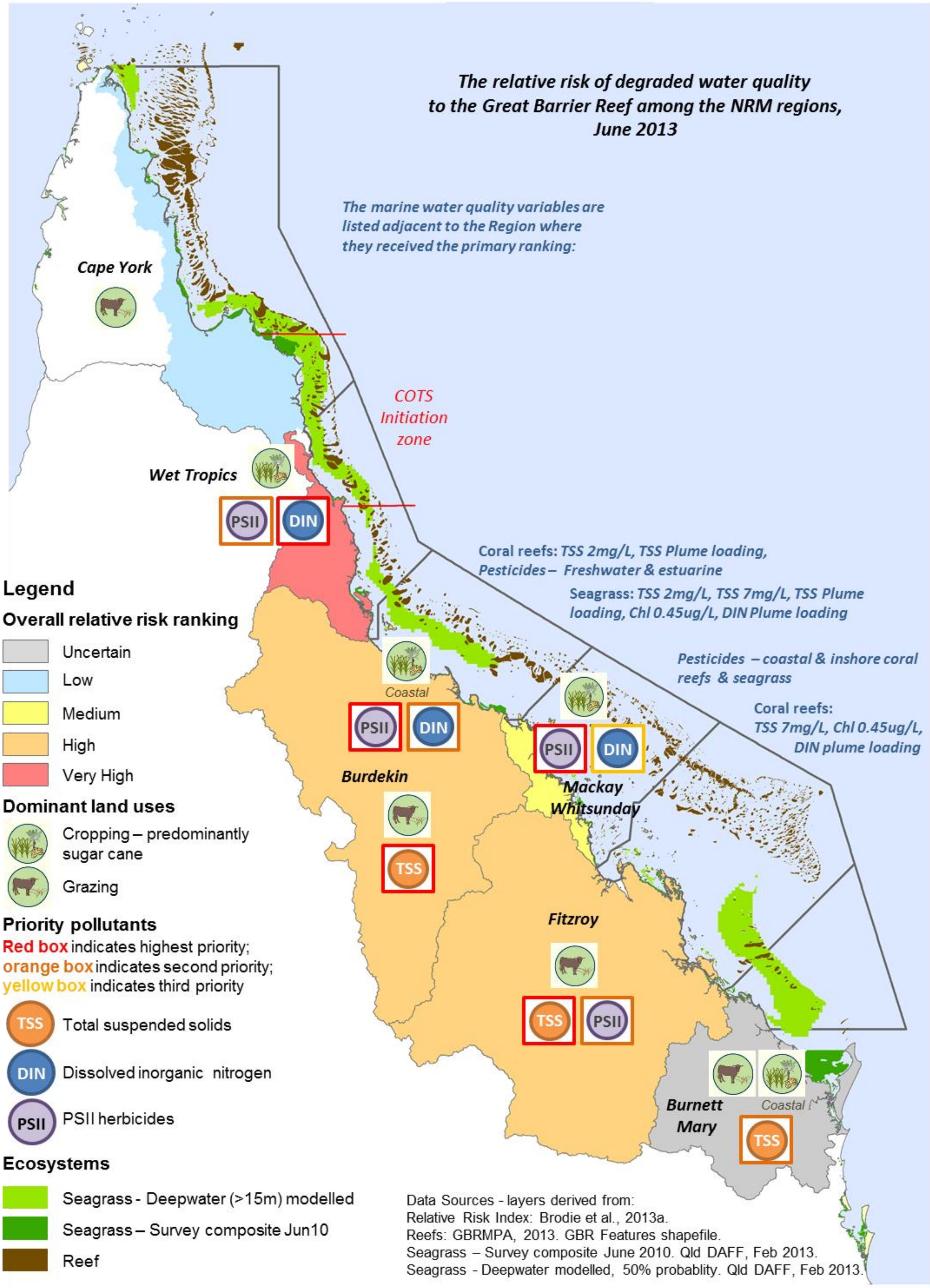
								anthropogenic TSS load of all Great Barrier Reef catchments		All variables rank relatively low, however, there is high uncertainty in this result given the lack of data on the full extent and condition of corals and seagrass (which are outside the GBRWHA) available for this assessment.	

[1]There is insufficient knowledge of the sources of dissolved inorganic nitrogen in the Fitzroy region to make recommendations about management priorities for these. Further knowledge of the role of particulate nitrogen, which is largely derived from grazing lands, and the processing of this into dissolved inorganic nitrogen is important for making future management recommendations in the large grazing catchments of the Fitzroy region. TSS: total suspended solids; DIN: dissolved inorganic nitrogen; PSII: photosystem II inhibiting; CR: coral reefs; SG: seagrass; COTS: crown-of-thorns starfish; GBRWHA: Great Barrier Reef World Heritage Area.

Table 10. Summary of management priorities for reducing the relative risk of degraded water quality to the Great Barrier Reef. Source: Brodie *et al.,* (2013a).

Relative Priority	Management Priorities			
	Region	**Pollutant Management**	**Key land uses**	**Comments**
1	Wet Tropics	Fertiliser nitrogen reduction	Sugarcane, Bananas	Note that these actions should not be prioritised at the exclusion of other practices that are already in place to manage losses of other pollutants in the regions
	Burdekin	Erosion management in Burdekin	Grazing	
	Fitzroy	Erosion management in Fitzroy	Grazing, Cropping	
2	Burdekin	Pesticide reduction in (lower) Burdekin and Haughton	Sugarcane	
	Mackay Whitsunday	Pesticide reduction in all catchments	Sugarcane	
	Burdekin	Fertiliser nitrogen reduction in (lower) Burdekin and Haughton	Sugarcane	
3	Mackay Whitsunday	Fertiliser nitrogen reduction	Sugarcane	
	Burnett Mary	Erosion management in all catchments	Grazing	
	Wet Tropics	Pesticide reduction in all catchments	Sugarcane	
	Fitzroy	Pesticide reduction in all catchments	Grazing, Cropping	
4	Burnett Mary	Further information is required to inform the assessment, including data on the full extent and condition of corals and seagrass (which are outside the Great Barrier Reef World Heritage Area) in the region		Habitat mapping, ecological value assessment and monitoring of ecosystem condition is required
5	Cape York	Further information is required to understand local influences		As a relatively low impacted area, management efforts should aim to maintain the current values of the region

Figure 4. Illustration of the overall outcomes of the assessment of the relative risk of degraded water quality to Great Barrier Reef coral reefs and seagrass. The map shows the dominant land uses and priority pollutants and results of the overall relative risk ranking in each natural resource management region. Source: Brodie *et al.,* (2013a).



When are the risks highest or the benefits of improved management greatest?

An assessment of **when the greatest risks occur** depends on the parameter of interest, seasonal climate and weather, geochemical and water residence times, biogeochemical transformation processes and interactions with other stressors as summarised below. This information is drawn from a review of the current evidence, and not the assessment described in Sections (a) and (b) of this chapter.

For the materials of concern (total suspended solids, nutrients, photosystem II inhibiting herbicides), the degree of ecological risk depends upon the level of exposure (concentration), the duration of exposure (delivery and dispersion) and the susceptibility of the species or community of concern to the pollutant (ecophysiology).

Because of the monsoonal climate of the Great Barrier Reef, most sediment, nutrients and pesticides are delivered to the Great Barrier Reef lagoon during the summer wet season (December-April) when rivers are more active and most flooding occurs. The quantity of material delivered is generally proportional to the runoff volume over any particular time interval as this reflects the degree of erosion and transport of materials from catchments; however, the relationship is not a straightforward one as export in runoff depends upon a variety of factors, including quantity of material available in catchments, its geochemical mobility and dilution in the runoff. In general, early wet-season flood events and the leading edge of most floods contain the highest concentrations of suspended sediment, nutrients, and presumably, pesticides (e.g. Furnas, 2003; Devlin *et al.,* 2012).

As described in Chapter 1, a number of estimates of water (and by implication, pollutant) residence or flushing times in the Great Barrier Reef lagoon have been made. Taking a variety of approaches, these studies have arrived at estimates of water residence times which range from 15 days on the outer-shelf in the central Great Barrier Reef (Wang *et al.,* 2007) to a year for water parcels transported north and south in the coastal boundary layer (Luick *et al.,* 2007). However, while the residence times of water in the Great Barrier Reef lagoon may be relatively short, Brodie *et al.,* (2012b) suggest that the residence times of fine sediments, reactive nitrogen and phosphorus, photosystem II inhibiting herbicides and trace metals are likely to be considerably longer due to biogeochemical cycling and storage (Brodie *et al.,* 2012b).

Further knowledge is also available on movement and transformation of pollutants in the Great Barrier Reef lagoon which is summarised below.

Nutrients:

- River runoff is the largest external source of 'new' nutrients (sensu Dugdale and Goering, 1967) to the Great Barrier Reef system.
- Compared to the water column, large pools of nitrogen and phosphorus are stored in Great Barrier Reef sediments and benthic biota, principally as organic detritus, but also as bio-available soluble forms in pore waters and bound to sediment particles. These nutrients can be mobilised over a range of time scales up to years depending on the nutrient form and mobilisation process. The main mechanisms for loss of nitrogen and phosphorus are denitrification (nitrogen only), cross-shelfbreak mixing and burial [mainly phosphorus] (Brodie *et al.,* 2012b).
- River nutrients can influence crown-of-thorns starfish outbreak dynamics when large discharges (approximately more than 10 kilometres cubed) occur during the early wet season (November-February) while phytoplankton-feeding crown-of-thorns larvae are

present in the water column. There appears to be a discharge threshold on the order of 10 kilometres cubed in this period in order to produce sufficient phytoplankton biomass at the proper time to sustain enhanced crown-of-thorns starfish larval survival. Further development of a crown-of-thorns starfish outbreak, however, depends on there being sufficient live coral cover to sustain adult populations.

Suspended sediments:

- Droughts lead to reduced vegetation cover in catchments, making soils more prone to erosion, mobilisation and transport into coastal waters during floods (reviewed in Furnas, 2003). The risk of soil erosion and delivery to the Great Barrier Reef is predicted to increase with the intensity of extreme weather events (refer to *Chapter 2 Resilience of Great Barrier Reef marine ecosystems and drivers of change* [Johnson *et al.*, 2013] for further information).
- Wind-driven resuspension of fine terrigenous sediments occurs year round on the shallow inner-shelf, reducing light penetration for periods of days to weeks. The degree of resuspension appears to attenuate towards the second half of the dry season (Fabricius *et al.,* 2013) as fine material deposited after wet season floods is moved to deeper water or coastal depositional areas (Larcombe *et al.,* 1995).
- Fine sediments have potential residence times of decades on the shallow inner shelf, during which they remain available for resuspension and affect coastal turbidity (Brodie *et al.,* 2012b). These sediments are ultimately transported to deeper water or coastal depositional areas (e.g. Bowling Green Bay, Princess Charlotte Bay).
- Only a small proportion of the sediment load delivered by rivers ultimately makes it to coral reefs on the mid and outer shelf. Most fresh sediment is initially deposited in the estuaries (e.g. Fitzroy River: see Bostock *et al.,* 2007) or close to the river mouth (see Orpin *et al.,* 2004; Bartley *et al.,* in review). Sediment transported more than one kilometre offshore is generally the clay to fine silt (less than 16 micrometres) fraction (Bainbridge *et al.,* 2012).
- Catchment sources of fine clay sediments are still under investigation. Recent tracing studies in the Burdekin catchment (Lewis *et al.,* in press; Bainbridge *et al.,* in review) and Fitzroy catchments (Douglas *et al.,* 2008; Smith *et al.,* 2008) provide further information of primary sources of these fine sediment fractions in the Great Barrier Reef catchment.
- Light limitation is presently regarded as the primary driver of seagrass production (Collier and Waycott 2009) in the Great Barrier Reef, and reductions in light availability have been directly linked to seagrass loss (Collier et al 2012). Light penetration into coastal waters is strongly regulated by the resuspension of fine sediments.

Pesticides:

- Critical periods of pesticide input to the Great Barrier Reef are associated with the ‘first flush’ of terrestrial discharge which generally occurs in November or December each year. These events often coincide with or closely follow end-of-dry-season pesticide application in key agricultural industries (Lewis *et al.,* 2009).
- Coral reefs shown signs of increased stress to pesticide exposure during times when there are also elevated dissolved inorganic nitrogen concentrations (Negri *et al.,* 2011).
- Photosystem II inhibiting herbicides such as diuron and atrazine occur in Great Barrier Reef lagoon sediment and water column compartments (Brodie *et al.,* 2012b). It appears they are primarily removed by chemical (including photolysis) and biological degradation (van Dam *et al.,* 2012).

Studies have demonstrated that soluble photosystem II inhibiting herbicides in flood plumes display conservative mixing behaviour along the salinity gradient, becoming increasingly diluted as the river waters progressively mix with seawater (Lewis *et al.,* 2009). Partitioning studies show that they are not strongly bound to particles (Davis *et al.,* 2012). Soluble photosystem II inhibiting herbicides show little degradation in seawater over time periods relevant to flood plumes – at least months (Navarro *et al.,* 2004; Meakins *et al.,* 1995; Thomas *et al.,* 2002). In addition, these photosystem II inhibiting herbicides have moderate to high persistence in freshwaters (aqueous hydrolysis) of over 50 days (see 'Footprint' Pesticide Properties Database http://sitem.herts.ac.uk/aeru/footprint/en/index.htm; PPDB, 2011) and also appear quite persistent in the Great Barrier Reef lagoon waters with low (nanograms per litre) concentrations throughout the dry season (Shaw *et al.,* 2010; Kennedy *et al.,* 2012a). Thus the Colour Dissolved Organic Matter (CDOM)-salinity relationship (Schroeder *et al.,* 2012) and the predicted salinities where threshold values are reached can be used to show the areas of risk off each region. The technique has been applied by Kennedy *et al.,* (2012a) and more recently by Lewis *et al.,* (2013).

Other factors:

- During periods of prolonged elevated sea surface temperature, coral reefs are more susceptible to coral bleaching if these conditions coincide with degraded water quality (e.g. Wooldridge, 2009). Peak annual temperatures typically occur in the month of February.

What are the consequences of the water quality impact and which pollutants pose the greatest risk?

Research to date has identified that elevated levels of fine sediments (generally less than 64 micrometres), excess nitrogen (dissolved inorganic nitrogen = ammonium + nitrite + nitrate (NH_4^++NO_2^-+NO_3^-) dissolved organic nitrogen, particulate nitrogen), excess phosphorus (PO_4^{3-}, dissolved organic phosphorus, particulate phosphorus) and pesticides (herbicides, insecticides) are the most important pollutants in terms of the potential impact on Great Barrier Reef ecosystems (Brodie *et al.,* 2012a; Brodie et al. 2011; Waterhouse *et al.,* 2012; De'ath and Fabricius, 2010; Lewis *et al.,* 2009, 2012a). While other micropollutants may also be a risk to Great Barrier Reef water quality, our knowledge of their prevalence and effects is so limited at present that their impact cannot be properly assessed (Brodie *et al.,* 2012a).

The process of prioritising management effort between pollutants poses a substantial challenge to researchers and managers, particularly in the context of potential cumulative effects, pollutant interactions and climate variability. Current water quality targets for nitrogen and phosphorus under Reef Plan 2009 (Queensland Department of the Premier and Cabinet, 2009) and Reef Rescue treat them as equally important, but this is not based on a robust scientific analysis. This dilemma is not unique to the Great Barrier Reef and is being debated globally. Discussions continue as to the primacy of reducing nitrogen loads or phosphorus loads, or both, to prevent eutrophication in estuarine, coastal and marine environments (Conley *et al.,* 2009; Howarth *et al.,* 2011; Paerl, 2009; Schindler *et al.,* 2008). The results of the risk assessment in Section (a) and (b) above, coupled with recent studies enable us to draw conclusions of the relative risk of pollutants with greater confidence. These are summarised below.

Nutrients

Great Barrier Reef reefs are naturally exposed to episodic river runoff carrying elevated nutrient and suspended sediment loads. There is little evidence that elevated nutrient concentrations *per se* increase coral mortality; however, enhanced nutrient availability within the ecosystem can have deleterious indirect effects on reef communities (e.g. De'ath and Fabricius 2010). One important effect is that higher nutrient availability can support increased phytoplankton biomass during the early wet-season period (November to February) when crown-of-thorns starfish larvae are in their pelagic filter-feeding stage. Evidence has been mounting that there is a causative link between higher phytoplankton biomass in reef waters and crown-of-thorns starfish outbreaks (Lucas, 1982; Birkeland, 1982; Brodie, 1992; Brodie *et al.,* 2005; Okaji, 1996; Fabricius *et al.,* 2010). The Great Barrier Reef has experienced three outbreak waves since scientific reporting began, two following the largest recent (1974, 1991) floods of the Burdekin River. A fourth outbreak appears to be getting underway. Experiments show that high phytoplankton availability increases survival probabilities of the phytoplankton-feeding *A. planci* larvae up to approximately 60-fold, which may be sufficient to initiate population growth from very low to locally high densities, i.e. the formation of primary outbreaks (Fabricius *et al.,* 2010). Once a primary outbreak is established, high adult crown-of-thorns starfish numbers provide sufficient larvae even at lower phytoplankton densities to sustain an ongoing outbreak until coral cover is depleted.

A variety of observational evidence indicates that primary crown-of-thorns starfish outbreaks originate on reefs between Cairns and Lizard Island (17.2–14.5 degrees South latitudes). Outbreaks were first reported at Green Island in 1962 and 1978 (Endean and Stablum, 1975; Cameron and Endean, 1981), but data for these two events are too sparse to substantiate the concept of a discrete seed area or a specific 'high-risk' region. Various authors have suggested the primary outbreaks of 1960s and 1970s were located 'north of Green Island' (Kenchington 1977), 'behind the ribbon reefs' (Dight *et al.,* 1990a,b), 'most likely between 15–16 degrees South, but also possible in a band as wide as three to four degrees latitude' (Reichelt *et al.,* 1990), or 'around 16 degrees South' (Moran and De'ath, 1992). In contrast, the 1993 outbreak was first detected at Lizard Island (Pratchett, 2005; Sweatman, 2008). The 'high-risk' area for primary crown-of-thorns starfish outbreaks between 14.5 and 17 degrees South contains approximately 200 reefs with an aggregate outer reef slope circumference close to 2000 kilometres (GBRMPA GIS Group, personal communication).

The analysis conducted by Furnas *et al.,* (2013a) strongly supports the hypothesis that nutrient loading associated with river discharge is a primary driver of regional lagoonal chlorophyll concentrations. The critical factor is the amount of discharge during the early wet season (November-February) when crown-of-thorns starfish larvae are present in the water column. There appears to be an important threshold of the order of 10 kilometres cubed of discharge in this period (at current nutrient concentrations) to produce sufficient phytoplankton at the proper time to sustain high crown-of-thorns starfish larval survival and promote a subsequent crown-of-thorns starfish outbreak. The choice of a 10 kilometre cubed threshold is somewhat arbitrary, but is indicative of the order of runoff (with available nutrients) needed to produce significant regional phytoplankton populations. Further development of a crown-of-thorns starfish outbreak, however, depends on there being sufficient coral cover to sustain local adult populations. This is why outbreaks did not follow the significant early season runoff of the 1981-1982 wet season and the wet seasons between 1997 and 2001.

Hydrodynamic modelling has been applied to rank the influence of individual rivers with discharges that affect the Cairns – Lizard Island region. The analysis indicates rivers between (and including) the Burdekin and the Daintree have some degree of influence. Riverine inputs were ranked using both the magnitude and duration of exposure, and show that discharges from the Daintree, Russell-Mulgrave, Tully and Barron rivers dominate the northern Cairns – Lizard Island region, with the Burdekin River also contributing significantly to the southern part of this region. When the contribution of dissolved inorganic nitrogen was considered, the Russell-Mulgrave, Tully, Johnstone and Burdekin rivers together contributed more than 80 per cent to the total region.

Assessment of land use information shows that the greatest source of anthropogenic nitrogen from the Wet Tropics and Burdekin catchments is from agricultural fertilizer (Waters *et al.,* in press).

Sugarcane is the primary crop in the coastal areas of the Great Barrier Reef, but bananas and other horticultural crops are grown. As described above and in Chapter 4, it is estimated that 43 per cent of the anthropogenic dissolved inorganic nitrogen loading to the Great Barrier Reef is sourced from the Wet Tropics catchments, with large contributions also seen from the Burdekin.

A number of environmental factors influence thermal bleaching resistance of corals (West and Salm, 2003). Elevated nutrient concentrations have been identified as one of the most important (Wooldridge, 2009; Wooldridge and Done, 2009; Carilli *et al.,* 2009, 2010; Wagner *et al.,* 2010). DIN availability is important in the functioning of the coral-algae symbiosis, and elevated dissolved inorganic nitrogen concentrations can cause changes which disrupt the ability of the coral host to maintain an optimal population of algal symbionts (e.g. Dubinsky *et al.,* 1990; Marubini and Davies, 1996). Mechanisms have been proposed to explain this effect (Wooldridge and Done, 2009; Wiedenmann *et al.,* 2013; Cunning *et al*., 2012). Dissolved inorganic nitrogen concentrations on the order of one to –10 micrometres can increase symbiont losses, even at normal summer temperatures which typically range between 27 and 29 degrees Celsius. Further discussion of this is also included in Chapter 1 (Schaffelke *et al.,* 2013).

Macroalgal cover on central Great Barrier Reef coral reefs is correlated with increased turbidity (De'ath and Fabricius 2010, Fabricius *et al.,* 2012). The mechanisms whereby macroalgae flourish in shallow turbid environments are not well understood, but appear related to grazing pressure (e.g. Wolanski *et al.,* 2003) and to a lesser extent to the capacity of macroalgae to store nutrients and take preferential advantage of microbial nutrient remineralisation of deposited organic matter (Schaffelke 1999), or low abundances of herbivorous fishes in turbid environments (Wolanski *et al.,* 2003).

Macroalgae suppress coral recruitment through space occupancy, allelopathy, silt-trapping and shading. Mat-forming macroalgae may damage or kill understorey corals by restricting gas exchange and creating hypoxia when mats die (Hauri *et al.,* 2010). Tall perennial macroalgae such as *Sargassum* spp., do not usually kill corals, but can reduce coral growth by shading and tissue abrasion (Littler and Littler 2007). As a result, corals may be out-competed by macroalgae that grow well in more turbid or high-nutrient environments - as long as light is not limiting.

Grazing pressure by herbivorous fish can exert a strong control on macro-algal cover on Great Barrier Reef coral reefs (Hughes *et al.,* 2007; Wismer *et al.,* 2009). However, macroalgae still cover extensive areas on many inshore reefs (De'ath and Fabricius, 2010), suggesting that herbivore control is incomplete at these sites. The intensity of fish grazing is influenced by water quality. For example, Wolanski *et al.,* (2003) and Cheal et al. (2010) have reported inverse relationships between turbidity and herbivorous fish abundance on Great Barrier Reef coral reefs, where there is little human fishing pressure on herbivores. The mechanisms behind this relationship are still not well understood, but may include an avoidance (Wolanski *et al.,* 2003), increased predation on herbivores in turbid habitats, reduced food palatability if algae trap large amounts of sediments (Mallela *et al.,* 2007) or reduced larval fish settlement (Wenger *et al.,* 2011, 2012, in press).

Most of the terrestrial nitrogen and phosphorus discharged into the Great Barrier Reef is in particulate form (Furnas, 2003). The dissolved inorganic forms of nitrogen and phosphorus are immediately bio-available, while the particulate forms undergo diagenesis and become bio-available over longer time frames.

Plankton ecologists and geochemists have long debated whether the oceans are nitrogen or phosphorus limited (e.g. Smith, 1984). Freshwater systems are most commonly regarded as phosphorus limited (e.g. Schindler, 1977). Careful bioassay testing of nitrogen versus phosphorus limitation (e.g. Ptacnik *et al.,* 2010) indicate a broad boundary between nitrogen and phosphorus limitation in natural systems which is very much influenced by conditions and affected communities at the time. Available nutrient data from the Great Barrier Reef system (reef waters, rainfall, Coral Sea, rivers) clearly shows that phytoplankton biomass is constrained by the availability of readily bio-available inorganic forms of nitrogen (Furnas *et al.,* 2013b). Furnas *et al.,* (2013b) found that:

- Ratios of dissolved inorganic nitrogen: dissolved inorganic phosphorus are almost universally less than the canonical Redfield (N_{16}:P_1) ratio (Redfield, 1934).
- Dissolved inorganic nitrogen to silicate ratios are also considerably lower than the nominal 'Redfield' value (N_1:Si_1). Silicate is unlikely to limit Great Barrier Reef phytoplankton as the dominant cyanobacteria do not require silicate.
- Dissolved organic nitrogen: Dissolved organic phosphorus ratios in Great Barrier Reef waters are considerably greater than the Redfield ratio. This is due to the large stocks of biologically recalcitrant dissolved organic nitrogen in Great Barrier Reef waters. Some forms of dissolved organic nitrogen (dissolved amino acids, urea, and nucleic acids) are bio-available, but these pools are very small. While most dissolved organic nitrogen is ultimately biologically degradable, decomposition time frames (months to centuries) are far longer than phytoplankton and bacterial generation times or water residence times on the shelf.
- Total dissolved nitrogen: total dissolved phosphorus ratios exhibit a persistent cross-shelf gradient, with higher ratios inshore, reflecting a terrestrial total dissolved nitrogen source.
- Nitrogen: phosphorus ratios in suspended particulate matter are very close to the Redfield ratio in composition. This particulate organic material is largely plankton-sourced and is actively consumed and cycled.
- Total nitrogen: total phosphorus ratios (median values 25-35) in Great Barrier Reef waters largely track total dissolved nitrogen: total dissolved phosphorus ratios, primarily because of the large pool of dissolved organic nitrogen in reef waters.
- Rainwater has very high dissolved inorganic nitrogen: dissolved inorganic phosphorus and dissolved inorganic nitrogen: silicate ratios, primarily due to the very low concentrations of dissolved inorganic phosphorus and silicate in rainwater.
- Nitrogen: phosphorus ratios (all species) in river waters flowing into the Great Barrier Reef are highly variable across all river systems sampled. With few exceptions, nitrogen: phosphorus ratios were either flow-invariant or decreased with increasing flow. Wet tropics rivers (Barron to Herbert rivers) are characterized by supra-Redfield (more than 16:1) dissolved inorganic nitrogen: dissolved inorganic phosphorus ratios, while southern Great Barrier Reef rivers (Barratta Creek to Burnett River) had sub-Redfield (less than 16:1) dissolved inorganic nitrogen: dissolved inorganic phosphorus rations. Catchments with significant areas of fertilised sugarcane cultivation are present in both groups.
- The low median dissolved inorganic nitrogen: dissolved inorganic phosphorus ratio (1.6) in Great Barrier Reef waters relative to dissolved inorganic nitrogen: dissolved inorganic phosphorus and total nitrogen: total phosphorus ratios in external nutrient sources (upwelled Coral Sea thermocline waters, rainwater, river waters and nitrogen-fixation) indicate that bio-available nitrogen is being preferentially removed. The nitrogen is either being sequestered in non-bioactive dissolved organic nitrogen and exported, or is denitrified in Great Barrier Reef shelf sediments (e.g. Alongi *et al.,* 2006, 2007a, 2007b).
- Nitrogen: phosphorus ratios in seagrass in inshore estuarine, coastal and reef habitats, indicate that seagrasses are generally replete in both nitrogen and phosphorus (Mckenzie *et al.,* 2012a). Land runoff and remineralisation are primary sources of dissolved inorganic nitrogen and dissolved inorganic phosphorus for inshore seagrasses. There has been limited exploration to date of seagrass nutrient dynamics and nutrient limitation in the Great Barrier Reef (Udy *et al.,* 1999; Mellors 2003). Light limitation is presently regarded as the primary driver of seagrass production (Collier and Waycott 2009).

- Whether trace elements such as iron (Entsch *et al.,* 1983; Fu and Bell, 2003) limit phytoplankton biomass or growth in the Great Barrier Reef remains to be established.

Particulate nutrients are central to Great Barrier Reef nutrient cycling over a wide range of time scales. Day-to-day nutrient (nitrogen, phosphorus) demand in the water column is overwhelmingly supplied by the continuous remineralisation of particulate organic matter in the water column (Furnas *et al.,* 2005; 2011). Other particulate nutrient pools cycle over longer time frames. Most particulate nitrogen is in the form of biomass and organic detritus. Nitrate does not adsorb onto particles and ammonium only on some clays. In contrast, the particulate phosphorus pool may contain significant amounts of inorganic phosphate ions adsorbed onto clay particles and incorporated into mineral phases (e.g. apatites). In estuaries and rivers the bound phosphate may desorb and become bioavailable. Desorption has been used to explain differences between the phosphorus content of Johnstone River suspended sediments (higher) compared to the lagoonal sediments immediately offshore (lower; McCulloch *et al.,* 2003). Bulk nitrogen and phosphorus remineralisation times in Great Barrier Reef waters and sediments are still not well resolved, but likely span a considerable range (hours to years).

Suspended sediment and turbidity

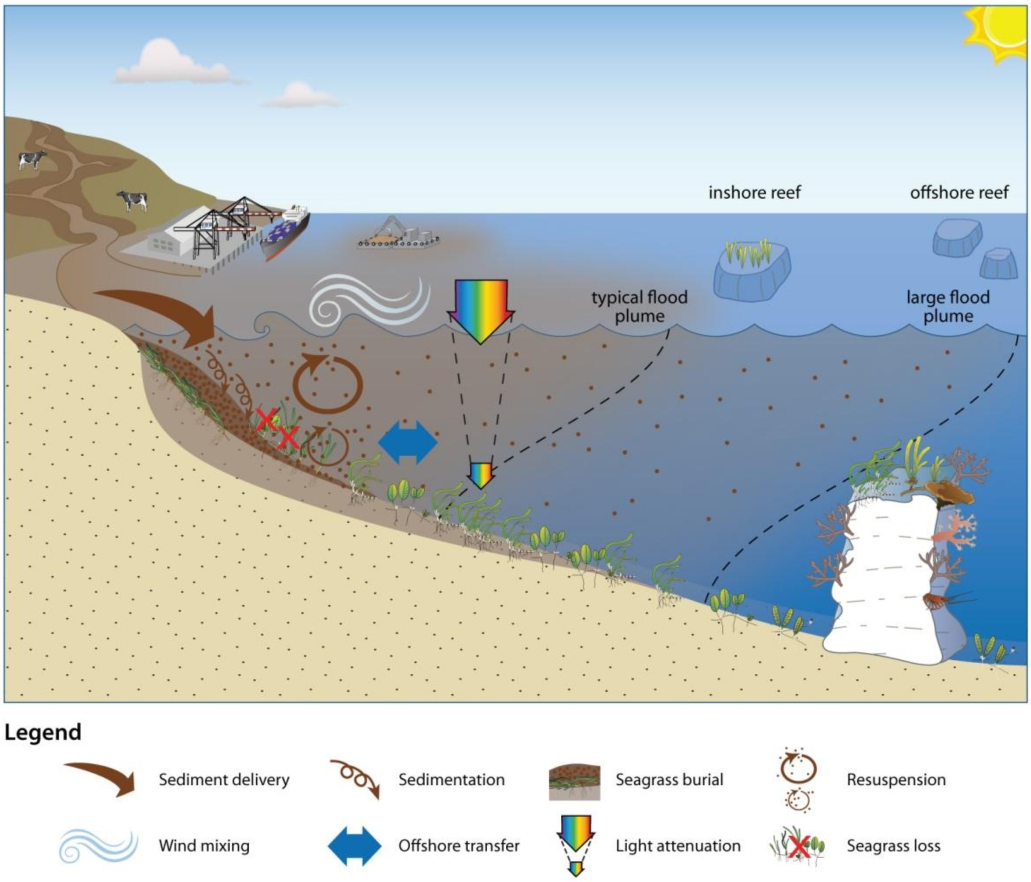
As described in Chapter 1, turbidity strongly influences the ecology of coastal marine ecosystems. Turbidity reduces light penetration to both phytoplankton and benthic primary producers such as seagrass (Collier *et al.,* 2012) and corals (Fabricius, 2005) (refer to Figure 7). Great Barrier Reef water clarity is primarily driven by the resuspension of fine sediment by wind-generated waves and tidal currents (Larcombe *et al.,* 1995; Wolanski *et al.,* 2005; Storlazzi *et al.,* 2009). Recurrent wind-driven resuspension maintains high turbidity in nearshore waters even during relatively low runoff periods (Fabricius *et al.,* 2013; Devlin *et al.,* 2013b) , perpetuating the effect of river discharge through time. At regional scales, turbidity is also influenced by proximity to fine sediment sources such as shallow bays or rivers. Inshore turbidity may vary 10-fold with distance from a river mouth source (Fabricius *et al.,* 2013). While changes in seawater turbidity (water clarity) have been related to anthropogenic nutrient loading (e.g. McQuatters-Gollop *et al.,* 2009; Schoellhamer 1996, 2002; Schoellhamer *et al.,* 2007; Chen *et al.,* 2007), this is not a significant problem at the nutrient loading levels occurring in the Great Barrier Reef system. Turbidity in Great Barrier Reef waters exhibits hysteresis following sediment input events (floods) on a range of time scales. Depending on location and conditions, surficial sediments may remain mobile for weeks to years until they are ultimately sequestered in low energy depositional centres or deep lagoon waters beyond the reach of surface waves.

Site-specific rates of sedimentation on corals and surrounding substrata are determined by local sediment supply, particle grain size distribution and the local hydrodynamic regime (Wolanski *et al.,* 2005). Calcium carbonate sands, which dominates sedimentation offshore, have little effect on coral, while deposits of organic-enriched fine terrestrial silts, which dominate sedimentation inshore (Bannister *et al.,* 2012) are detrimental (Weber *et al.,* 2006, 2012). The large surface area of fine sediments facilitates adsorption of organic matter, nutrient ions and pesticides. Sediments with high organic content can cause microbial oxygen depletion on the coral surface within a few hours, leading to hypoxia and eventual coral mortality (Weber *et al.,* 2012). Fine sediments are also more difficult to remove from colony surfaces than coarser particle sizes (Weber *et al.,* 2006). The autochthonous formation of marine snow (with or without sediment) (Passow 2002) can exacerbate the impacts greatly (Fabricius and Wolanski 2000; Fabricius *et al.,* 2003).

Juvenile corals are particularly susceptible to sedimentation. The tolerance of coral recruits to sediment is at least one order of magnitude lower than that of adult corals (Fabricius 2005) and rates of fertilisation and embryogenesis are affected by suspended sediments (Humphrey *et al.,* 2008). Sediment accumulation physically blocks access to suitable settlement substrata (Birrell *et al.,* 2005) and alters surface microbial communities which disrupts chemical cues for settlement and metamorphosis (Negri *et al.,* 2001, Webster *et al.,* 2004). Sediments alter or damage essential settlement substrata such as coralline algae, especially when co-occurring with herbicides such as diuron (Harrington *et al.,* 2005). Cover of crustose coralline algae on Great Barrier Reef coral reefs is inversely related to sedimentation rates (Kendrick, 1991; Fabricius and De'ath 2001). Once settled, juvenile corals are vulnerable to sedimentation as their small size precludes passive shedding and smaller energy reserves limit active removal.

Seagrass meadows primarily grow in soft sediment habitats, which are subject to patterns of tidal and wind driven resuspension. The maximum depth limit of seagrasses is strictly determined by light availability, with shallower depth limits in turbid waters (Abal and Dennison 1996). Seagrass species vary in their light requirements, so elevated turbidity influences local species composition (Erftemeijer and Lewis, 2006). Long-term mean light availability has important implications for the energy budget of seagrasses and corals, with organisms in low-light habitats suffering from reduced energy availability, which in turn increases their vulnerability to other stresses (Collier *et al.,* 2011; Fabricius *et al.,* 2012, 2013; Brodie *et al.,* 2013). This has flow on consequences for populations that are reliant on these habitats. Episodic or recurrent burial of seagrass occurs naturally where seagrass meadows grow close to river mouths with large sediment discharge (Campbell and McKenzie, 2004). These localised burial events are difficult to document and monitor. As a result, the occurrence of such events in the Great Barrier Reef is essentially unknown.

Figure 5. Process affecting turbidity in the coastal zone of the Great Barrier Reef include runoff, dredging, resuspension and tidal currents, with shallow inshore coastal seagrasses being the most readily affected by these processes. Source: Collier, 2013.



Loss of seagrass habitat as a result of severe weather events and degraded water quality has led to increased mortality of dugong and turtles in recent years. Cyclone Yasi in the central Great Barrier Reef and flooding in the southern Great Barrier Reef in 2011 resulted in devastating loss of seagrass (McKenzie and Unsworth, 2011; McKenzie *et al.,* 2012a,b) along the coast from Hervey Bay to Cairns. This loss came on top of declining seagrass health in the central Great Barrier Reef (McKenzie *et al.,* 2010a,b). The dugong population in the Great Barrier Reef is totally reliant on seagrass communities. Evidence shows that the southern dugong population was significantly reduced by commercial harvesting between 1847 and 1969 so the population is at best only about 25 per cent what might be expected (Marsh *et al.,* 2005). Given this population (reduced though it is) is a potential surrogate for the quantity of seagrass needed to maintain it, the loss of seagrass from the chronic impacts of water quality followed by the acute impact of the extreme cyclonic event and flooding in 2011 saw the southern dugong population reduce from an estimate of 2500 animals in 2005 to 600 in November 2011 (Sobtzick *et al.,* 2012). It is considered that much of the change in population estimates between 2005 and 2011 can be explained by animals moving to locations outside the survey area to search for seagrasses (Sobtzick *et al.,* 2012).

The number of recorded dugong and turtle strandings has also increased significantly in recent years. In 2011 there were over 180 recorded deaths of dugong on the Queensland coast (Meager and Limpus, 2012) believed to be due mainly to starvation associated with the loss of seagrass (Bell and Ariel, 2011). Turtle deaths (mostly green turtles) on the Queensland coast nearly doubled between 2010 and 2011 (Meager and Limpus, 2012). This has been attributed to a range of complications resulting from a lack of food. An assessment of the effects of the 2010-2011 flood events in the Great Barrier Reef show that the dugong deaths were potentially increasing both because of the chronic loss of seagrass (2009 and 2010) and increased dramatically in 2011 (GBRMPA, 2011).

This evidence, coupled with current knowledge of the impacts of degraded water quality on seagrass in the Great Barrier Reef (see above and Chapter 1), strengthens the importance of the implications of increased suspended sediment discharge from land based sources to the Great Barrier Reef.

Pesticides

Photosystem II inhibiting herbicides have been detected in the Great Barrier Reef lagoon during flood events at concentrations exceeding regulatory guidelines and known to affect microalgae, corals and seagrass (Lewis *et al.,* 2009, 2012; Smith *et al.,* 2012). Photosystem II inhibiting herbicides affect corals (Jones and Kerswell, 2003; Negri *et al.,* 2005), microalgae (Bengtson Nash *et al.,* 2005; Magnusson *et al.,* 2008), crustose coralline algae (Negri *et al.,* 2011); foraminifera (van Dam *et al.,* 2012) and seagrass (Haynes *et al.,* 2000; Gao *et al.,* 2011). Reduced photosynthesis of microphytobenthos due to acute herbicide exposure reduces growth (Magnusson *et al.,* 2008) and influences species composition (Magnusson *et al.,* 2012). Effects of chronic herbicide exposures in inshore Great Barrier Reef environments are unknown but are likely to affect coral reproduction (Cantin *et al.,* 2009).

Recent studies have examined various components of the ecological risk of herbicides in Great Barrier Reef ecosystems (Lewis *et al.,* 2009, 2012; Davis *et al.,* in press; Kennedy *et al.,* 2012a,b; Smith *et al.,* 2012). Lewis *et al.,* (2013) made a detailed assessment of the potential risk of pesticides other than photosystem II inhibiting herbicides that have been detected in recent monitoring programs (e.g. metolachlor and imidachloprid) to keystone ecosystems of the Great Barrier Reef including coral reefs and seagrass using monitoring and plume exposure data. They arrived at the following potential ranking of risk to ecosystems:

1. Freshwater wetlands (High risk) (Davis *et al.,* 2012, in press; Smith *et al.,* 2012).

2. Estuaries (Medium risk) (Davis *et al.,* 2012, in press; Smith *et al.,* 2012; Lewis *et al.,* 2012).
3. Coastal marine environment including intertidal and subtidal seagrass meadows (Medium risk) (Lewis *et al.,* 2009, 2012; Smith *et al.,* 2012; Kennedy *et al.,* 2012a,b; Shaw *et al.,* 2010).
4. Inner shelf coral reef and seagrass meadows (Low-Medium risk) (Lewis *et al.,* 2009, 2012; Shaw *et al.,* 2010; Kennedy *et al.,* 2012a,b).
5. Mid-outer shelf coral reefs (Low risk) (Lewis *et al.,* 2009, 2012; Kennedy *et al.,* 2012 a,b; Shaw *et al.,* 2010).

Current herbicide risk assessments are largely based upon sampling in major regional river systems. Additional analysis shows that small streams in large areas of intensive agriculture (e.g. Barratta Creek within the Burdekin region) may have much higher exposures to herbicides. At present, relatively little is known regarding Great Barrier Reef risks associated with chronic or repeated exposures to pesticides. Pesticide inputs to receiving waterways typically occur in pulses or time-varying and/or repeated exposures (Reinert et al 2002).

Other pollutants

Specific pollutants (e.g. microplastics, endocrine disrupting substances, oil and polycyclic aromatic hydrocarbons, pharmaceuticals and heavy metals) may pose risks in specific sites or ecosystems, but limited current knowledge of the extent and degree of their influence precludes a quantitative estimation of risk to wider areas (Berry *et al.,* 2013). The current water quality management framework for the Great Barrier Reef is largely driven by Reef Plan and focuses on agriculturally derived (non-point source) pollution. This focus is based on the relatively small contribution of point sources (urban areas, ports, shipping, mining, industrial areas) to overall nutrient and pollutant loads, and that point sources of pollution were adequately addressed under existing policy and legislative frameworks. Other pollutants [pharmaceuticals, polycyclic aromatic hydrocarbons, trace metals (e.g. Jones *et al.,* 2005), endocrine disrupting substances, coal dust (Burns and Brinkman, 2011), xenobiotic chemicals in general (e.g. Humphrey *et al.,* 2007; Codi *et al.,* 2004), nanomaterials, litter (e.g. Haynes 1997), ghost nets (Wilcox *et al.,* 2013), antifoulants (tributyltin**,** irgarol, diuron, copper) (e.g. Andersen 2004; Haynes *et al.,* 2002; Negri and Marshall, 2009; Marshall et al 2002) are outside of Reef Plan's scope. Many of these pollutants are recognised as serious threats to coastal and marine ecosystems (Schwarzenbach *et al.,* 2006; Dachs and Méjanelle, 2010).

Limitations to the risk assessment and future improvements

The risk assessment described in this chapter provides the best available assessment of the relative risk of degraded water quality to the Great Barrier Reef and can be used as the first step in prioritising management focused on the regional 'hot spots' of pollutant sources, the contributing industries and the resulting impacts in the marine environment. However, there are several limitations to the assessment that are important to identify, and are summarised below.

Limitations to the input datasets in terms data collection, temporal and spatial resolution, influence the certainty of the outcomes. Several examples are presented here:

Total suspended solids and chlorophyll exceedance is based on daily observations over a 10 year monitoring period (with only one or two valid observations every five days), while surface exposure of total suspended solids and dissolved inorganic nitrogen is based on a mean of 2007 to 2011 (which were in fact relatively wet years in the long term record), and photosystem II inhibiting herbicide exposure is based on single flood events. For these reasons, the final conclusions of the assessment are supported by additional evidence of known water quality conditions, spatial and temporal patterns and ecological impacts. Additional variables that were considered but not included due to the current lack of temporal and spatial data, and / or knowledge of ecological impacts include chronic exposure to photosystem II inhibiting herbicides and non-photosystem II inhibiting herbicides, particulate nutrients and phosphorus exposure, and presence and distribution of other pollutants (e.g. microplastics, endocrine disrupting substances, oil and polycyclic aromatic hydrocarbons, pharmaceuticals and heavy metals) in the Great Barrier Reef.

The modelled estimates of anthropogenic end-of-catchment loads used in the assessment are long term averages over the period 1986 to 2009. Empirical datasets included in the assessment (e.g. total suspended solids and dissolved inorganic nitrogen plume loading) are based on annual results or shorter time periods of five to 10 years and therefore, are more sensitive to large scale flood events. In comparing the modelled end of catchment load results against empirical data, the relative contributions of individual regions are in general agreement with monitoring data except during extreme wet seasons.

The assessed risk posed by pesticides is most probably an underestimate. Only a few of the pesticides detected in the Great Barrier Reef lagoon are considered. The risk posed by multiple pesticides, in combination with other contaminants found in flood plumes (e.g. elevated total suspended solids and nutrients) and other environmental stressors (temperature) have not been assessed. Cumulative impacts from the multiple plumes that occur each year are also not accounted for. Toxicity of photosystem II inhibiting herbicides is time dependent (Vallotton *et al.,* 2008), i.e. the toxicity to phototrophs increases with duration of the exposure. For this risk assessment, only acute exposure was used to assess the potential impacts to seagrass and corals.

Potential risk has not been assessed equally across all regions. For example, there are less data on the extent and condition of corals and seagrasses of the Burnett Mary region, which are outside the Great Barrier Reef World Heritage Area. The wider Burnett Mary region contains a large area of seagrass to the south of the Great Barrier Reef World Heritage Area boundary in Hervey Bay which provides important habitat and foraging grounds for mobile species that also inhabit the Great Barrier Reef World Heritage Area. The seagrass area in Hervey Bay supports the highest density dugong habitat south of the Torres Strait (Grech *et al.,* 2011). These seagrass meadows have been severely impacted by several high discharge events from the rivers in the Burnett Mary region in 1992 (Preen and Marsh, 1995; Preen *et al.,* 1995), again in 1999 (Campbell and McKenzie, 2004) and in 2011 (Coles *et al.,* 2011; McKenzie and Unsworth, 2011; McKenzie *et al.,* 2012a). The loss of seagrass after these floods had dramatic effects on dugong mortality and migration (Preen and Marsh, 1995; Preen *et al.,* 1995). There are also important areas of coastal coral reef in the area south of the Great Barrier Reef World Heritage Area boundaries (Zann, 2012) that have been impacted by river discharge events from Burnett Mary rivers. Finally, pesticides discharged from the Mary River have been found in estuarine and marine sections of Hervey Bay at concentrations potentially able to reduce photosynthesis in seagrass (McMahon *et al.,* 2005). Given these considerations, the conclusions of relative risk between regions is likely to be an underestimate for the Burnett Mary. These areas should be incorporated in any future assessments of the influence of water quality on regional habitats. A similar argument could be made for the coral reef and seagrass habitats of the northern Great Barrier Reef in the Torres Strait.

Estimates of regional river influences on the Great Barrier Reef are assumed to be constrained within adjacent marine boundaries due to currently limited capacity to quantify the transport and dispersion of individual river plumes in the Great Barrier Reef lagoon. It is fully understood that river plumes, particularly from the large Burdekin and Fitzroy river catchments can cover large areas within the Great Barrier Reef lagoon. Observations (e.g. Wolanski and vanSenden, 1983), hydrodynamic modelling (e.g. King *et al.,* 2002) and satellite imagery (e.g. Devlin *et al.,* 2012) during periods of high flow has shown that the Burdekin River influences the shelf into the Wet Tropics marine region, and that the Fitzroy River plume may reach the Mackay Whitsunday marine region.

The risk classes for individual water quality variables are not equivalent in terms of ecological impact, and are therefore not directly comparable. Further studies should adequately address this limitation to provide a better representation of the severity of potential ecological impacts between assessment classes. The approach to classification used is also a potential weakness of Multi Criteria Analysis, which is an interval scale approach, while risk consequence is inherently oriented to a need for quantification of magnitudes. In addition, the assessment does not account for the potential synergistic or antagonistic effects that these multiple stressors when acting together may have on ecosystems.

Only a limited sensitivity analysis that tested weighting of variables has been conducted. More scenarios that scale or 'weight' individual factors or pollutants as being more or less important and the effect of only selecting the highest assessment classes in the final analysis should be tested. For example, a more detailed assessment of the patterns in the lower assessment classes should be considered in future work, particularly given the potential influence of chronic exposure to pollutants, or the effects of periodic exposure to high concentrations of pollutants.

Further validation of remote sensing-based results is required for locations where high turbidity that confounds existing algorithms may naturally occur. These areas include the Cape York region north of Cooktown, coastal areas around Shoalwater Bay and the Rodds Bay area north of Curtis Island which are naturally turbid. Uncertainties in products derived from remote sensing of these areas have not been resolved. In addition, the number of valid observations for the remote sensing assessment varies between seasons and locations and over the year equates to an average of less than two valid observations every five days.

Limitations to the scope of the assessment including coverage of social and economic issues and other Great Barrier Reef ecosystems. It should be recognised and highlighted that the results presented in this study only represent the biophysical perspective of management priorities required to reduce pollutant impacts on the Great Barrier Reef. However, further consideration of the relative priorities between the regions and industries requires incorporation of the current adoption of management practices, the feasibility of adopting the most effective practices in terms of water quality benefits, the relative cost effectiveness of these practices, existing management programs in place, and the range of management strategies available to address these issues.

A majority of the assessment is limited to the consideration of relative risk of degraded water quality to coral reefs and seagrass, except for the additional pesticide assessment which also includes coastal ecosystems. While the actual risk assessment (Brodie *et al.,* 2013a) did consider the area of Great Barrier Reef lagoon waters, there was no specific assessment of the relevance of these results to other Great Barrier Reef ecosystems. Any further assessments should aim to expand the scope to incorporate coastal ecosystems such as freshwater and coastal wetlands, mangroves and estuarine environments, and non-reef bioregions.

These limitations have been translated into the following priority information needs for future risk assessments of water quality in the Great Barrier Reef:

1. Scoping of the availability of, and acquisition of, more consistent temporal and spatial data for all water quality variables (including those not included in the most recent assessment such as phosphorus and particulate nutrients) and their ecological impacts to enable improved classification in terms of ecological risk and application of a formal risk assessment framework (which includes assessments of likelihood and consequence).

2. Better understanding of the responses of key Great Barrier Reef ecosystem components to cumulative impacts of repeated exposure to poor water quality, and the cumulative impacts of multiple water quality pressures.
3. Definition of zones of river influence in the Great Barrier Reef for each catchment using hydrodynamic and pollution distribution models so that water quality risk from individual and combined pollutants can be attributed back to individual rivers. With this information it would be possible to estimate source-sink relationships for every pollutant, every river, and every part of the Great Barrier Reef lagoon. It is the ultimate intent of eReefs to deliver this type of information.
4. Collation of all existing information on the distribution and condition of coral reef and seagrass habitats in the Burnett Mary and Cape York regions, with support for resources to undertake further assessment if gaps are identified.
5. Validation of the remote sensing data for turbidity and chlorophyll, particularly in areas which are known to be naturally highly turbid or where existing validation data is limited such as in Cape York and Burnett Mary regions.
6. Better understanding of the prevalence and associated effects of other pollutants (e.g. microplastics, endocrine disrupting substances, oil and polycyclic aromatic hydrocarbons, pharmaceuticals and heavy metals) on Great Barrier Reef ecosystems.
7. Extending the habitat assessments beyond coral reefs and seagrass to include coastal ecosystems such as freshwater and coastal wetlands, mangroves and estuarine environments, and non-reef bioregions.

Despite these limitations and scope for future improvement, the risk analysis described in this chapter is considered to be the most quantitative and rigorous yet undertaken. As a next step, current knowledge of the effectiveness of management practices (in terms of water quality benefits and socio economic outcomes) across the main agricultural industries in the Great Barrier Reef catchments can be used to inform investment options to address these water quality priorities. This information is captured in the Scientific Consensus Statement Chapter 5 (Thorburn *et al.,* 2013).

Conclusions

From the information summarised in this chapter, it is concluded that *all risks posed to the Great Barrier Reef from degraded water quality are important.* Increased catchment loads of suspended sediment, nutrients (nitrogen and phosphorus) and pesticides all pose an unacceptable risk to some parts of the Great Barrier Reef. However in the context of health of the Great Barrier Reef overall, the greatest water quality risks to the Great Barrier Reef are from nitrogen discharge, associated with crown-of-thorns starfish outbreaks and their destructive effects on coral reefs, and fine sediment discharge which increases sedimentation and reduces the levels of light reaching seagrass and inshore coral reef communities. Pesticide inputs pose a risk to freshwater, estuarine and some inshore and coastal habitats.

The results from this combined assessment of anthropogenic load and water quality variables in the marine environment are summarised below. The combination of these assessments allows us to draw conclusions about the overall risk of pollutants to the Great Barrier Reef. In summary, the greatest risk to each habitat in terms of the potential water quality impact from all of the assessment variables in the Great Barrier Reef and end-of-catchment anthropogenic loads of dissolved inorganic nitrogen, total suspended solids and photosystem II inhibiting herbicides is:

- **Coral reefs:** Wet Tropics region, followed by the Fitzroy region. The rank of the remaining regions is the Mackay Whitsunday, Burdekin, Cape York and Burnett Mary regions.
- **Seagrass**: Burdekin region, followed by the Wet Tropics. The rank of the remaining regions is the Fitzroy, Mackay Whitsunday, Burnett Mary and Cape York regions.
- **Coral reefs and seagrass combined:** Wet Tropics, followed by the Fitzroy and Burdekin. The relative risk to the Mackay Whitsunday region is half the greatest risk, followed by the Burnett Mary and Cape York regions.

It must be reiterated that these are relative assessments indicating that the risk posed to ecosystems from degraded water quality in the Burnett Mary and Cape York regions is low relative to the other regions. However, ecosystems in these regions may be exposed to a range of risks that still require improved pollutant management to recover or maintain ecosystem values.

In addition a number of conclusions can be made about priority areas for management of each pollutant.

- Nitrogen management: Wet Tropics
- Photosystem II inhibiting herbicide management: Mackay Whitsunday and Burdekin (lower Burdekin)
- Suspended sediment management: Burdekin and Fitzroy

As a next step, current knowledge of the effectiveness of management practices (in terms of water quality benefits and socio-economic outcomes) across the main agricultural industries in the Great Barrier Reef catchments should be used to inform investment options to address these water quality priorities. The information presented the Scientific Consensus Statement, Chapter 5 (Thorburn *et al.,* 2013) provides the basis for this type of assessment.

Reference list

AS/NZS, 2004. Risk management. Joint Australian/New Zealand Standard prepared by Joint Technical Committee OB-007, Risk Management. AS/NZS 4360:2004.

Abal, E.G., Dennison, W.C., 1996. Seagrass depth range and water quality in southern Moreton Bay, Queensland, Australia. Marine and Freshwater Research 47, 763-771.

Alongi, D.M., Pfitzner, J., Trott, L.A., 2006. Deposition of carbon and nitrogen in carbonate mud of the lagoon of Arlington and Sudbury Reefs, Great Barrier Reef. Coral Reefs 25, 123-143.

Alongi, D.M., L.A. Trott, Pfitzner, J., 2007a. Biogeochemistry of the inter-reef sediments on the northern and central Great Barrier Reef. Coral Reefs 27, 407-420.

Alongi, D.M., Trott, L.A., Pfitzner, J. 2007b. Deposition, mineralization and storage of carbon and nitrogen in sediments of the far northern and northern Great Barrier Reef. Continental Shelf Research 27, 2595-2622.

Álvarez-Romero, J.G., Devlin, M., Teixeira da Silva, E., Petus, C., Ban, N.C., Pressey, R.L., Kool, J., Roberts, J.J., Cerdeira-Estrada, S., Wenger, A.S., Brodie, J., 2013. A novel approach to model exposure of coastal-marine ecosystems to riverine flood plumes based on remote sensing techniques. Journal of Environmental Management 119, 194-207.

Andersen, L.E., 2004. Imposex: a biological effect of TBT contamination in Port Curtis, Queensland. Australian Journal of Ecotoxicology 10, 105-113.

Babcock, R., Davies, P. 1991. Effects of sedimentation on settlement of Acropora–Millepora. Coral Reefs 9(4), 205–208.

Bainbridge, Z., Wolanski, E., Alvarez-Romero, J., Lewis, S., Brodie, J., 2012. Fine sediment and nutrient dynamics related to particle size and floc formation in a Burdekin River flood plume, Australia. Mar Pollut Bull 65, 236–248.

Bainbridge, Z., Lewis, S., Kuhnert, P., Henderson, B., Smithers, S., Brodie, J. In Review. Sources, transport and delivery of suspended sediment in a large, dry tropical river basin. Water Resources Research.

Bartley, B., Bainbridge, Z., Lewis, S., Kroon, F., Brodie, J., Wilkinson, S., Silburn, M. In review. Linking sediment impacts on coral reefs to catchment sources processes and management. Science of the Total Environment.

Bannister, R.J., Battershill, C.N. De Nys, R., 2012. Suspended sediment grain size and mineralogy across the continental shelf of the Great Barrier Reef: Impacts on the physiology of a coral reef sponge. Continental Shelf Research 32, 86-95.

Bell, I., Ariel, E., 2011. Dietary shift in green turtles. Seagrass-Watch News 44: 2-5.

Bengtson Nash, S.M., McMahon, K., Eaglesham, G., Muller, J.F., 2005. Application of a novel phytotoxicity assay for the detection of herbicides in Hervey Bay and the Great Sandy Straits. Marine Pollution Bulletin 51, 351-360.

Berry, K.L.E., O'Brien, D., Burns, K.A., Brodie, J., 2013. Unrecognised Pollutant Risks to the Great Barrier Reef. Centre for Tropical Water and Aquatic Ecosystem Research (TropWATER) Publication, James Cook University, Townsville, 38 pp.

Birkeland, C., 1982. Terrestrial runoff as a cause of outbreaks of Acanthaster planci (Echinodermata: Asteroidea). Marine Biology 69, 175-185.

Birrell, C. L., Mccook, L.J., Willis., B.L., 2005. Effects of algal turfs and sediment on coral settlement. Marine Pollution Bulletin 51, 408-414.

Bostock, H.C., Brooke, B.P., Ryan, D.A., Hancock, G., Pietsch, T., Packett, R., Harle, K., 2007. Holocene and modern sediment storage in the subtropical macrotidal Fitzroy River estuary, Southeast Queensland, Australia. Sedimentary Geology 201(3-4), 321-340.

Brando, V.E., Blondeau-Patissier, D., Schroeder, T., Dekker, A.G., Clementson, L., 2013. Reef Rescue Marine Monitoring Program: Assessment of terrestrial run-off entering the Reef and inshore marine water quality monitoring using earth observation data. Final Report for 2011/12 Activities. CSIRO, Canberra.

Brodie, J., 1992. Enhancement of larval and juvenile survival and recruitment in Acanthaster planci from the effects of terrestrial runoff: a review. Australian Journal of Marine and Freshwater Research 43, 539–554.

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

Brodie, J., Binney, J., Fabricius, K., Gordon, I., Hoegh-Guldberg, O., Hunter, H., O'Reagain, P., Pearson, R., Quirk, M., Thorburn, P., Waterhouse, J., Webster, I., Wilkinson, S., 2008. Synthesis of evidence to support the Scientific Consensus Statement on Water Quality in the Great Barrier Reef. The State of Queensland (Department of the Premier and Cabinet) Brisbane. <http://www.reefplan.qld.gov.au/publications/scientific_consensus_statement.shtm>.

Brodie, J., Waterhouse, J., 2009. Assessment of relative risk of the impacts of broad-scale agriculture on the Great Barrier Reef and priorities for investment under the Reef Protection Package, Stage 1 Report April 2009. ACTFR Report 09/17.

Brodie, J., Mitchell, A., Waterhouse, J., 2009. Regional assessment of the relative risk of the impacts of broad-scale agriculture on the Great Barrier Reef and priorities for investment under the Reef Protection Package, Stage 2 Report, July 2009. ACTFR Report 09/30.

Brodie, J.E., Devlin, M.J., Haynes, D., Waterhouse, J., 2011. Assessment of the eutrophication status of the Great Barrier Reef lagoon (Australia). Biogeochemistry 106, 281-302. DOI 10.1007/s10533-010-9542-2.

Brodie, J., Wolanski, E., Lewis, S., Bainbridge, Z., 2012a. A review of the residence times of land-sourced contaminants in the Great Barrier Reef lagoon and the implications for management of these contaminants on the Great Barrier Reef catchment. Marine Pollution Bulletin 65, 267-279. doi:10.1016/j.marpolbul.2011.12.011.

Brodie, J., Kroon, F., Schaffelke, B., Wolanski, E., Lewis, S., Devlin, M., Bainbridge, Z., Waterhouse, J., Davis, A., 2012b. Terrestrial pollutant runoff to the Great Barrier Reef: current issues, priorities and management responses. Marine Pollution Bulletin 65, 81–100.

Brodie, J., Fabricius, K., Lewis, S., Bainbridge, Z., Bartley, R., 2013. Chapter 3: Review of increased suspended sediment delivery to the GBR and the effects of subsequent sedimentation and light reduction on GBR ecosystems. In: Assessment of the relative risk of water quality to ecosystems of the Great Barrier Reef: Supporting Studies. A report to the Department of the Environment and Heritage Protection, Queensland Government, Brisbane. TropWATER Report 13/30, Townsville, Australia.

Burke, L., Reytar, K., Spalding, M., Perry, A., 2011. Reefs at risk revisited. World Resources Institute, Washington, DC, p. 114. Available at http://www.wri.org

Burns, K.A.,Brinkman, D., 2011. Organic biomarkers to describe the major carbon inputs and cycling of organic matter in the central Great Barrier Reef region. Estuarine Coastal and Shelf Science 93, 132-141.

Burgman, M.A., 2005. Risks and decisions for conservation and environmental management. Cambridge University Press, Cambridge. 314 p. ISBN 0521835348.

Campbell, S.J., Mckenzie, L.J., 2004. Flood related loss and recovery of intertidal seagrass meadows in southern Queensland, Australia. Estuarine, Coastal and Shelf Science 60, 477-490.

Cameron, A.M., Endean, R., 1981. Renewed population outbreaks of a rare and specialised carnivore (the starfish *Acanthaster planci*) in a complex high-diversity system (the Great Barrier Reef), in: Gomez, E.D., Birkeland, C.E., Buddemeier, R.W., Johannes, R.E., Marsh, J.A., Jr., Tsuda, R.T. (Eds.), Fourth International Coral Reef Symposium, Manila (Philippines), pp. 593-596.

Cantin, N.E., van Oppen, M.J.H., Willis, B.L., Mieog, J.C., Negri, A.P., 2009. Juvenile corals can acquire more carbon from high-performance algal symbionts. Coral Reefs 28, 405-414.

Carilli, J.E., Norris, R.D., Black, B., Walsh, S.M., McField, M., 2010. Century-scale records of coral growth rates indicate that local stressors reduce coral thermal tolerance threshold. Global Change Biology 16, 1247-1257.

Carilli, J.E., Prouty, N.G., Hughen, K.A., Norris, R.D., 2009. Century-scale records of land-based activities recorded in Mesoamerican coral cores. Marine Pollution Bulletin 58, 1835-1842.

Cheal, A.J., MacNeil, M.A., Cripps, E., Emslie, M.J., Jonker, M., Schaffelke, S., Sweatman, H., 2010. Coral-macroalgal phase shifts or reef resilience: links with diversity and functional roles of herbivorous fishes on the Great Barrier Reef. Coral Reefs 29, 1005-1015.

Chen, Z., Muller-Karger, F.E., Hu, C., 2007. Remote sensing of water clarity in Tampa Bay. Remote Sensing of Environment 109, 249-259.

Chesworth, J.C., Donkin, M.E., Brown, M.T., 2004. The interactive effects of the antifouling herbicides Irgarol 1051 and Diuron on the seagrass *Zostera marina* (L.). Aquatic Toxicology 66, 293-305.

Codi S, Humphrey C, Klumpp D and Delean S. 2004. Barramundi as an indicator species for environmental monitoring in north Queensland, Australia: laboratory versus field studies. Environmental Toxicology and Chemistry23, 2737-2744.

Coles, R., McKenzie, L., De'ath, G., Roelofs, A., Lee Long, W., 2009. Spatial distribution of deepwater seagrass in the inter-reef lagoon of the Great Barrier Reef World Heritage Area. Marine Ecology Progress Series 392, 57–68.

Coles, R.G., Grech, A., McKenzie, L., Rasheed, M. 2011. Evaluating risk to seagrasses in the tropical Indo-Pacific region. CERF 2011, 21st Biennial Conference of the Coastal and Estuarine Research Federation Conference Abstracts. Societies, Estuaries & Coasts: Adapting to Change. 6-10 November 2011, Daytona Beach, Florida, USA. p.43.

Collier, C., 2013. Chapter 7: Risks to seagrasses of the Great Barrier Reef caused by declining water quality. In: Assessment of the relative risk of water quality to ecosystems of the Great Barrier Reef: Supporting Studies. A report to the Department of the Environment and Heritage Protection, Queensland Government, Brisbane. TropWATER Report 13/30, Townsville, Australia.

Collier, C., Waycott, M., 2009. Drivers of change to seagrass distributions and communities on the Great Barrier Reef: Literature review and gaps analysis. Report to the Marine and Tropical Sciences Research Facility. Reef and Rainforest Research Centre Limited.

Collier, C.J., Uthicke, S., Waycott, M., 2011. Thermal tolerance of two seagrass species at contrasting light levels: implications for future distribution in the Great Barrier Reef. Limnology and Oceanography 56, 2200-2210.

Collier, C.J., Waycott, M., Giraldo Ospina, A., 2012. Responses of four Indo-West Pacific seagrass species to shading. Marine Pollution Bulletin 65, 342–354.

Conley, D.J., Paerl, H.W., Howarth, R.W., Boesch, D.F., Seitzinger, S.P., Havens, K.E., Lancelot, C., Likens, G.E., 2009. Controlling eutrophication: nitrogen and phosphorus. Science 323, 1014–1015.

Cotsell, P., Gale, K., Hajkowicz, S., Lesslie, R., Marshall, N., Randall, L., 2009. Use of a multiple criteria analysis (MCA) process to inform Reef Rescue regional allocations. In: Proceedings of the 2009 Marine and Tropical Sciences Research Facility Annual Conference 28–30 April 2009 Rydges Southbank Hotel, Townsville. Compiled by Shannon Hogan and Suzanne Long Reef and Rainforest Research Centre Limited. http://www.rrrc.org.au/publications/downloads/Theme-5-RRRC-2009-Annual-Conference-Proceedings.pdf

Cunning, R., Baker, A.C., 2012. Excess algal symbionts increase the susceptibility of reef corals to bleaching. Nature Climate Change doi:10.1038/nclimate1711.

Dachs, J., Méjanelle, L., 2010. Organic Pollutants in Coastal Waters, Sediments, and Biota: A Relevant Driver for Ecosystems During the Anthropocene? The H.T. Odum Synthesis Essay, Estuaries and Coasts 33, 1–14. DOI 10.1007/s12237-009-9255-8

Davis, A.M., Lewis, S.E., Bainbridge, Z.T., Glendenning, L., Turner, R., Brodie, J.E., 2012. Dynamics of herbicide transport and partitioning under event flow conditions in the lower Burdekin region, Australia. Marine Pollution Bulletin 65, 182-193.

Davis, A.M., Thorburn, P.J., Lewis, S.E., Bainbridge, Z.T., Attard, S.J., Milla, R., Brodie, J.E., in press. Environmental impacts of irrigated sugarcane production: Herbicide run-off dynamics from farms and associated drainage systems. Agriculture, Ecosystems and the Environment.

De'ath, G., Fabricius, K.E., 2008. Water quality of the Great Barrier Reef: distributions, effects on reef biota and trigger values for the protection of ecosystem health. Final Report to the Great Barrier Reef Marine Park Authority. Australian Institute of Marine Science, Townsville. (104 pp.)

De'ath, G., Fabricius, K., 2010. Water quality as a regional driver of coral biodiversity and macroalgae on the Great Barrier Reef. Ecological Applications 20, 840-850.

De'ath, G., Fabricius, K.E., Sweatman, H., Puotinen, M., 2012. The 27–year decline of coral cover on the Great Barrier Reef and its causes. Proceedings of the National Academy of Sciences of the United States of America 109 (44), 17734-17735.

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

Devlin, M.J., McKinna, L.I.W., Alvarez-Romero, J.G., Abott, B., Harkness, P., Brodie, J., 2012. Mapping the pollutants in surface river plume waters in the Great Barrier Reef, Australia. Marine. Pollution Bulletin 65, 224–235.

Devlin, M., Petus, C., da Silva, E., Alvarez-Romero, J.G., Zeh, D., Waterhouse, J., Brodie, J., 2013a. Chapter 5: Mapping of exposure to flood plumes, water types and exposure to pollutants (DIN, TSS) in the Great Barrier Reef: toward the production of operational risk maps for the World's most iconic marine ecosystem. In: Assessment of the relative risk of water quality to ecosystems of the Great Barrier Reef: Supporting Studies. A report to the Department of the Environment and Heritage Protection, Queensland Government, Brisbane. TropWATER Report 13/30, Townsville, Australia.

Devlin, M., Petus, C., Collier, C., Zeh, D., McKenzie, L., 2013b. Chapter 6: Seagrass and water quality impacts including a case study linking annual measurements of seagrass change against satellite water clarity data (Cleveland Bay). In: Assessment of the relative risk of water quality to ecosystems of the Great Barrier Reef: Supporting Studies. A report to the Department of the Environment and Heritage Protection, Queensland Government, Brisbane. TropWATER Report 13/30, Townsville, Australia.

Dight, I.J., Bode, L., James, M.K., 1990a. Modelling the larval dispersal of *Acanthaster planci* . 1. Large scale hydrodynamics, Cairns Section, Great Barrier Reef Marine Park. Coral Reefs 9, 115-123.

Dight, I.J., James, M.K., Bode, L., 1990b. Modelling the larval dispersal of *Acanthaster planci*. 2. Patterns of reef connectivity. Coral Reefs 9, 125-134.

Douglas, G.B., Ford, P.W., Palmer, M.R., Noble, R.M., Packett, R.J., Krull, E.S., 2008. Fitzroy River Basin, Queensland, Australia. IV. Identification of flood sediment sources in the Fitzroy River. Environmental Chemistry 5, 243-257, 10.1071/en07091.

Dubinsky, Z., Stambler, N., Ben-Zion, M., McClosky, L., Muscatine, L., Falkowski, P., 1990. The effect of external nutrient resources on the optical properties and photosynthetic efficiency of *Stylophora pistillata*. Proceedings of the Royal Society London, Biological Sciences 239, 231-246.

Dugdale, R.C., Goering, J.J., 1967. Uptake of new and regenerated forms of nitrogen in primary productivity. Limnology and Oceanography 12, 196-206.

Elledge, A., Thornton, C., 2012. The Brigalow Catchment Study: Nitrogen runoff generation rates from pasture legumes and changes since land development. In: Proceedings of the 34th Hydrology and Water Resources Symposium. Sydney. (Ed. S. Westra). Pages 1000-1007. Engineers Australia.

Endean, R., Stablum, W., 1975. Population explosions of *Acanthaster planci* and associated destruction of the hard-coral cover of reefs of the Great Barrier Reef, Australia. Environment Conservation 2, 247-256.

Entsch, B., Sim, R.G., Hatcher. B.G., 1983. Indications from photosynthetic components that iron is a limiting nutrient in primary producers on coral reefs. Marine Biology 73, 17-30.

Erftemeijer, P.L.A., Robin Lewis Iii, R.R., 2006. Environmental impacts of dredging on seagrasses: A review. Marine Pollution Bulletin 52, 1553-1572.

Fabricius, K.E,. 2005. Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. Marine Pollution Bulletin 50: 125-146.

Fabricius, K.E., Wolanski, E., 2000. Rapid Smothering of Coral Reef Organisms by Muddy Marine Snow. Estuarine and Coastal Shelf Science 50, 115-120.

Fabricius, K., De'ath, G., 2001. Environmental factors associated with the spatial distribution of crustose coralline algae on the Great Barrier Reef. Coral Reefs 19: 303-309.

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

Fabricius, K.E., Okaji, K., De'ath, G., 2010. Three lines of evidence to link outbreaks of the crown-of-thorns seastar *Acanthaster planci* to the release of larval food limitation. Coral Reefs 29, 593-605.

Fabricius, K.E., Cooper, T.F., Humphrey, C., Uthicke, S., De'ath, G., Davidson, J., LeGrand, H., Thompson, A., Schaffelke, B., 2012. A bioindicator system for water quality on inshore coral reefs of the Great Barrier Reef. Marine Pollution Bulletin 65, 320-332.

Fabricius, K., De'ath, G., Humphrey, C., Zagorskis, I., Schaffelke, B., 2013. Intra-annual variation in turbidity in response to terrestrial runoff at near-shore coral reefs of the Great Barrier Reef. Estuarine and Coastal Shelf Science 116, 57-65.

Flores, F., Collier, C.J., Mercurio, P., Negri, A.P., in review. Phototoxicity of four photosystem II herbicides to tropical seagrasses. PLoS ONE.

Fu, F.-X., Bell, P.R.F., 2003. Growth, N2 fixation and photosynthesis in a cyanobacterium, Trichodesmium sp. under Fe stress. Biotechnology Letters 25, 645-649.

Furnas, M., 2003. Catchments and Corals: Terrestrial Runoff to the Great Barrier Reef. Australian Institute of Marine Science, Townsville. 334 pp.

Furnas, M., Brinkman, R., Fabricius, K., Tonin, H., Schaffelke, B., 2013a. Chapter 1: Linkages between river runoff, phytoplankton blooms and primary outbreaks of crown-of-thorns starfish in the Northern GBR. In: Assessment of the relative risk of water quality to ecosystems of the Great Barrier Reef: Supporting Studies. A report to the Department of the Environment and Heritage Protection, Queensland Government, Brisbane. TropWATER Report 13/30, Townsville, Australia.

Furnas, M., O'Brien, D. and Warne, M., 2013b. Chapter 2: The Redfield Ratio and potential nutrient limitation of phytoplankton in the Great Barrier Reef. In: Assessment of the relative risk of water quality to ecosystems of the Great Barrier Reef: Supporting Studies. A report to the Department of the Environment and Heritage Protection, Queensland Government, Brisbane. TropWATER Report 13/30, Townsville, Australia.

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

Furnas, M., Alongi, D., McKinnon, D., Trott, L., Skuza, M., 2011. Regional-scale nitrogen and phosphorus budgets for the northern (14ºS) and central (17ºS) Great Barrier Reef shelf ecosystem. Continental Shelf Research 31, 1967-1990.

Gao, Y., Fang, J., Zhang, J., Ren, L., Mao, Y., Li, B., Zhang, M., Liu, D., Du, M., 2011. The impact of the herbicide atrazine on the growth and photosynthesis of seagrass *Zostera marina* (L.), seedlings. Marine Pollution Bulletin 62, 1628-1631.

Great Barrier Reef Marine Park Authority, 2009. Water Quality Guidelines for the Great Barrier Reef Marine Park. Great Barrier Reef Marine Park Authority, Townsville, 99p.

GBRMPA, 2011 http://www.gbrmpa.gov.au/__data/assets/pdf_file/0016/14308/GBRMPA-ExtremeWeatherAndtheGBR-2010-11.pdf

Grech, A., Sheppard, J., Marsh, H., 2011. Informing species conservation at multiple scales using data collected for marine mammal stock assessments. PLoS ONE 6 (3), e17993. doi:10.1371/journal.pone.0017993.

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

Harrington, L., Fabricius, K., Eaglesham, G., Negri, A., 2005. Synergistic effects of diuron and sedimentation on photosynthetic yields and survival of crustose coralline algae. Marine Pollution Bulletin 51, 415-427.

Hart, B.T., Pollino, C.A., 2008. Increased Use of Bayesian Network Models Will Improve Ecological Risk Assessments, Human and Ecological Risk Assessment 14, 851-853.

Hart, B.T., Burgman, M., Grace, M., Pollino, C., Thomas, C., Webb, J.A., Allison, G.A., Chapman, M., Duivenvoorden, L., Feehan, P., Lund, L., Carey, J., McCrea, A., 2005. Ecological Risk Management Framework for the Irrigation Industry. Land and Water Australia, Canberra (Technical Report).

Hauri, C., Fabricius, K.E., Schaffelke, B., Humphrey, C., 2010. Chemical and physical environmental conditions underneath mat- and canopy-forming macroalgae, and their effects on understorey corals. PLoS ONE 5: e12685. doi:12610.11371/journal.pone.0012685.

Haynes, D., 1997. Marine park debris in the Far Northern Section of the Great Barrier Reef Marine Park. Reef Research, Vol. 7, No. 3-4.

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

Haynes, D., Christie, C., Marshall, P., Dobbs, K., 2002. Antifoulant concentrations at the site of the Bunga Teratai Satu grounding, Great Barrier Reef, Australia. Marine Pollution Bulletin 44, 956-976.

Howarth, R., Chan, F., Conley, D.J., Garnier, J., Doney, S.C., Marino, R., Billen, G., 2011. Coupled biogeochemical cycles: eutrophication and hypoxia in temperate estuaries and coastal marine ecosystems. Frontiers in Ecology and Environment 9, 18–26.

Hughes, T.P., Rodrigues, M.J., Bellwood, D.R., Ceccerelli, D., Hoegh-Guldberg, O., McCook, L., Moltchaniwskyj, N., Pratchett, M.S., Steneck, R.S. Willis, B.L., 2007. Regime-shifts, herbivory and the resilience of coral reefs to climate change. Current Biology 17, 360–365.

Humphrey, C., Codi King, S. and Klumpp, D., 2007. The use of biomarkers in barramundi (Lates calcarifer) to monitor contaminants in estuaries of Tropical North Queensland. Report to the Marine and Tropical Sciences Research Facility. Reef and Rainforest Research Centre Limited, Cairns (32pp.)

Humphrey, C., Weber, M., Lott, C., Cooper, T., Fabricius K., 2008. Effects of suspended sediments, dissolved inorganic nutrients and salinity on fertilisation and embryo development in the coral *Acropora millepora* (Ehrenberg, 1834). Coral Reefs 27, 837-850.

Johnson, J.E., Maynard, J.A., Devlin, M.J., Wilkinson, S., Anthony, K.R.N., Yorkston, H., Heron, S.F., Puotinen, M.L., van Hooidonk, R., 2013. Chapter 2: Resilience of Great Barrier Reef marine ecosystems and drivers of change. Reef Water Quality Scientific Consensus Statement 2013. Department of the Premier and Cabinet, Queensland Government, Brisbane.

Jones, R.J., Kerswell, A.P., 2003. Phytotoxicity of photosystem II (PS II) herbicides to coral. Marine Ecology Progress Series 261, 149–159.

Jones, R.J., Mueller, J.F., Haynes, D., Schreiber, U., 2003. Effects of herbicides diuron and atrazine on corals of the Great Barrier Reef, Australia. Marine Ecology Progress Series 251, 153–167.

Jones, M.A., Stauber, J., Apte, S., Simpson, S., Vicente-Beckett, V., Johnson, R. and Duivenvoorden, L. 2005. A risk assessment approach to contaminants in Port Curtis, Queensland, Australia. Marine Pollution Bulletin 51, 448-458.

Kenchington, R.A., 1977. Growth and recruitment of *Acanthaster planci* (L.) on the Great Barrier Reef. Biological Conservation 11, 103-118.

Kendrick, G.A., 1991. Recruitment of coralline crusts and filamentous turf algae in the Galapagos archipelago: Effect of simulated scour, erosion and accretion. Journal of Experimental Marine Biology and Ecology 147, 47-63.

Kennedy, K. Schroeder, T. Shaw, M. Haynes, D. Lewis, S. Bentley, C. Paxman, C. Carter, S. Brando, V. Bartkow, M. Hearn, L. Mueller, J.F., 2012a. Long term monitoring of photosystem II herbicides – Correlation with remotely sensed freshwater extent to monitor changes in the quality of water entering the Great Barrier Reef, Australia. Marine Pollution Bulletin 65, 292-305.

Kennedy, K., Devlin, M., Bentley, C., Lee-Chue, K., Paxman, C., Carter, S., Lewis, S.E., Brodie, J., Guy, E., Vardy, S., Martin, K.C., Jones, A., Packett, R., Mueller, J.F., 2012b. The influence of a season of extreme wet weather events on exposure of the World Heritage Area Great Barrier Reef to pesticides. Marine Pollution Bulletin 64, 1495–1507.

King, B.J., Zapata, M., McAllister, F., Done, T., 2002. Modelling the distribution of river plumes in the central and northern Great Barrier Reef shelf, Technical Report No. 44, CRC Reef Research Centre, Townsville.

Kroon, F., Turner, R.D.R., Smith, R., Warne, M.St.J., Hunter, H., Bartley, R., Wilkinson, S., Lewis, S., Waters, D., Carroll, C., 2013. Chapter 4: Sources of sediment, nutrients, pesticides and other pollutants in the Great Barrier Reef catchment. Reef Water Quality Scientific Consensus Statement 2013. Department of the Premier and Cabinet, Queensland Government, Brisbane.

Larcombe, P., Ridd, P.V., Prytz, A., Wilson, B., 1995. Factors controlling suspended sediment on inner-shelf coral reefs, Townsville, Australia. Coral Reefs 14, 163–171.

Lewis, S.E., Brodie, J.E., Bainbridge, Z.T., Rohde, K.W., Davis, A.M., Masters, B.L., Maughan, M., Devlin, M.J., Mueller, J.F., Schaffelke, B., 2009. Herbicides: A new threat to the Great Barrier Reef. Environmental Pollution 157, 2470–2484.

Lewis, S.E., Schaffelke, B., Shaw, M., Bainbridge, Z.T., Rohde, K.W., Kennedy, K.E., Davis, A.M., Masters, B.L., Devlin, M.J., Mueller, J.F., Brodie, J.E., 2012. Assessing the risks of PS-II herbicide exposure to the Great Barrier Reef. Marine Pollution Bulletin 65, 280-291.

Lewis, S., Smith, R., O'Brien, D., Warne, M.St.J., Negri, A., Petus, C., da Silva, E., Zeh, D. Turner, R.D.R., Davis, A., Mueller, J., Brodie, J., 2013. Chapter 4: Assessing the risk of additive pesticide exposure in Great Barrier Reef ecosystems. In: Assessment of the relative risk of water quality to ecosystems of the Great Barrier Reef: Supporting Studies. A report to the Department of the Environment and Heritage Protection, Queensland Government, Brisbane. TropWATER Report 13/30, Townsville, Australia.

Lewis, S.E., Bainbridge, Z.T., Kuhnert, P.M., Sherman, B.S., Henderson, B., Dougall, C., Cooper, M., Brodie, J.E., In press. Calculating sediment trapping efficiencies for reservoirs in tropical settings: a case study from the Burdekin Falls Dam, NE Australia. Water Resources Research 49, 1-13, doi: 10.1002/wrcr.20117.

Littler, M.M., Littler, D. S., 2007. Assessment of coral reefs using herbivory/nutrient assays and indicator groups of benthic primary producers: a critical synthesis, proposed protocols, and critique of management strategies. Aquatic Conservation-Marine and Freshwater Ecosystems 17, 195-215.

Loya, Y., Lubinevsky, H., Rosenfeld, M., Kramarsky-Winter, E., 2004. Nutrient enrichment caused by in situ fish farms at Eilat, Red Sea is detrimental to coral reproduction. Marine Pollution Bulletin 49(4), 344-353.

Lucas, J.S., 1982. Quantitative studies of feeding and nutrition during larval development of the coral reef asteroid *Acanthaster planci* (L.). Journal of Experimental Marine Biology and Ecology 65, 173-194.

Luick, J.L., Mason, L., Hardy, T., Furnas, M.J., 2007. Circulation in the Great Barrier Reef Lagoon using numerical tracers and in situ data. Continental Shelf Research 27, 757-778.

Magnusson, M., Heimann, K., Negri, A.P., 2008. Comparative effects of herbicides on photosynthesis and growth of tropical estuarine microalgae. Marine Pollution Bulletin 56, 1545–1552.

Magnusson, M., Heimann, K., Quayle, P., Negri, A.P., 2010. Additive toxicity of herbicide mixtures and comparative sensitivity of tropical benthic microalgae. Marine Pollution Bulletin 60, 1978–1987.

Magnusson, M., Heimann, K., Ridd, M., Negri, A.P., 2012. Chronic herbicide exposures affect the sensitivity and community structure of tropical benthic microalgae. Marine Pollution Bulletin 65, 363–372.

Mallela, J., Roberts, C., Harrod, C., Goldspink, C.R., 2007. Distributional patterns and community structure of Caribbean coral reef fishes within a river-impacted bay. Journal of Fish Biology 70, 523-537.

Marsh, H., De'ath, G., Gribble, N., Lane, B., 2005. Historical marine population estimates: triggers or targets for conservation? The dugong case study. Ecological Applications 15, 481-492. doi:10.1890/04-0673.

Marshall, P., Christie, C., Dobbs, K., Green, A, Haynes, D., Brodie, J., Michalek-Wagner K., Smithe, A., Storrie, J., Turak, E., 2002. Grounded ship leaves TBT-based antifoulant on the Great Barrier Reef: An overview of the Environmental response. Spill Science & Technology Bulletin, Special Report 7, 215-221.

Marubini, F., Davies, P.S., 1996. Nitrate increases zooxanthellae population density and reduces skeletogenesis in corals. Marine Biology 127, 319-328.

Maughan, M., Brodie, J., 2009. Reef exposure to river-borne contaminants: a spatial model. Marine and Freshwater Research 60, 1132–1140. http://dx.doi.org/10.1071/MF08328

McCulloch, M.T., Fallon, S., Wyndham, T., Hendy, E., Lough, J., Barnes, D., 2003. Coral record of increased sediment flux to the inner Great Barrier Reef since European settlement. Nature 421, 727–730.

McKenzie, L.J., Unsworth, R.K.F., 2011. Surviving the flood: How long can seagrass "hold its breath"? SeagrassWatch Magazine 43, 2-4.

McKenzie, L.J., Unsworth, R.K.F., Waycott, M., 2010a. Reef Rescue Marine Monitoring Program: Intertidal Seagrass, Annual Report for the Sampling Period 1st September 2009 – 31st May 2010. Fisheries Queensland, Cairns p. 136. http://www.gbrmpa.gov.au/__data/assets/pdf_file/0009/7677/RRMMP_Seagrass_annual_report_2009_10.pdf.

McKenzie, L.J., Yoshida, R., Grech, A., Coles, R., 2010b. Queensland seagrasses. Status 2010 – Torres Strait and East Coast. Fisheries Queensland (DEEDI), Cairns. 6pp.

McKenzie, L., Collier, C.J., Waycott ,M., 2012a. Reef Rescue Marine Monitoring Program: Inshore seagrass, annual report for the sampling period 1st September 2010-31st May 2011, p. 230pp. Fisheries Queensland, Cairns.

McKenzie, L., Collier, C., Waycott, M., Unsworth, R., Yoshida, R., Smith, N., 2012b. Monitoring inshore seagrasses of the GBR and responses to water quality. Proceedings of the 12th International Coral Reef Symposium, Cairns, Australia, 9-13 July 2012. Mini-Symposium 15b – Seagrasses and seagrass ecosystems. Available at: http://www.icrs2012.com/proceedings/manuscripts/ICRS2012_15B_4.pdf.

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

McQuatters-Gollop, A., Gilbert, A.J., Mee, L.D., Vermaat, J.E., Artioli, Y., Humborg, C., Wulff, F., 2009. How well do ecosystem indicators communicate the effects of anthropogenic eutrophication? Estuarine, Coastal and Shelf Science 82, 583-596.

Meager, J.J., Limpus, C.J., 2012. Marine wildlife stranding and mortality database annual report 2011. I Dugong. Conservation Technical and Data Report 2011 (1), 1-30.

Meakins, N.C., Bubb, J.M., Lester, J.N., 1995. The mobility, partitioning and degradation of atrazine and simazine in the salt marsh environment. Marine Pollution Bulletin 30, 812-819.

Mellors, J.E., 2003. Sediment and nutrient dynamics in coastal intertidal seagrass of north eastern tropical Australia. PhD Thesis. James Cook University, Townsville.

Moran, P.J., De'ath, G., 1992. Estimates of the abundance of the crown-of-thorns starfish Acanthaster planci in outbreaking and non-outbreaking populations on reefs within the Great Barrier Reef. Marine Biology 113, 509-515.

Negri, A.P., Webster, N.S., Hill, R.T., Heyward, A.J., 2001. Metamorphosis of broadcast spawning corals in response to bacteria isolated from crustose algae. Marine Ecology Progress Series 223, 121-131.

Negri, A., Vollhardt, C., Humphrey, C., Heyward, A., Jones, R., Eaglesham, G., Fabricius, F., 2005. Effects of the herbicide diuron on the early life history stages of coral. Marine Pollution Bulletin 51, 370–383.

Negri, A.P., Flores, F., Röthig, T., Uthicke, S., 2011. Herbicides increase the vulnerability of corals to rising sea surface temperature. Limnolology and Oceanography 56, 471–485.

Negri, A.P., Marshall, P., 2009. TBT contamination of remote marine environments: Ship groundings and ice-breakers as sources of organotins in the Great Barrier Reef and Antarctica. Journal of Environmental Management 90, S31-S40.

Okaji, K., 1996. Feeding ecology in the early life stages of the crown-of-thorns starfish, *Acanthaster planci* (L.). James Cook University.

Orpin, A.R., Ridd, P.V., Thomas, S., Anthony, K.R.N., Marshall, P., Oliver, J., 2004. Natural turbidity variability and weather forecasts in risk management of anthropogenic sediment discharge near sensitive environments. Marine Pollution Bulletin 49(7-8), 602-612.

Paerl, H.W., 2009. Controlling eutrophication along the freshwater–marine continuum: dual nutrient (N and P) reductions are essential. Estuaries Coasts 32, 593–601.

Pandolfi, J.M., Bradbury, R.H., Sala, E., Hughes, T.P., Bjorndal, K.A., Cooke, R.G., McArdle, D., McClenachan, L., Newman, M.J.H., Paredes, G., Warner, R.R., Jackson, J.B.C., 2003. Global trajectories of the long-term decline of coral reef ecosystems. Science 301, 955–958.

Passow, U., 2002. Transparent exopolymer particles (TEP) in aquatic environments. Progress in Oceanography 55, 287-333.

PPDB, 2011. Pesticide Properties DataBase, University of Hertfordshire, UK, viewed 22 May 2013, http://sitem.herts.ac.uk/aeru/footprint/en/index.htm

Pratchett, M.S., 2005. Dynamics of an outbreak population of Acanthaster planci at Lizard Island, northern Great Barrier Reef (1995–1999). Coral Reefs 24, 453–462.

Preen, A., Marsh, H., 1995. Response of dugongs to large-scale loss of seagrass from Hervey Bay,Queensland, Australia. Wildlife Research 22, 507-519.

Preen, A.R., Long, W.J., Coles, R.G., 1995. Flood and cyclone related loss, and partial recovery, of more than 1000 km2 of seagrass in Hervey Bay, Queensland, Australia. Aquatic Botany 52, 3-17.

Ptacnik, R., Andersen, T., Tamminen, T., 2010. Performance of the Redfield Ratio and a family of nutrient limitation indicators as thresholds for phytoplankton N vs P limitation. Ecosystems 13, 1201-1214.

Queensland Department of the Premier and Cabinet, 2009. Reef Water Quality Protection Plan 2009: For the Great Barrier Reef World Heritage Area and adjacent catchments, Queensland Department of Premier and Cabinet, Brisbane. http://www.reefplan.qld.gov.au/library/pdf/paddock-to-reef.pdf

Redfield, A.C., 1934. On the proportion of organic derivatives in sea water and their relation to the composition of plankton. Pp. 176-192, In: James Johnstone Memorial Volume, R.J. Daniel (Ed.), University of Liverpool.

Reichelt RE, Bradbury RH, Moran PJ (1990) Distribution of Acanthaster planci outbreaks on the Great Barrier Reef between 1966 and 1989. Coral reefs 9, 97-103

Reinert, K.H., Giddings, J.M., Judd, L., 2002. Effects analysis of time-varying or repeated exposures in aquatic ecological risk assessment of agrochemicals. Environmental Toxicology and Chemistry, 21, 1977–1992.

Schaffelke, B. 1999. Particulate organic matter as an alternative nutrient source for tropical Sargassum species (*Fucales, Phaeophyceae*). Journal of Phycology 35,` 1150-1157.

Schaffelke, B., Anthony, K., Blake, J., Brodie, J., Collier, C., Devlin, M., Fabricius, K., Martin, K., McKenzie, L., Negri, A., Ronan, M., Thompson, A., Warne, M.St.J., 2013. Chapter 1: Marine and coastal ecosystem impacts. Reef Water Quality Scientific Consensus Statement 2013. Department of the Premier and Cabinet, Queensland Government, Brisbane.

Schoellhamer, D.H., 1996. Factors affecting suspended solids concentrations in South San Francisco Bay, California. Journal of Geophysical Research 101 (C5), 12087-12095.

Schoellhamer, D.H., 2002. Variability of suspended-sediment concentration at tidal to annual time scales in San Francisco Bay, USA. Continental Shelf Research 22, 1857-1866.

Schoellhamer, D.H., Mumley, T.E., Leatherbarrow, J.E., 2007. Suspended sediment and sediment-associated contaminants in San Francisco Bay. Environmental Research 105, 119-131.

Schindler, D.W. (1977) The evolution of phosphorus limitation in lakes. Science 195: 260-262.

Schindler, D.W., Hecky, R.E., Findlay, D.L., Stainton, M.P., Parker, B.R., Paterson, M.J., Beaty, K.G., Lyng, M., Kasian, S.E.M., 2008. Eutrophication of lakes cannot be controlled by reducing nitrogen input: Results of a 37-year whole-ecosystem experiment. Proc. Natl. Acad. Sci. U S A 105, 11254–11258.

Schroeder T., Devlin, M.J., Brando, V.E., Dekker, A.G., Brodie, J.E., Clementson, L.A., McKinna, L., 2012. Inter-annual variability of wet season freshwater plume extent into the Great Barrier Reef lagoon based on satellite coastal ocean colour observations. Marine Pollution Bulletin 65, 210–223.

Schwarzenbach, R.P., Escher, B.I., Fenner, K., Hofstetter, T.B., Johnson, C.A., von Gunten, U., Wehrli, B., 2006. Science 313 (5790), 1072e1077. doi:10.1126/ science. 1127291

Shaw, M., Furnas, M.J., Fabricius, K., Haynes, D., Carter, S., Eaglesham, G., Mueller, J.F., 2010. Monitoring pesticides in the Great Barrier Reef. Marine Pollution Bulletin 60, 113-122.

Smith, S.V., 1984. Phosphorus versus nitrogen limitation in the marine environment. Limnology and Oceanography 29, 1149-1160.

Smith, J., Douglas, G.B., Radke, L.C., Palmer, M., Brooke, B.P., 2008. Fitzroy River Basin, Queensland, Australia. III. Identification of sediment sources in the coastal zone. Environmantal Chemistry 5, 231–242.

Smith, R., Middlebrook, R., Turner, R., Huggins, R., Vardy, S.,Warne, M., 2012. Largescale pesticide monitoring across Great Barrier catchments – paddock to Reef Integrated Monitoring, Modelling and Reporting Program. Marine Pollution Bulletin 65, 117–127.

Sobtzick, S., Hagihara, R., Grech, A., Marsh, H., 2012. Aerial survey of the urban coast of Queensland to evaluate the response of the dugong population to the widespread effects of the extreme weather events of the summer of 2010-11. Final Report to the Australian Marine Mammal Centre and the National Environment Research Program June 1 2012. James Cook University, Queensland.

Storlazzi, C.D., Field, M.E., Bothner, M.H., Presto, M.K., Draut, A.E., 2009. Sedimentation processes in a coral reef embayment: Hanalei Bay, Kauai. Marine Geology 264, 140-151.

Sweatman, H., 2008. No-take reserves protect coral reefs from predatory starfish. Current Biology 18, R598-R599.

Thomas, K.V., McHugh, M., Waldock, M., 2002. Antifouling paint booster biocides in UK coastal waters: inputs, occurrence and environmental fate. Science of the Total Environment 293, 117-127.

Thompson, A., Costello, P., Davidson, J., Logan, M., Schaffelke, B., Uthicke, S., Takahashi, M., 2011. Reef Rescue Marine Monitoring Program. Report of AIMS Activities Inshore coral reef monitoring 2011. Australian Institute of Marine Science, Townsville.

Thorburn, P., Rolfe, J., Wilkinson, S., Silburn, M., Blake, J., Gongora, M., Windle, J., VanderGragt, M., Wegschield, C., Ronan, M., Carroll, C., 2013. Chapter 5: The water quality and economic benefits of agricultural management practices. Reef Water Quality Scientific Consensus Statement 2013. Department of the Premier and Cabinet, Queensland Government, Brisbane.

Thornton, C., Elledge, A., 2012. The Brigalow Catchment Study: Increases in runoff associated with land development can still be detected in flood events at a small catchment scale. In: Proceedings of the 34th Hydrology and Water Resources Symposium. Sydney. (Ed. S. Westra). Pages 1565-1570. Engineers Australia.

Traas, T.P., Van de Meent, D., Posthuma, L., Hamers, T., Kater, B.J., De Zwart, D., Aldenberg, T., 2002. The potentially affected fraction as a measure of ecological risk. In: Posthuma L, Suter II GW, Traas TP, eds. Species sensitivity distributions in ecotoxicology. Boca Raton, FL, USA: CRC Press.

Udy, J.W., Dennison, W.C., Long, W.J.L., Mckenzie, L.J., 1999. Responses of seagrass to nutrients in the Great Barrier Reef, Australia. Marine Ecology Progress Series 185, 257-271.

US EPA (U.S. Environmental Protection Agency) 1998. Guidelines for Ecological Risk Assessment. EPA/630/R-95/002F. Risk Assessment Forum, Washington, DC, USA.

Vallotton, N., Eggen, R.I.L., Escher, B.I., Krayenbühl, J., Chèvre, N., 2008. Effect of pulse herbicidal exposure on *Scenedesmus vacuolatus*: A comparison of two photosystem II inhibitors. Environmental Toxicology and Chemistry 27, 1399–1407. doi: 10.1897/07-197.

van Dam, J.W., Negri, A.P., Mueller, J.F., Uthicke, S., 2012. Symbiont-specific responses in foraminifera to the herbicide diuron. Marine Pollution Bulletin 65, 373–383.

Wagner, D. E., Kramer, P., Van Woesik, R., 2010. Species composition, habitat, and water quality influence coral bleaching in southern Florida. Marine Ecology Progress Series 408, 65-78.

Wang, Y., Ridd, P.V., Heron, M.L., Stieglitz, T.C., Orpin, A.R., 2007. Flushing time of solutes and pollutants in the central Great Barrier Reef lagoon, Australia. Marine Freshwater Research 58, 778–791. doi:10.1071/MF06148.

Waterhouse, J., Brodie, J., Lewis, S., Mitchell., A., 2012. Quantifying the sources of pollutants to the Great Barrier Reef. Marine Pollution Bulletin 65, 394–406.

Waterhouse, J., Maynard, J., Brodie, J., Randall, L., Zeh, D., Devlin, M., Lewis, S., Furnas, M., Schaffelke, B., Fabricius, K., Collier, C., Brando, V., McKenzie, L., Warne, M.St.J., Smith, R., Negri, A., Henry, N., Petus, C., da Silva, E., Waters, D., Yorkston, H., Tracey, D., 2013. Section 2: Assessment of the risk of pollutants to ecosystems of the Great Barrier Reef including differential risk between sediments, nutrients and pesticides, and among NRM regions. In: Brodie *et al.,*, Assessment of the relative risk of water quality to ecosystems of the Great Barrier Reef. A report to the Department of the Environment and Heritage Protection, Queensland Government, Brisbane. TropWATER Report 13/28, Townsville, Australia.

Waters, D.K., Carroll, C., Ellis, R., Hateley, L., McCloskey, J., Packett, R., Dougall, C., Fentie, B., in press. Modelling reductions of pollutant loads due to improved management practices in the Great Barrier Reef Catchments – Whole of GBR, Volume 1. Department of Natural Resources and Mines. Technical Report (ISBN: 978-1-7423-0999).

Weber, M., De Beer, D. Lott, C. Polerecky, L. Kohls, K. Abed, R. Ferdelman, T. Fabricius, K., 2012. Mechanisms of damage to corals exposed to sedimentation. . Proceedings of the National Academy of Sciences of the United States of America 109(24), E1558–E1567.

Weber, M., Lott, C., Fabricius, K., 2006. Different levels of sedimentation stress in a scleractinian coral exposed to terrestrial and marine sediments with contrasting physical, geochemical and organic properties. Journal of Experimental Marine Biology and Ecology 336, 18-32.

Webster, N.S., Smith, L.D., Heyward, A.J., Watts, J.E.M., Webb, R.I., Blackall, L.L., Negri, A.P., 2004. Metamorphosis of a scleractinian coral in response to microbial biofilms. Applied and Environmental Microbiology 70, 1213-1221.

Wenger, A.S., Johansen, J.L., Jones, G.P., 2011. Suspended sediment impairs habitat choice and chemosensory discrimination in two coral reef fishes. Coral Reefs 30: 879-887.

Wenger, A.S., Johansen, J.L., Jones, G.P., 2012. Increasing suspended sediment reduces foraging, growth and condition of a planktivorous damselfish. Journal of Experimental Marine Biology and Ecology 428, 43-48.

Wenger, A.S., McCormick, M., McLeod, I.M., Jones, G.P., in press. Suspended sediment alters predator–prey interactions between two coral reef fishes. Coral Reefs 32, 369-374. http://dx.doi.org/10.1007/s00338-012-0991-z.

Wenger, A.S., McCormick, M.I., in press. Determining trigger values of suspended sediment for behavioral changes in a coral reef fish. Marine Pollution Bulletin http://dx.doi.org/10.1016/j.marpolbul.2013.02.014

West, J.M., Salm., R.V., 2003. Resistance and resilience to coral bleaching: implications for coral reef conservation and management. Conservation Biology 17, 956-967.

Wiedenmann, J., D'Angelo, C., Smith, E.G., Hunt, A.N., Legiret, F.-E., Postle, A.D., Achterberg, E.P., 2013. Nutrient enrichment can increase the susceptibility of reef corals to bleaching. Nature Climate Change 3(5), 160-164. doi: http://www.nature.com/nclimate/journal/vaop/ncurrent/abs/nclimate1661.html#supplementary-information

Wilcox, C., Hardesty, B.D., Sharples, R., Griffin, D.A., Lawson, T.J., Gunn, R., 2013. Ghostnet impacts on globally threatened turtles, a spatial risk analysis for northern Australia. Conservation Letters, 1-8.

Wismer, S., Hoey, A.S. and Bellwood, D.R., 2009 Cross-shelf benthic community structure on the Great Barrier Reef: relationships between macroalgal cover and herbivore biomass. Marine Ecology Progress Series 376, 45–54.

Wolanski, E., Fabricius, K., Spagnol, S., Brinkman, R., 2005. Fine sediment budget on an inner-shelf coral-fringed island, Great Barrier Reef of Australia. Estuarine and Coastal Shelf Science 65, 153-158.

Wolanski, E., Richmond, R. Mccook, L., Sweatman, H., 2003. Mud, marine snow and coral reefs. American Scientist 91, 44-51.

Wolanski, E., van Senden, D., 1983. Mixing of Burdekin River flood waters in the Great Barrier Reef. Australian Journal of Marine and Freshwater Research 34, 49-63.

Wooldridge, S.A., 2009. Water quality and coral bleaching thresholds: Formalising the linkage for the inshore reefs of the Great Barrier Reef, Australia. Marine Pollution Bulletin 58, 745–751.

Wooldridge, S.A., Done, T.J., 2009. Improved water quality can ameliorate effects of climate change on corals. Ecological Applications 19, 1492–1499.

Zann, M., 2012. The use of remote sensing and field validation for mapping coral communities of Hervey Bay and the Great Sandy Strait and implications for coastal planning policy. Unpublished M.Phil.thesis, the University of Queensland, Brisbane.