Brodie, Jon E. (2016) ***Terrestrial pollutant runoff to the Great Barrier Reef: effects, causes, sources and management.*** **PhD thesis, James Cook University.**

Terrestrial pollutant runoff to the Great Barrier Reef: effects, causes, sources and management

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in August 2016

for the degree of Doctor of Philosophy by prior publication

in the College of Marine and Environmental Sciences

James Cook University

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Co-authorship in chapters for peer-reviewed publication

This thesis includes a large amount of collaborative work. My co-authors on the published papers were (with a number of these co-authors on more than one paper):

Caroline Christie, Michelle Devlin, David Haynes, Sheriden Morris, Michelle Ramsay, Jane Waterhouse, Hugh Yorkston, Katharina Fabricius, Glenn De'ath, Ken Okaji, Thomas Schroeder, Ken Rohde, John Faithful, Bronwyn Masters, Arnold Dekker, Vittorio Brando, Mirjam Maughan, Miles Furnas, Margaret Wright, Stephen Lewis, Zoe Bainbridge, Alan Mitchell, Frederieke Kroon, Britta Schaffelke, Eric Wolanski, Iris Bohnet, Aaron Davis, Richard Pearson

Contributions to the eight papers

The 10 chapters of this thesis comprise eight previously published papers that represent my research over the period 1984 to 2016, and an introduction and concluding chapter. For the eight papers the contributions of myself and my co-authors to each paper is as follows:

Chapter 2. Paper 1. State of knowledge in 2001.

Brodie, J., Christie, C., Devlin, M., Haynes, D., Morris, S., Ramsay, M., Waterhouse, J., Yorkston, H. 2001. Catchment management and the Great Barrier Reef. Water Science and Technology, 43 (9), 203-211.

My contribution: - Conception of the paper, structure, writing several sections, coordination of final paper. Caroline Christie and Michelle Ramsey contributed to the overall coordination and integration of the paper. Hugh Yorkston and Sheriden Morris wrote much of the catchment management sections. Michelle Devlin and David Haynes wrote the marine impact sections. Jane Waterhouse contributed to the management sections and the final editing of the paper.

Link to paper: http://wst.iwaponline.com/content/43/9/203.abstract

Chapter 3. Paper 2. Link between nutrient discharge and crown of thorns starfish

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

My contribution: - Conception of the paper, structure, primary interpretation of the results, conclusions. Glenn De'ath carried out most of the statistical analysis. Ken Okaji wrote sections of the paper associated with phytoplankton biomass and larval survivorship. Katharina Fabricius contributed to the interpretation of the results and the conclusions.

Link to paper: http://www.sciencedirect.com/science/article/pii/S0025326X04003868

Chapter 4. Paper 3. Discharge and flood plume dynamics

Brodie, J., Schroeder, T., Rohde, K., Faithful, J., Masters, B., Dekker, A., Brando, V., Maughan, M. 2010. Dispersal of suspended sediments and nutrients in the Great Barrier Reef lagoon during river-discharge events: Conclusions from satellite remote sensing and concurrent flood-plume sampling. Marine and Freshwater Research, 61 (6), 651-664.

My contribution: - conception of the study, field work, interpretation of the results, conclusions. Thomas Schroeder, Arnold Dekker and Vittorio Brando carried out the analysis of the satellite remote sensing data. Ken Rohde, John Faithful and Bronwyn Masters carried out field work, analysed samples and interpreted the marine water quality data. Mirjam Maugham carried out the spatial analysis.

Link to paper: http://www.publish.csiro.au/?paper=MF0803

Chapter 5. Paper 4. Linking nutrient discharges to phytoplankton dynamics

Brodie, J., De'ath, G., Devlin, M., Furnas, M., Wright, M. 2007. Spatial and temporal patterns of near-surface chlorophyll a in the Great Barrier Reef lagoon. Marine and Freshwater Research, 58 (4), 342-353.

My contribution: - conception of the study, establishment and continuation of the study, interpretation of the results, conclusions. Glenn De'ath carried out the statistical analysis. Margaret Wright carried out the water sample analysis and interpretation of these results. Michelle Devlin contributed to the data analysis and interpretation. Miles Furnas contributed to the conception of the study, establishment of the study, interpretation of the results and conclusions.

Link to paper: http://www.publish.csiro.au/?paper=MF06236

Chapter 6. Paper 5. GBR eutrophication

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

My contribution: - conception of the paper, structure, primary interpretation of the hypothesis, coordination of the final ms. Michelle Devlin and David Haynes contributed to the interpretation of the results and the writing of the ms. Jane Waterhouse contributed to the writing of the ms, the coordination of the ms and the final editing of the text.

Link to paper: http://link.springer.com/article/10.1007/s10533-010-9542-2

Chapter 7. Paper 6. Target setting

Brodie, J., Lewis, S., Bainbridge, Z., Mitchell, A., Waterhouse, J., Kroon, F. 2009. Target setting for pollutant discharge management of rivers in the Great Barrier Reef catchment area. Marine and Freshwater Research, 60 (11), 1141-1149.

My contribution: - Conception of the idea of river discharge pollutant load targets based on the desired ecological condition for the GBR, conception of the paper, primary writing, and coordination of final ms. Stephen Lewis and Zoe Bainbridge contributed to sections on sediment targets for the Burdekin River, Alan Mitchell on the sections on nitrate targets for the Tully River, Frederieke Kroon on the conceptual approach to target setting and Jane Waterhouse to all sections and coordination and integration of the different sections of the ms.

Link to paper: http://www.publish.csiro.au/?paper=MF08339

Chapter 8. Paper 7. State of knowledge in 2012. Cf Chapter 2.

Brodie, J.E., Kroon, F.J., Schaffelke, B., Wolanski, E.C., Lewis, S.E., Devlin, M.J., Bohnet, I.C., Bainbridge, Z.T., Waterhouse, J., Davis, A.M. 2012.Terrestrial pollutant runoff to the Great Barrier Reef: An update of issues, priorities and management responses. Marine Pollution Bulletin, 65 (4-9), 81-100.

My contribution: - Conception of the paper’s structure, writing some sections, coordination of the final ms, conclusions. Britta Schaffelke, Eric Wolanski and Michelle Devlin wrote marine sections, Frederiek Kroon, Stephen Lewis and Zoe Bainbridge wrote much of the catchment based sections, Iris Bohnet wrote the social science sections, Aaron Davis wrote the pesticide and coastal wetlands sections and Jane Waterhouse wrote the risk analysis sections and contributed greatly to the overall coordination and integration of the sections of the ms.

Link to paper: http://www.sciencedirect.com/science/article/pii/S0025326X11006503

Chapter 9. Paper 8. Management of the GBR

Brodie, J., Waterhouse, J. 2012. A critical review of environmental management of the 'not so Great' Barrier Reef. Estuarine, Coastal and Shelf Science, 104-105, 1-22.

My contribution: - conception of the paper, writing most of the text, conclusions. Jane Waterhouse wrote large sections of the text and contributed to the overall coordination and integration of the final ms.

Link to paper: http://www.sciencedirect.com/science/article/pii/S0272771412000856

Acknowledgements

I am indebted to my Mentor during the production of this thesis, Professor Richard Pearson, who has been my colleague and friend for the many years we have spent working together on the protection of the Great Barrier Reef (GBR) and the ecosystems of its catchment. I would also like to particularly thank Professor Helene Marsh for her support in the process of finally writing the thesis. Thanks to Jane Waterhouse, Stephen Lewis and Zoe Bainbridge for help with reviews of parts of the chapters, preparing figures, formatting the thesis and discussing the content. A special thanks also to Eric Wolanski for his encouragement and help in getting Chapter 10 published as a stand-alone paper.

During my 40 years working on the marine environment I encountered and worked with more than 1000 GBR, coral reef and marine scientists (both from Australia and around the world), natural resource managers, Conservation NGO people, farmers, agricultural industry people, environmental consultants, in all, a set of wonderful, earnest and enthusiastic persons who shared the vision of protecting the marine environment. For most of them, working in and around the field of marine protection was much more than a job, it was their life (stealing a line from Stjepan Keckes, the long-time Director of the UNEP Regional Seas Programme). I acknowledge deeply their contribution to my career.

My mentors, inspirers and a special colleague –

Dr Stjepan Keckes - Director of UNEP's Regional Seas Programme 1975 – 1990. Stjepan introduced me to the international world of marine environmental management and following his nomination I spent several years on the UN body - the Group of Experts on the Scientific Aspects of Marine Pollution.

Dr John Morrison – Director, Institute of Natural Resources, University of the South Pacific. 1982 – 1987. John was a wonderful boss and friend during the establishment and expansion of the Institute of Natural Resources at the University of the South Pacific.

Graeme Kelleher – Chair, Great Barrier Reef Marine Park Authority. The one who allowed me free-reign when I joined GBRMPA in 1990 to start to actively manage water quality, beginning with GBR islands sewage treatment plants and their discharges to the GBR Marine Park.

Dr Don Kinsey, GBRMPA. Renowned researcher on the effects of nutrients on corals reefs and my mentor in setting up a water quality program at GBRMPA in the early 1990s when he was Executive Office of GBRMPA.

Robert Hill (Senator), Minister for the Environment in the Australian Government, 1996 – 2001. The greatest of our Environment Ministers and responsible for the passing of the Environment Protection and Biodiversity Conservation (EPBC) legislation. At a GBR Ministerial Council in Cairns in 2001 he tasked me (then Director of Water Quality and Coastal Development at GBRMPA) to set targets for reduction of river pollution loads to the GBR. With his support we developed the GBR Water Quality Action Plan containing these targets. Two years later the Reef Water Quality Protection Plan (2003) was in place.

Jane Waterhouse, my friend, closest colleague and business partner over the last 19 years. Although the GBR is in a perilous state at the moment I like to think that Jane's and my joint efforts to protect the GBR have had some positive effect.

I would also like to thank my family, my parents Marie Brodie and Edward Brodie who instilled a love of nature and learning in me from a young age, and Gilianne, Tim, Paul, Steven, Nicola, Ann-Marie and Charlie who, at various times throughout my career, have provided support and, in the case of Gilianne, scientific collaboration.

Contents

Chapter 1. The History of Water Quality Studies in the Great Barrier Reef region and the link to management 1890 – 2016: Contention and consensus

1.1 Preamble

This thesis presents a cross-section of research on the development and application for management of water quality research on the Great Barrier Reef (GBR) and its catchment area undertaken by myself and colleagues between 1980 and 2016. Over this period, I have published ~90 peer-reviewed papers on this topic of which I was first author on 14 (Appendix 1) and ~300 other reports, conference papers and book chapters (Appendix 2). The small selection of papers presented as chapters in this thesis represent benchmarks in the progress of this research.

In this introductory chapter I present a background to this research including the historical and political contexts, and the development of research and management of water quality issues and controversies in the GBR region. The science to management analysis ends at the formation of the Reef Water Quality Protection Plan (Reef Plan 2003) in 2003. However, I review the science up to 2016 by discussing the debates towards the resolution of scientific questions for management. In this chapter I highlight all contributions on which I was an author in boldface.

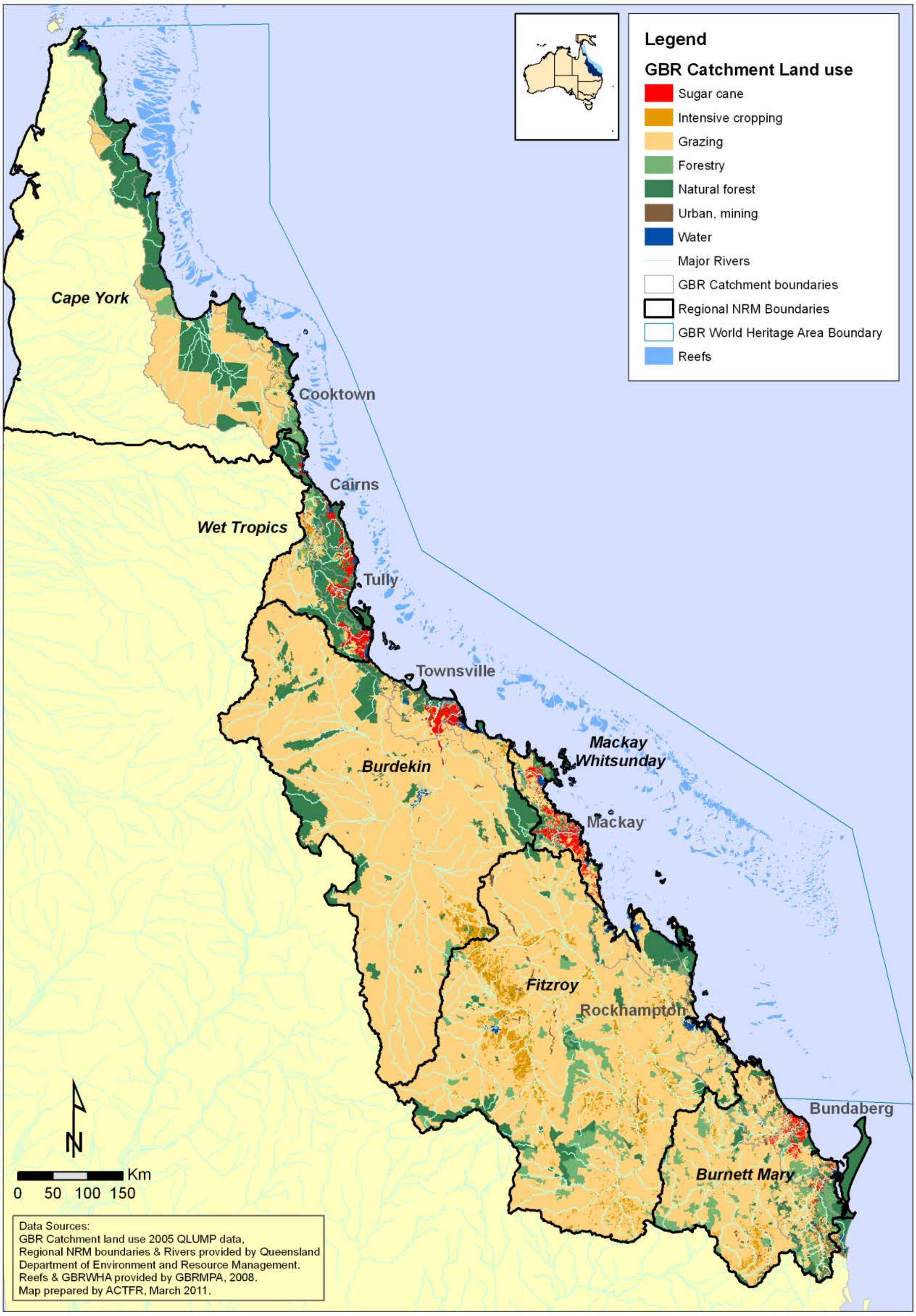
In the final chapter I present an analysis of the success of management of the GBR since 2003, the current state of knowledge of the issue drawn from the 2013 Scientific Consensus Statement (**Brodie et al. 2013a**), including new knowledge gained in the period 2013 – 2016, a summary of the management plans being applied in 2016 and beyond, my own assessment of the management steps needed to improve water quality in the GBR lagoon such that GBR water quality guidelines are largely met, and the likelihood, in my estimation, of further substantive progress in managing the issue.

1.2 Introduction and background

The Great Barrier Reef (GBR) is an extensive coral reef system lying off the north-eastern Australian coast on the shallow continental shelf (Figure 1). The area of the official World Heritage Area is 348,000 km^2 with the Great Barrier Reef Marine Park slightly smaller at 344,400 km^2 (Kenchington and Day 2011). Seven percent of the GBRWHA consists of 2900 individual coral reefs (Day, 2008, 2011). However, the GBR extends to the north beyond the boundary of the GBRWHA for more than 100 km, finally ending at Bramble Cay just off the Papua New Guinea coast at 9^0 S. The GBR has an adjacent catchment area of 400,000 km^2 (the Great Barrier Reef Catchment Area – GBRCA) (**Brodie et al. 2012a**). The GBR has been managed as a national Marine Park (the GBRMP) since 1975 (*Great Barrier Reef Marine Park Act 1975*) with an ecosystem-based management approach and regular reporting framework (Dobbs et al. 2011), and was listed as a World Heritage Area (WHA) in 1981 for its outstanding universal value (Day and Dobbs 2013). The GBRWHA encompasses large areas of coral reefs, seagrass meadows and mangrove forests, providing habitat to endangered and threatened marine megafauna including turtles, dugong, whales and dolphins (Great Barrier Reef Marine Park Authority 2014) and high diversity of other plants and animals. In addition to its biodiversity and cultural heritage values, it is estimated that the collective monetary value of a broad range of services provided by the GBR is likely to be between $15 billion and $20 billion AUD per annum (Stoeckl et al. 2014). A number of histories of the GBR and its management have been written (e.g. Bowen and Bowen 2002; Laurence et al. 2002; Daley 2005, 2014) which have described the scientific, legal and political background to the establishment of the GBRMP and the listing of the GBRWHA.

Recognition of the potential impact of land degradation on downstream waters occurred even before the establishment of the GBRMP – for example, increased erosion from rainforest clearing (Douglas 1967). However, establishment of the GBRMP prompted greater focus on this issue, indicated by the new Great Barrier Reef Marine Park Authority (GBRMPA) providing staff to investigate such issues (Bennell 1979).

The idea that the GBR had a definable catchment (the GBRCA) came rather late in the planning process for the GBRMP but was well conceived by the late 1980s when funding for end-of-river monitoring for sediment and nutrient loads was provided to Miles Furnas and Alan Mitchell at AIMS by the GBRMPA (Mitchell et al. 1991; Furnas 2003) and maps of the GBRCA started to be produced (e.g. Moss et al. 1992). The concept that, in managing water quality in the marine environment for the GBR, most management would have to take place on the GBRCA and often hundreds of kilometres inland on agricultural and urban lands was also clarified by 1990 (e.g., Hunter and Rayment 1991; **Brodie 1991**).



Data Sources:
GBR Catchment land use 2005 QLUMP data,
Regional NRM boundaries & Rivers provided by Queensland Department of Environment and Resource Management.
Reefs & GBRWHA provided by GBRMPA, 2008.
Map prepared by ACTFR, March 2011.

Figure 1. The Great Barrier Reef and its catchments, showing land uses and the six Natural Resource Management regions.

1.3 The historic context

The results of studies on the GBR carried out long before the establishment of the GBRMP, although not specifically addressing terrestrial runoff, are still used to examine “baseline” conditions in some areas of the GBR. Important examples of these studies include:

i. William Saville-Kent’s photographs of reef flats, generally at low tide so the coral can be seen, in many areas of the GBR including the Torres Strait (Saville-Kent 1893). These historical photographs have been used frequently in the last 30 years to compare current reef coral status to that visible at the period Saville-Kent was active (Bell 1992; Wachenfeld 1997; Hughes et al. 2010; Ryan et al. 2016; **Clark et al. 2016**). It is notable that Saville-Kent took the photographs in the 1890s specifically as a “baseline” so that future researchers could use them to assess change in the reefs. Other photographs of reef flats at low tide, dating from throughout the 20th century, have been used in a similar way (Endean 1982, Bell 1992, Wachenfeld 1997).

ii. Studies on Low Isles by the British Museum Expedition of 1928-29 were the then highpoint of scientific research on the GBR (Yonge 1930). Results associated with “water quality” parameters included the status of nutrients (Orr 1933), plankton (Marshall 1933) and reef-flat coral sedimentation (Marshall and Orr 1931). Results of these Low Isles studies have been used as starting points for more modern comparative research aimed at measuring change (Bell and Elmetri 1993; Stephenson et al. 1958).

   While the marine fauna of Low Isles was surveyed by the British Museum 1928-9 Expedition, studies continued focussed on the damaging effects of the 1934 cyclone on *Porites* sp. corals examined by Moorhouse (1936) and other changes to the island and reef noted by Spender (1936). Results on the geomorphology of the area were published later (Fairbridge and Teichert 1947, 1948). Another cyclone in 1950 caused damage to the island's coral, and an expedition visited Low Isles in 1954 with the prime objectives of assessing the extent of this damage, and of ascertaining the extent and nature of changes undergone by the island and its fauna and flora since 1929. Results were published specifically focussed on geomorphology and corals (e.g. Stephenson and Wells 1956; Stephenson et al. 1958) and showed that the cyclone had caused great destruction to branching corals but that massive corals had, in most cases, survived. Soft corals, which appeared to have been unaffected by the cyclone, had spread, and appeared to be competing with hard corals for the available substratum. The mangrove area had increased in extent compared to 1928.

iii. The Second International Coral Reef Society (ICRS) expedition was conducted by The Great Barrier Reef Committee on board the M.V. Marco Polo while cruising in the waters of The Great Barrier Reef Province from 22nd June to 2nd July 1973. The symposium was attended by 264 scientists and formal sessions were conducted while the ship was under way in order to allow the maximum time for the field program. One hundred and twenty papers were presented during the symposium. “Water quality” studies were conducted and several seminal papers given at the Symposium – for example, on fertilisation studies at One Tree Island, where corals were subjected to a range of added nitrogen and phosphorus compounds for an extended period (Kinsey and Domm 1974; Kinsey and Davies 1979).

Commencing in the 1970s, GBRMPA initiated a number of workshops and technical reviews of water quality issues for the GBR. Some of the workshops were not specifically focused on water quality but were important for the light they shed on aspects of water quality dynamics – for example, the Fringing Reef Workshop (Baldwin 1987).

In 1984 GBRMPA organised a Workshop on Contaminants in Waters of the Great Barrier Reef Marine Park (Dutton 1985). The workshop concentrated on heavy metals, polychlorinated biphenyls (PCBs) and other organochlorines (e.g. insecticides) and hydrocarbons. In attempting to assign priorities to areas of further research, participants noted that sediments and nutrients were more likely to be of greater concern to the GBR than the three contaminant groups considered at that workshop. In particular, an area recommended for further research was: "the effects of agricultural fertilisers and other nutrients exported to the GBR from the mainland."

Important workshops, technical reports, reviews and strategic direction and policy statements in the 1980s, (summarised in Table 1) led to the identification by 1990 of sediment and nutrient discharged from the land, primarily from agriculture and urban development, as posing the greatest water quality threat to the GBR. In contrast pesticides (organochlorine insecticides) (Smillie and Waid 1985), hydrocarbons (Coates et al. 1986; Smith et al. 1985), heavy metals (Denton and Burdon-Jones 1986a,b), PCBs, sewage effluent bacterial status, anti-fouling toxins and oxygen-depleting substances were assessed as being of much lower threat. (Table 1).

Following 1990 and the commencement of a formal water quality research and monitoring program, workshops were held and numerous reports, papers, reviews, strategic documents, policy statements and synthesis reports related to water quality were produced, many contributing to the first Scientific Consensus Statement (Williams et al. 2002), the Great Barrier Reef Catchment Water Quality Action Plan (Brodie et al. 2001a) and also thus to Reef Plan 2003. A large selection of the most important of these is tabulated in Table 2.

Table 1. Summary of workshops, technical reports, reviews and statements relevant to GBR water quality, 1983 – 1990.

Date	Editors/author	Title and details	Example paper
1983	Barnes D.J. (ed)	Perspectives on Coral Reefs 1983. Australian Institute of Marine Science, Townsville.	Crossland C.J., 1983. Dissolved nutrients in coral reef waters.
1983	Baker, J., Carter, R., Sammarco, P., Stark, K. (eds)	Proceedings of the inaugural Great Barrier Reef Conference: 1983. James Cook University and the Australian Institute of Marine Science. 545 pp.	Johannes, R., Wiebe, W., Crossland, C. 1984. Three patterns of nutrient flux in a coral reef community.
1984	Dutton, I. (ed)	Workshop on Contaminants in Waters of the Great Barrier Reef. Workshop Series No. 5. Great Barrier Reef Marine Park Authority, Townsville, 43 pp.	Burdon-Jones, C., Denton, G. 1984. Metals in marine organisms from the Great Barrier Reef – Study Outline 1980 – 1983.
1986	Dutton, I.M. (ed)	Workshop on the offshore effects of cyclone Winifred	Furnas, M. and Mitchell, A., 1986. Oceanographic conditions on the north Queensland shelf after passage of cyclone Winifred.
1987	Baldwin, C.L. (ed)	Fringing Reef Workshop: Science, Industry and Management. Workshop Series No. 9, Great Barrier Reef Marine Park Authority, Townsville, 280 pp.	Kinsey, D.W. 1987**.** Effects of run-off, siltation, and sewage.
1987	Baldwin, C.L. (ed)	Nutrients in the Great Barrier Reef Region 1987 Workshop Series No. 10.	Mitchell, A. 1987. River inputs of nutrients.
1987	Bell P., P. Greenfield, D. Connell & D. Hawker	Guidelines for management of waste discharges into the Great Barrier Reef Marine Park, Vol.1. Report to GBRMPA. 82pp.	

Date	Editors/author	Title and details	Example paper
1990	Baldwin, C.	Impact of elevated nutrients in the Great Barrier Reef, GBRMPA Research Publication No. 20, GBRMPA, Townsville.	
1990	Yellowlees, D. (ed)	Conference on Land use patterns and nutrient loading of the Great Barrier Reef region James Cook University, Townsville.	Furnas, M. 1991. Nutrient status and trends in waters of the Great Barrier Reef Kinsey, D. W. 1991b. Water quality and its effect on reef ecology

Table 2. Selection of important workshops, statements and reports relevant to GBR water quality, 1992 – 2004.

Date	Editors/authors	Title and details	Example paper
1992	Moss, A.J., Rayment, G.E., Reilly, N., Best, E.K.	A preliminary assessment of sediment and nutrient exports from Queensland coastal catchments, Technical Report No. 4, Queensland Department of Environment and Heritage, Brisbane, 33 p.	
1992	**Brodie, J.**	Sewage Policy for outfalls into the GBRMP. First established 1992, updated in 2005. Brodie 1992	Papers associated with this policy: **Brodie, J.E. 1991**, **1994**; Waterhouse, J. and Johnson, J. 2002.
1992	Hunter, H.M.	Agricultural contaminants in aquatic environments: a review. Department of Primary Industry, Brisbane.	Hunter 1992.
1996	Pulsford, J.S.	Historical Nutrient Usage in Coastal Queensland River Catchments Adjacent to the Great Barrier Reef Marine Park, Report to the Great Barrier Reef Marine Park Authority, Townsville.	Pulsford 1996
1994	Raymond, K. and Craik, W. (compilers).	A 25 year Strategic Plan for the Great Barrier Reef World Heritage Area, Great Barrier Reef Marine Park Authority, Townsville, 64 p.	Great Barrier Reef Marine Park Authority, 1994; Raymond 1996
1995	Wachelfeld, D., Oliver, J., Davis, K. (eds)	Proceedings of the State of the Great Barrier Reef World Heritage Area Workshop: proceedings of a technical workshop (Workshop No. 23) held in Townsville, Queensland, Australia, 27-29 November 1995. 561 pp.	**Brodie, J. 1995b.** The water quality status of the Great Barrier Reef World Heritage Area.
1995	Larcombe, P., Woolfe, K. (eds)	Great Barrier Reef: Terrigenous Sediment Flux and Human Impacts. 2nd ed. CRC Reef Research Centre.174 p	**Larcombe et al. 1996.** Terrigenous sediment fluxes and the central Great Barrier Reef shelf: the current state of knowledge.
1995	Zann, L., Kailola, P. (eds)	The State of the Marine Environment Report for Australia Technical Annex 2: Pollution. Great Barrier Reef Marine Park Authority, Townsville.	**Brodie, J. 1995c.** The problems of nutrients and eutrophication in the Australian marine environment.

Date	Editors/authors	Title and details	Example paper
1995	Furnas, M.J., Mitchell, A.W. & Skuza, M.	Nitrogen and phosphorus budgets for the central Great Barrier Reef shelf, GBRMPA Research Publication No. 36, GBRMPA, Townsville, 194 p.	Furnas et al. 1995
1996	H.M. Hunter, Eyres, A.G., Rayment, G.E. (eds).	Conference on Downstream Effects of Land Use. Queensland Department of Natural Resources, Brisbane	Neil, D.T., Yu, B. 1996. Fluvial sediment yield to the Great Barrier Reef lagoon: Spatial patterns and the effect of land use.
1996	Turia, N., Dalliston, C. (Compilers)	The Great Barrier Reef, science, use and management a national conference: proceedings. Vol. 1 (402 pp) and 2 (229 pp).	Rayment, G.E., Neil, D.T. 1996. Sources of material in river discharge.
1997	Steven, A. (ed)	Cyclone Sadie Flood Plumes in the Great Barrier Reef Lagoon: Composition and Consequences. Workshop Series no. 22, Great Barrier Reef Marine Park Authority, Townsville.	Mitchell and Bramley 1997. **Brodie 1995a**.
1997	Cosser, P.R. (ed)	Australia: State of the Environment Technical Paper Series (Estuaries and the Sea) (Nutrients in marine and estuarine environments, Technical Paper Series (Estuaries and the Sea), Department of the Environment, Canberra.).	**Brodie, J. 1997.** Nutrients in the Great Barrier Reef Region.
2000	**Haynes, D., Brodie, J., Christie, C., Devlin, M., Michalek- Wagner, K., Morris, S., Ramsay, M., Storrie, J., Waterhouse, J., Yorkston, H.**	Great Barrier Reef water quality: Current issues, Great Barrier Reef Marine Park Authority, Townsville.	**Haynes et al. 2001**
2000	**Gilbert, M., Brodie, J.**	Population and major land use in the Great Barrier Reef catchment area: spatial and temporal trends. GBRMPA Research Publication Series, Great Barrier Reef Marine Park Authority, Townsville.	**Gilbert and Brodie 2001**
2001	Prosser, IP, Rustomji P. Young WJ, Moran CJ, Hughes AO	Constructing river basin sediment budgets for the National Land and Water Resource Audit. Technical Report 15/01, CSIRO Land and Water, Canberra.	

Date	Editors/authors	Title and details	Example paper
2003	Baker, J. (ed)	A report on the study of land-sourced pollutants and their impacts on water quality in an adjacent to the Great Barrier Reef: An assessment to guide the development of management plans to halt any decline in the water quality of river catchments draining to the Reef, as a result of land-based pollution, and to achieve the long-term goal of reversing any trend in declining water quality.	Baker 2003
2001	Wolanski, E.	Oceanographic processes of coral reefs: physical and biological links in the Great Barrier Reef ISBN 084930833Z, 376 pages	
2001	**Devlin, M., Waterhouse, J., Taylor, J., Brodie, J.**	Flood plumes in the Great Barrier Reef: spatial and temporal patterns in composition and distribution. GBRMPA Research Publication Series, Great Barrier Reef Marine Park Authority, Townsville.	**Devlin et al. 2001**
2003	Productivity Commission	Industries, Land Use and Water Quality in the Great Barrier Reef Catchment, Research Report, Productivity Commission, Canberra.	
2003	Furnas, M.J.	Catchments and Corals: Terrestrial Runoff to the Great Barrier Reef. Australian Institute of Marine Science, CRC Reef. Townsville, Australia.	Furnas 2003
2004	Haynes D, Schaffelke B (eds).	Catchment to Reef. Water Quality Issues in the Great Barrier Reef Region. 9-11 March 2004, Townsville. Conference Abstracts. CRC Reef Research Centre Technical Report No. 53. CRC Reef Research Centre, Townsville.	Fabricius et al. 2005

The “consensus” position derived from this body of work is described later in this Chapter (Section 1.8) and formed the basis of water quality management after 2003.

1.4 Debates

During the 1980s, scientists and environmental managers engaged in a series of informal debates regarding issues relevant to GBR water quality, revealing gaps in understanding that helped to shape the research agenda in the 1990s and beyond. The debates on these issues have continued to the present and, although some "consensus" has developed from them, new research results open up the issues to further interpretation and debate as outlined below.

1.4.1 Debate over whether the GBR is degraded by anthropogenic influence to any extent

While there has been some consensus among scientists and managers who work on the GBR that there is degradation due to human activities such as fishing, water quality impairment, tourism, recreation and climate change since the 1990s (Pandolfi et al. 2003; DeVantier et al. 2006; Bruno and Selig 2007; De'ath et al. 2012; Hughes et al. 2003; **Hughes et al. 2011, 2015**; Talbot 2000), the extent and severity of the level of degradation and its causes have been hotly disputed (Hopley 1988, 1989; Carter 2006; Ridd 2007; Ridd et al. 2011, 2013). In addition, there are some who have disputed whether any level of degradation has occurred and assert that the GBR is still in good condition (Larcombe and Woolfe 1999b; Starck 2005).

One of the most visible signs of coral reef degradation has been where coral reef flats with good coral communities, photographed long ago, have been re-photographed more recently and found to have severely deteriorated. The most noteworthy of these reefs is at Stone Island in northern Edgecumbe Bay near Bowen, where cyclonic floods are believed to have caused extensive coral mortality in the area in 1918 (Hedley 1925; Rainford 1025). The reef flat was photographed by William Saville-Kent in the 1890s (Saville-Kent 1893) and then again by David Wachenfeld in 1994 (Wachenfeld 1997) (Figure 2 from **Clark et al. 2016**). Wachenfeld mentioned several caveats in the use of such images, in particular that it was very difficult to get the same location, state of tide and perspective when taking the modern photograph. The photographs from Stone Island reef have been used to claim anthropogenic reef degradation (e.g. Bell 1992; Hughes et al. 2010) while others claim the differences in the photographs are due to different states in an ongoing intermittent disturbance regime (DeVantier et al. 1998). Wachenfeld (1997) indicated that out of 14 reefs investigated, six showed no obvious changes, four showed decreases in hard coral cover and four showed no obvious changes in some areas, but decreases in coral cover in others. While the study demonstrated that some reef flats had undergone significant decline in coral cover and diversity, the cause of the change could not be determined from the photographs alone.

In 2015 Piers Larcombe (a sceptic concerning water quality affecting the GBR seriously – e.g., Larcombe and Wolfe 1999a) has reignited debate as to the significance of the historical photos at Stone Island and Bramston Reefs just as new papers resulting from greatly improved dating techniques (Clark et al. 2012, 2014) and years of research at reefs in Edgecumbe Bay are being published (Ryan et al. 2016a,b; **Clark et al. 2016**). While Larcombe has implied that coral growth has recovered at the reefs in this area in public presentations (with new photos), in fact coral recovery has only visibly occurred at Bramston Reef. There is good evidence that there were extensive coral-dominated reef flats at Stone Island in 1894 and 1915, which were not observable in 1994 or at any time since. Recent surveys show there is still little coral on reef flats anywhere on Stone Island (**Clark et al. 2016**; Ryan et al. 2016a - Figure 2). In contrast, at Bramston Reef (a reef much closer to the coast), while there was extensive live coral on the reef flat in the 1890s, there was little live cover in 1994 (although dead massive corals were common), but there has now been some recovery (Ryan et al. 2016a; **Clarke et al. 2016**).

Debate about the coral communities present on Low Isles in 1928 (Yonge 1930; Stephenson 1930, 1958) compared to recent times has also occurred with similar claims of change/degradation (Bell 1992) or no change (Frank and Jell 2006), with reef conditions shown to be at least equal to those at Heron Island at the southern end of the GBR through comparison of foram communities (Schueth and Frank 2008). Similarly, the water quality and plankton community data at Low Isles from 1928 has been compared to modern measurements, using both modern techniques and the original methods (Bell and Elmetri 1993). Secchi depth measurements show a halving of clarity between 1928 and 1997, attributed to greatly increased discharge of mud from rivers in the region (Wolanski and Spagnol 2000). Comparison of *Trichodesmium* abundance shows an approximate tenfold increase in the years between 1928 and 1992/93, attributed to increased delivery of phosphorus and other nutrients from intensely developed GBR catchments (Bell et al. 1999).

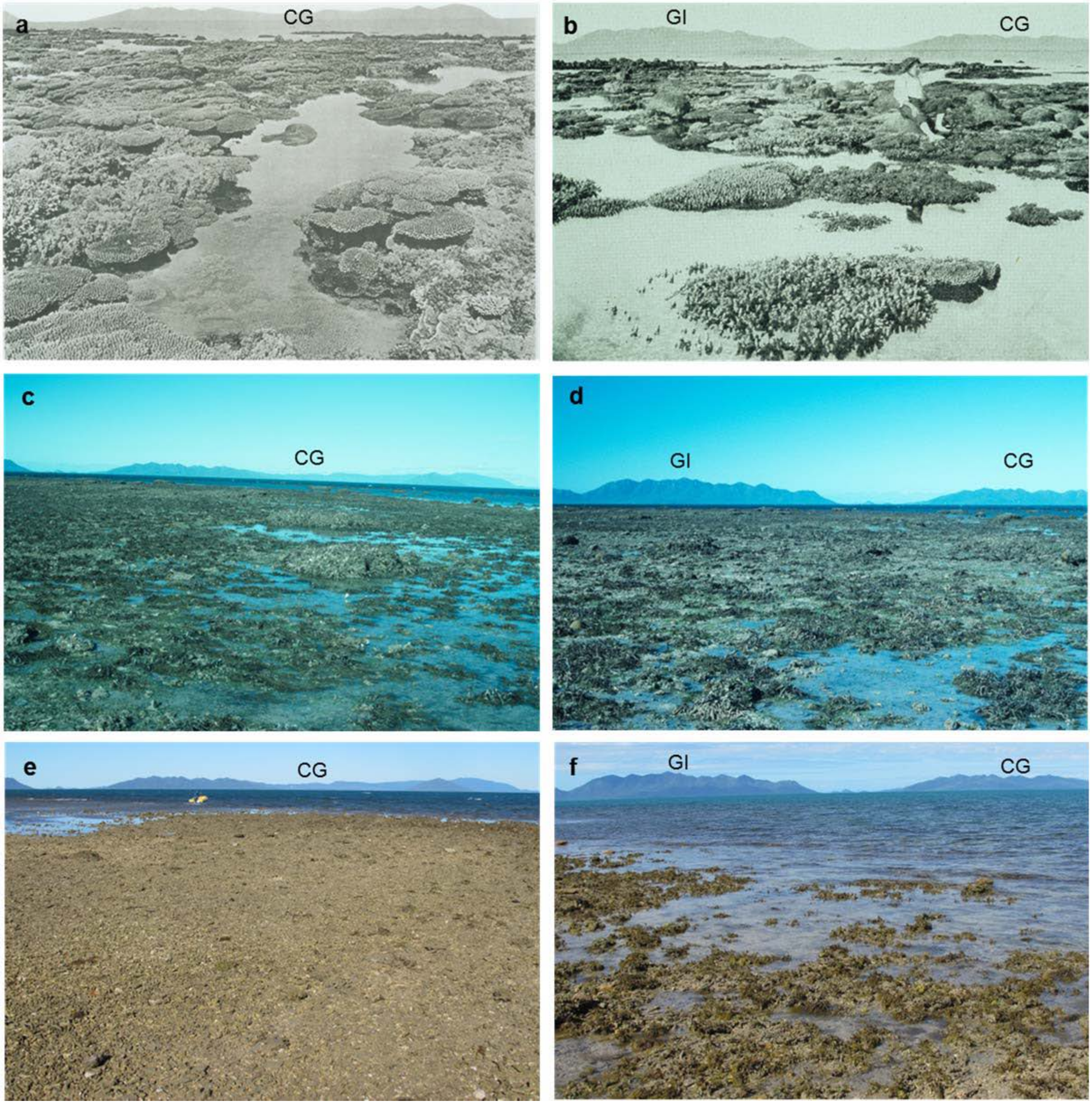


Figure 2. Historical and modern photographs of Stone Island. (a) Photograph taken by William Saville-Kent (1893) in ca. 1890 depicting high cover of branching and tabular Acropora; (b) Photograph taken in 1915 showing similarly high coral cover with large faviid colonies in the background of the image (photographer unknown); (c-d) Photographs of Stone Island taken in 1994 in conjunction with David Wachenfeld [Photographer: A. Elliot (© Commonwealth of Australia GBRMPA)]; (e) Photograph taken during this study on 30 July 2012 representing a time-series for images a and c (Photographer: T. Clark); (f) Photograph taken during this study on 31 July 2012 representing a time-series for images b and d (Photographer: H. Markham). Geological features in the background of the images used to identify the location of the historical photographs include Gloucester Island (GI) and Cape Gloucester (CG). Modified from Clark et al. (2016) with permissions from Dr Tara Clark and Ms Hannah Markham.

A more recent debate centres on the decline in calcification rate and its cause over the last decade , such as bleaching, generally warmer water, ocean acidification, river discharge and reduced water quality (De’ath et al. 2009; Cooper et al. 2008; D’Olivo et al. 2013). Some researchers have attempted to refute the notion of wide-scale reduced calcification in a paper entitled “Have coral calcification rates slowed in the last twenty years?” (Ridd et al. 2013). De’ath et al. (2013) responded with the title “Yes: Coral calcification rates have decreased in the last twenty-five years!” Meanwhile, Cantin and Lough (2014) showed that calcification rates can recover within 4 years following bleaching events. The cause of any reduced calcification is also in some dispute with thermal stress, bleaching and ocean acidification implicated in some studies (De’ath et al. 2009) while ocean acidification is seen as less of an issue in other studies (Cooper et al. 2008). Differences in causes depending on location across the shelf have been postulated, with inner-shelf reefs showing decreased calcification due to thermal stress (Cooper et al. 2008) or water quality issues (D’Olivo et al. 2013), including pH changes due to terrestrial runoff (D’Olivo et al. 2015), whereas reduced calcification on mid- and outer-shelf reefs is attributed to thermal stress (D’Olivo et al. 2013).

A comprehensive assessment of the current status of GBR coral reefs based on all the available monitoring data has not been produced. The landmark De’ath et al. (2012) paper which documented a 50% decline in coral cover (from about 28% to 14%) on the reefs they surveyed (from the AIMS Long Term Monitoring Program (LTMP) – Australian Institute of Marine Science 2016) used reefs which were primarily situated on the mid-shelf of the GBR, with only a few on the outer-shelf or inner-shelf, and relied on manta-tow data from shallow sections of the reefs. For inner-shelf reefs the results from the Marine Monitoring Program (MMP) (which specifically targets inner-shelf reefs) have been summarised in Thompson et al. (2014) and these results are discussed below. Osborn et al (2011) used results from video transects at about 6 - 8m from LTMP reefs and ascribed the causes of damage and coral loss to somewhat different causes from the manta-tow results from the same reefs (De’ath et al. 2012). In addition, long-term studies of individual reefs have shown coral decline and recovery (e.g. Pandora Reef – Done et al. 2007). The likely decline in coral cover since the 1960s is approximately 75% (Bruno and Selig 2007; **Hughes et al. 2011**) from around 50% cover in the 1960s to the current 14%. Coral cover in the Torres Strait section of the GBR was in better condition than most of the rest of the GBR, averaging about 50% in 2014/15 (Sweatman et al. 2015); however, cover will have declined precipitously in 2016 with the major bleaching event (Normile 2016), as will cover across much of the northern half of the GBR (Great Barrier Reef Marine Park Authority 2016). Studies using coral cores (**Lewis et al 2012a**; Mallela et al 2013) and reef matrix cores (Roff et al 2013) have provided clear evidence for regional and local anthropogenic influences on reef growth, decline and recovery. A recent summary of reef condition and change in condition in the central GBR for the Burdekin WQIP (**Coppo and Brodie, 2015**), drawing on the LTMP (Australian Institute of marine Science 2015) and MMP (Thompson et al. 2014) surveys as well as some of the individual studies cited above, shows that reefs in this region have poor coral cover (<10%) with the only exceptions being Pandora and Middle Reefs, which are close to the coast.

Many questions remain as to the main factors driving GBR degradation but there is little doubt that the combined stresses of water quality decline and climate change impacts such as bleaching (Thompson and Dolman 2010; Done et al. 2007; D'Olivo et al. 2013) are important. While the debate continues, large-scale assessments of the "health" of the GBR continue – for example, GBRMPA's Outlook Reporting (Great Barrier Reef Marine Park Authority 2009, 2014) – and management proceeds on the basis of a consensus view that the GBR is in poor condition due to combined stressors, that the decline in condition continues (Great Barrier Reef Marine Park Authority 2014) and that a large increase in the management response is needed to reverse the decline (**Hughes et al. 2015).**

1.4.2 Debate over the water quality status, the extent and degree of damage from terrestrial pollutants, and the extent of eutrophication of the GBR

The debate about the water quality status of the GBR began in the 1980s (e.g. Kinsey 1988) and focussed largely on nutrients and the possibility that the GBR was, or might become, eutrophic. The paper that sparked the debate was Bell and Gabric (1991), which appeared in the CSIRO magazine *Search* with the title "Must GBR pollution become chronic before management reacts?" Four other papers were published in the same issue as a form of debate of this question: Kinsey's "Can we resolve the nutrient issue for the reef" (Kinsey 1991a); Walker's "Is the reef really suffering from chronic pollution?" (Walker 1991); Barnes and Lough's "Nutrients and the need for scientific debate" (Barnes and Lough 1991); and Hopley's general response to the issues (Hopley 1991).

Given the title of Bell and Gabric's (1991) *Search* article it is now regrettable to be able to give a definitive "yes" in answer to their question. Indeed, pollution of the GBR did become chronic before important catchment management works were instituted under the Reef Rescue initiative in 2009 (**Brodie et al. 2012a**). Additionally, it is now widely believed that the time lag to management of 18 years meant that the works, when finally rolled out in catchments, were "too little, too late" (**Brodie and Waterhouse 2012**).

The initial debate involved claims that the GBR was already eutrophic (Bell and Gabric 1990, 1991; Bell 1991, 1992, 1993; Gabric and Bell 1993) and a range of other opinions that it was not (Walker 1991) or that it was not possible to decide with the data available around 1991 (Kinsey 1991; Barnes and Lough 1991; Hopley 1991). In subsequent years, various studies showed elevated concentrations of particulate and dissolved inorganic nutrients and chlorophyll-a in flood plumes (**Brodie 1995, 1996**; **Brodie and Furnas 1996; Devlin et al. 2001; Devlin and Brodie 2005**) while lower concentrations were observed in non-discharge periods (**Furnas and Brodie 1996; Brodie et al. 1997**). Chlorophyll concentrations, an indicator of phytoplankton biomass, were monitored extensively using grab sampling from the late 1980s to the mid-2000s with similar results – high concentrations in flood plumes (**Devlin et al. 2001; Devlin and Brodie 2005**) and lower concentrations in non-discharge conditions (**Brodie et al. 2007**), but with generally higher concentrations near the coast than further offshore, and higher concentrations south of Cooktown than on Cape York (**Brodie et al. 1997, 2007**). Information from remote sensing of chlorophyll concentrations using the Coastal Zone Colour Scanner (CZCS) suggested some degree of eutrophication in the GBR lagoon (Gabric et al. 1990) but, as for all satellite remote-sensing methods, there are doubts as to the reliability of chlorophyll measurements from satellite data in the turbid inshore waters of the GBR (**Waterhouse and Brodie 2015**). Bell and coauthors continued to publish on the state of eutrophication of the GBR (Bell et al. 2007, 2012).

The debate re-opened in 2014 with Bell et al. (2014a) asserting that "*it was now widely accepted that the lack of recovery of GBR reefs and the proliferation of COTS* [crown-of-thorns starfish] *are largely attributable to eutrophication. Evidence is emerging that coral skeletal disease (CSD) and coral bleaching are also promoted by eutrophication. Much of the increased fertility/eutrophication is due to the increased loads of nutrients exported via discharges from coastal developments*." Furnas et al. (2014) were highly critical of this paper, demonstrating that Bell et al. (2014a) misrepresent the current state of knowledge regarding water quality within the GBR and the processes that influence it in ten separate areas of knowledge, and also noted the lack of data available to validate Bell et al.'s assertions. Bell et al. (2014b) countered, claiming that "*while Furnas et al. (2014) suggest that there is a lack of relevant data to support some of the assertions/hypotheses there is sufficient data to draw robust conclusions. Bell et al. (2014b) agree that more data should be collected to better assess the impacts of STP discharges and links between eutrophication and the proliferation of the COTS larvae, jellyfish, diazotrophs, and CSD precursors. The current GBR research/monitoring programs are incapable of doing this and we recommend that a series of regular cross-shelf water-quality/ecological monitoring programs be established to collect the required data".*

Other studies focussed on experimental studies of the effects of nutrients on coral reefs. In the ENCORE experiment (**Koop et al. 2001**), individual reefs with experimental transplants of corals and other organisms were fertilised for a two year period in the early 1990s. A complex set of effects occurred (e.g. Ward and Harrison 2000; **Koop et al. 2001**), the meaning of which have been debated for the last 20 years (e.g. Bell et al. 2007).

Overall it is likely that the GBR is eutrophic at certain times and locations, especially when the criteria for eutrophication are based on conditions for coral reef waters (**Brodie et al. 2011**). Thus if we use criteria such as sufficient nutrient enrichment to cause:

- enhanced crown of thorns starfish outbreaks (**Brodie et al. 2005**; Fabricius et al. 2010);
- enhanced thermal coral bleaching response (e.g., Wooldridge and Done 2009; Wooldridge 2016) and changed energetic relationships between corals and zooxanthellae (Wooldridge 2013);
- increased bioerosion (Hutchings et al. 2005);
- increased turbidity (in association with increased fine sediment supply) (**Fabricius et al. 2014, 2016**);
- changed dominance of macroalgae over coral growth (De'ath and Fabricius 2010);
- changed phytoplankton species composition (**Furnas et al. 2005**; Jones et al. 2016); and
- increased incidence of some coral diseases (Bruno et al. 2003; Haapkyla et al. 2011),

then it is certain that some degree of eutrophication already exists in the GBR, especially during intense river runoff. However, eutrophication in coral reef situations is a complex issue (Fabricius et al. 2013a; D'Angelo and Wiedenmann 2014; Risk 2014) and controversy over the state of eutrophication of the GBR will, no doubt, continue.

1.4.3 Debates over loads of materials/pollutants delivered to the GBR in river discharge; the sources of these pollutants in catchments; the contributions from different land uses; the contributions from different types of erosion; the suitability of catchment models in use; and the balance between modelling and monitoring

Reliable estimates of the loads of substances such as fine sediment, nitrogen and phosphorus (and their various forms), and pesticides discharged from the rivers flowing into the GBR have been difficult to achieve (**Brodie et al. 2012a**). Accurate load estimates are required to establish material budgets for the GBR (e.g., Furnas et al. 2011), to assess how loads have changed since catchment development started in the 1830s (**Kroon et al. 2012**) and hence to evaluate the “anthropogenic load” and thereby set targets for load reduction (e.g., **Brodie et al. 2014; Wooldridge et al. 2015**).

Equally important are accurate estimates of the sources of the loads by, for example, land use (e.g. **Waterhouse et al. 2012**), sub-catchment (**Bainbridge et al. 2014, 2016**; Bartley et al. 2014b; Croke et al. 2015), agricultural management practice and erosion type (e.g. gully, hillslope, streambank, channel, rill) (Waters et al. 2014; Wilkinson et al. 2013, **Bartley et al. 2014a**, b; Olley et al. 2013; Brooks et al. 2009, 2014, 2015; Piesch et al. 2015). As the Burdekin River has been extensively studied for load estimation, here I use load estimates for fine sediment in that river to show how estimates have changed through time. Belperio (1979) used a regression-based sediment rating-curve to calculate an annual average load of 3.45 million tonnes of wash load (clay and silt) for the Burdekin region, using monitoring data from the 1970s. Subsequently, annual average suspended sediment load estimates for the Burdekin River have been derived using monitoring data (estimates of 3.8 – 4.6 million t yr^{-1}) and catchment models (2.4 – 9.0 million t yr^{-1}) with some models also predicting "natural" loads (0.48 – 2.1 million t yr^{-1}) (Table 3) **(Brodie et al. 2009a**). Therefore, there has been reasonable agreement on the order of magnitude of the fine sediment load, with only a few outliers, but also a gradual refinement in the estimate and its reliability and some resolution of the arguments about whether “monitoring” or “modelling” give the best estimate of long-term average loads.

There has also been considerable debate over the sources of sediment, nutrients and pesticides in rivers with the respect to land-use, industry and erosion processes, and the proportion of the total end-of-valley load from each. It is well demonstrated that most of the anthropogenic nitrate loads come from losses of fertilisers from sugarcane cultivation, that much of the anthropogenic fine sediment load comes from erosion in grazing lands and that the main discharge of pesticides (particularly PSII herbicides) results from use in the sugarcane industry (Waterhouse et al. 2012; Waters et al. 2014); however, the contributions of forest, woodland, pasture and introduced legume pasture, urban areas, horticulture, mines, grain cropping, cotton and aquaculture are still vigorously debated particularly by those involved in these industries or land uses.

Table 3. Annual average suspended sediment load estimates for the Burdekin River, 2009 – 2014, indicating methods sources and caveats.

Load (millions of tonnes)	Method	Reference	Caveats
3.0	Rating curve	Belperio 1979	Pre Burdekin Falls dam
2.8	Simple catchment model	Moss et al. 1992	Burdekin plus Haughton
9.0	Catchment model	Neil & Yu 1996	Burdekin plus Haughton
3.8	Monitoring with a modelling generalisation step	Furnas 2003	
8.0	Catchment model	Neil et al 2002	Burdekin plus Haughton
2.8	SedNet	**Brodie et al 2003**	Also: **McKergow et al. 2005a,b**
2.8	SedNet	Cogle et al 2006	
4.5	Compilation of estimates with quality control	**Brodie et al 2009b**	
4.0	Compilation of estimates with quality control	**Kroon et al 2012**	
6.5 – 12.7	Monitoring and linear interpolation	Joo et al 2012	Loads for 3 specific years in the period 2006 – 2009 (high rainfall years)
0.9 - 15	Linear regression estimator	**Kuhnert et al 2012**	Loads for 23 specific years in the period 1986 - 2010
3.9	Compilation of estimates with quality control	**Bainbridge et al. 2014**	
4.0	Source Catchments model	Dougall et al 2014	Also: Waters et al 2014

1.4.4 Debate over seaward extent of terrestrial material in the GBR

Opinions about the dispersion of material (sediment, nutrients, pesticides, metals, organic chemicals) carried in terrestrial runoff and the extent of dispersal into the GBR lagoon, have differed greatly through time. Wolanski and van Senden (1983) and Wolanski and Jones (1981) showed that river plumes from the Burdekin and Wet Tropics rivers could be detected through their reduced salinity signal for hundreds of kilometres to the north of river mouths and well offshore, but whether sediment and nutrients were transported so far was not examined (Wolanski et al. 1984; Johnson and Carter 1988; Gagan et al. 1987, 1988, 1990). Most terrestrial sediment deposited on the floor of the GBR lagoon forms a band within 15 km of the coast (Belperio 1983). Some studies suggest that terrigenous input reaches only halfway across the shelf while others have found terrigenous marker chemicals extending to the edge of the shelf break (e.g., Curry and Johns 1989). In general, there appears to be an inner reefal area dominated by terrestrial sediment and an outer area dominated by carbonate sediment (Johnson and Carter 1988; Wolanski and van Senden 1983).

Strong statements as to the spatial extent of terrestrial material transport across the GBR shelf towards the shelf-break were made following studies into the effects of Cyclone Winifred (Furnas and Mitchell 1986), a category 3 storm which crossed the GBR near Innisfail in early 1986, producing widespread benthic sediment resuspension (Gagan et al. 1988, 1990) and major river discharges into the GBR lagoon (Gagan et al. 1987), followed by a widespread phytoplankton bloom (Furnas 1989). Gagan et al. (1987) claimed there was very little transport of materials from river discharge (the Johnstone River primarily) across the shelf:

"Tropical Cyclone Winifred (1 February 1986) provided an ideal opportunity to examine the fate of high river discharge in the Central Great Barrier Reef by producing near-record floods between Townsville and Cairns. Comparison of the carbon isotope ratio of organic matter in shelf sediment collected immediately before and after the cyclone showed that the bulk of terrestrial plant detritus from the Johnstone River was deposited within 2 km of the river mouth and none moved more than 15 km offshore. By comparing the magnitude of the Johnstone River flow to the maximum recorded flows of other rivers in the Great Barrier Reef Province, ***we conclude that terrestrial runoff has not reached the Reef in historical times*** *except, perhaps, during rare Burdekin River floods."* [My emphasis added]. In this context "the Reef" is used to mean the mid and outer-shelf reefs of the GBR (and not the inner-shelf reefs). In contradiction of this statement, in the 30 subsequent years it has become clear that terrestrial runoff from large river discharge events reaches the mid and outer shelf of the GBR almost every year, but mostly as dissolved, not particulate, material (e.g**. Larcombe et al. 1996;** Devlin and Schaffelke 2008; **Alvarez-Romero et al. 2013; Devlin et al. 2012a**).

One major line of enquiry has been the study of river flood plumes and their behaviour in the GBR lagoon (following the studies of Wolanski mentioned above) using in-situ sampling, remote sensing (satellite and airborne) and modelling (**Devlin et al. 2015b**). Some studies concentrated on the composition of the plumes (**Brodie and Mitchell 1992; Brodie et al. 2010**), some on the extent of the plumes (Davies and Hughes 1983; **Brodie 1996; Schroeder et al. 2012**) and some on both extent and composition (**Devlin et al. 2001; Devlin and Brodie 2005**; Devlin and

Schaffelke 2009; **Devlin et al. 2012a**), while more recent efforts aimed to characterise water types and their potential effects on GBR organisms (**Devlin et al. 2013; Alvarez-Romero et al. 2013**). Other studies have used plume data and biological assessments to determine the effects of river discharge on coral reefs (Jones and Berkelmans 2014; Butler et al. 2013, 2015; Wenger et al. 2016) and seagrass meadows (Preen et al. 1995; Petus et al. 2014) and seagrass-associated biota such as dugong (Preen and Marsh 1995). Other studies used coral cores and the chemicals preserved in their annual banding to assess the influence of river discharge (e.g. McCulloch et al. 2003; Lough 2007, 2008; **Lewis et al. 2012a**).

From these studies it is clear that some materials discharged from rivers easily reach the mid-shelf reefs (e.g., from the Fitzroy River to Heron Island - **Brodie and Mitchell 1992**) and even the outer-shelf reefs and the Coral Sea occasionally (e.g., to the Coral Sea in 2008 – Devlin and Schaffelke 2009). Satellite images from 2007 clearly show plumes (visible due to algal blooms) dispersing across the shelf through the outer-shelf reefs and well into the Coral Sea (Figure 3) (**Brodie et al. 2011, 2012b**). As low-salinity water and its content of humic acids spread across the shelf during flood plumes, luminescent lines form in growing corals along with density banding due to seasonal growth (e.g., Lough 2011a) in massive corals such as *Porites* spp. The luminescent lines can be used as a signal of both the magnitude of river influence across the shelf (Lough 2011b) and the humic acid content of the discharge water. Studies of this type have identified river discharge effects right across the continental shelf (Lough et al. 2002). Recent studies have shown that the magnitude of river discharge has increased greatly in the period since about 1850, associated with large-scale oceanographic/climatic features in the Pacific Ocean affecting rainfall intensity (Lough et al. 2015).

Another line of enquiry has examined sediment dispersal and deposition. The early consensus was that most sediment discharged from rivers deposited quite close to the river mouth (e.g., Gagan et al. 1989) but that resuspension during strong wind conditions and transport by the prevailing south to north coastal currents (driven by the SE trade winds) moved the sediment up the coast before it was mostly trapped in northward facing bays (Orpin et al 1999, 2004). More recent studies **(Lewis et al. 2006**; Lewis et al. 2014) have confirmed that most sediment is deposited near river mouths, but have shown that there is little further dispersal. However, a small fraction of the fine sediment is transported in the flood plumes (**Bainbridge et al. 2012**) for large distances up the coast, forming rich organic flocs during transport and being largely responsible for the extra turbidity in coastal areas like Cleveland Bay, where they may last for a year or more following major discharges from the Burdekin River (**Fabricius et al. 2014, 2016; Logan et al. 2013, 2014**).

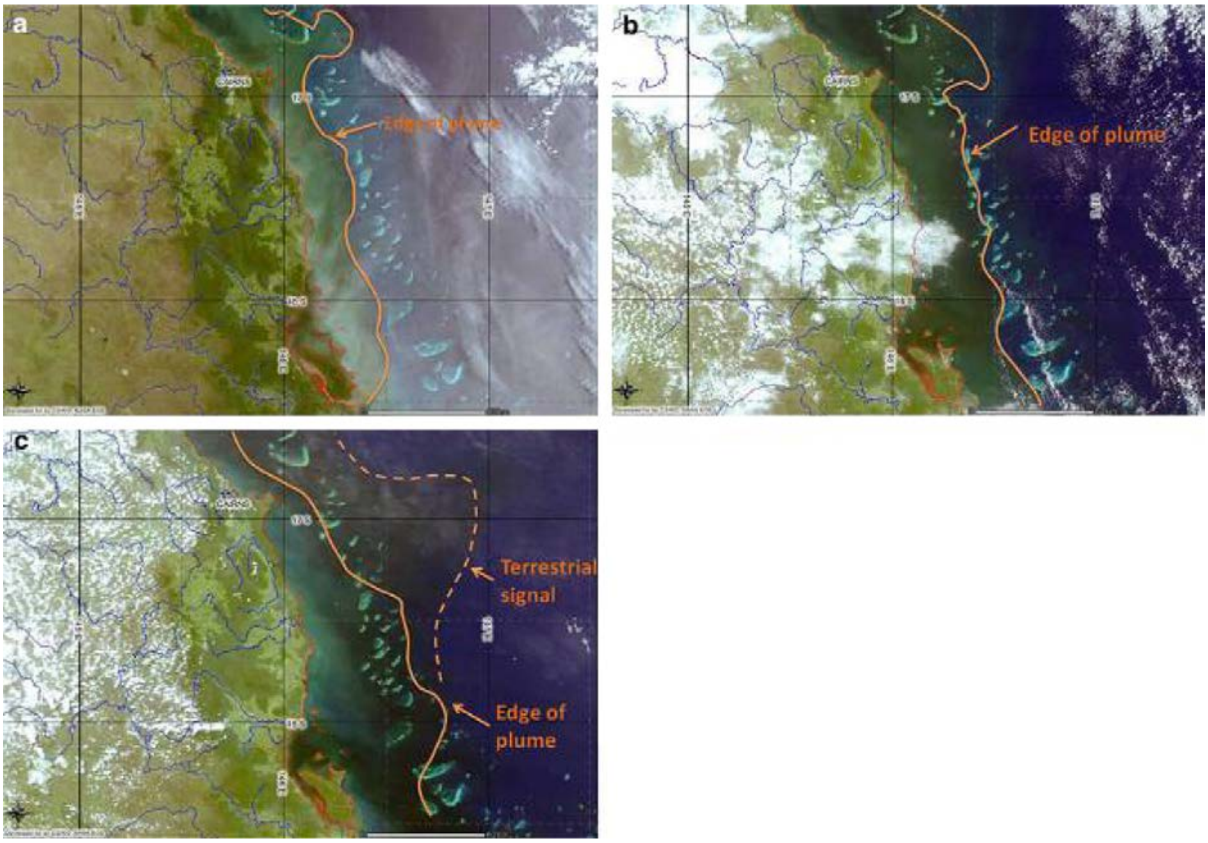


Figure 3. Progression (a–c) of a multiple river plume in the Wet Tropics (9, 11, 13 February 2007, respectively) extending from the coast to beyond the outer reef. The lines show the outer edge of the plume made visible by coloured dissolved organic matter and phytoplankton. Images a–c show the transformation from a plume dominated by terrestrial particulate matter into one dominated by a phytoplankton bloom driven by dissolved nutrients. A proportion of the nutrients in the plume may be seen 'escaping' to the Coral Sea in image c. Image courtesy of CSIRO. From Brodie et al., (2011, 2012b).

1.4.5 Debate over the relationship between increased nutrient loading and the frequency and severity of crown-of-thorns starfish outbreaks

The crown-of-thorns starfish (*Acanthaster planci* – COTS) is a specialised coral feeder found across the Indo-Pacific. Populations of COTS display cyclic oscillations between extended periods of low density, with individuals sparsely distributed, and episodes of unsustainably high densities, commonly termed "outbreaks". The outbreaks result in mass mortalities of corals with second-order and long-term consequences on various reef communities. COTS outbreaks usually spread to the entire reef ecosystem by larval transport, and commonly lead to increases in benthic algal density, loss of coral-feeding assemblages, overall collapse of reef structural complexity, and decline in biodiversity and productivity (Birkeland and Lucas 1990). COTS have caused widespread damage to many coral reefs in the Indo-Pacific over the past six decades as population "explosions" have occurred at regular intervals (**Zann et al. 1987, 1990**; Birkeland and Lucas 1990; Pratchett et al. 2014). However, our knowledge of the density of COTS on reefs before 1960 is very limited. Given the huge numbers of animals, which were found on reefs across the Indo-Pacific by the 1970s (Birkeland and Lucas 1990), it was postulated that these outbreaks could not have occurred in the past, or alternatively not at the frequency at which they were occurring by the 1990s. Hence a range of anthropogenic causes were postulated (Birkeland and Lucas 1990; **Brodie 1992**).

Outbreaks on the GBR have occurred from 1962 to 1976, 1979 to 1991, 1993 to 2005 (**Brodie et al., 2005**; Fabricius et al. 2010) and 2009 – present (Pratchett et al 2014; **Wooldridge and Brodie 2015**). Each outbreak has severely reduced coral cover, especially in the central section of the GBR (De'ath et al. 2012), but the cause (or causes) of the outbreaks remains a controversial issue. One view postulates that population outbreaks are a natural phenomenon due to the inherently unstable population sizes of highly fecund organisms such as COTS (Potts 1981). Conversely, outbreaks are blamed on anthropogenic changes to the environment of the starfish, with a range of possible causes, including: removal of predators on adult starfish (particularly fish and large gastropods (Sweatman 1995; Mendonca et al. 2010); changes to population structure of predators on larval and juvenile COTS, caused by chemical (possibly pesticide) pollution (Chesher 1969; Randall 1972); destruction of predators on larval COTS, particularly corals (which may feed on plankton), by construction activities on reefs; and larval food supply (phytoplankton) enhancement from nutrient-enriched terrestrial runoff (Lucas 1982; Bell and Gabric 1991; **Brodie 1992; Brodie et al. 2005**; Fabricius et al., 2010).

Birkeland (1981) hypothesised that COTS population outbreaks were more common on high islands in the Pacific due to runoff of terrestrial nitrogen and phosphorus than they were on atoll islands were there is no comparable runoff. The hypothesis was founded on the fact that COTS have a planktonic larval stage (of a few weeks) which feeds on phytoplankton and needs a certain amount of phytoplankton to reach a level of viability that allows settling on a reef. Nutrient runoff in river discharge from high islands can provide the conditions needed for phytoplankton to bloom and provide the food needed (Birkeland 1982; **Brodie 1992**). In “normal” nutrient conditions the larvae have insufficient phytoplankton food to reach competence (Lucas 1982).

Anthropogenic nutrient enrichment is derived from sewage discharge, fertiliser runoff and increased erosion of nutrient-rich soil and leads to enrichment of coastal waters, resulting in higher phytoplankton biomass, a shift to larger species of phytoplankton more suitable as COTS larval food and better survivorship of COTS larvae leading to more frequent outbreaks (**Brodie 1992, Brodie et al. 2005**). The possibility of this as an explanatory hypothesis for the large outbreaks of COTS on the GBR was first raised in the 1970s (Lucas 1982) but was by then only one of several hypotheses as to the cause of the outbreaks, given that the apparently increased frequency of COTS outbreaks on the GBR and elsewhere in the Indo-Pacific) was unlikely to be a natural occurrence (Potts 1981; Moran 1986).

Analysis of larval growth, the effects of environmental factors and experimental testing of the nutrient enrichment hypothesis was first carried out by Lucas and colleagues in the 1970s and showed that COTS larvae were food limited, not developing well in conditions of low nutrient concentrations and phytoplankton biomass (Henderson and Lucas 1971; Lucas 1973, 1982). However, subsequent experiments suggested no nutrient effect (Olson 1987), seemingly challenging the hypothesis, but there were doubts expressed about the Olson results and in the late 1980s the experiments were repeated, this time with more care given to strict protocols regarding nutrient supply. The new results did support the nutrient enrichment hypothesis (Ayuki et al. 1997; Okaji et al. 1997a, b; Fabricius et al 2010). COTS outbreaks associated with anthropogenic nutrient enrichment are now seen as one of the signals of partial eutrophication of the GBR (**Brodie et al. 2011**; Fabricius 2011). Recent refinements of the experiments have further supported the hypothesis (Uthicke et al. 2015a; Wolfe et al. 2015a). However, it has been shown recently that oceanographic conditions associated with the ENSO cycle (Hock et al. 2014) may play a part in the Cairns area of the GBR, and **Wooldridge and Brodie (2015)** have confirmed that both nutrient enrichment from river runoff and connectivity due to ENSO conditions are important in initiating outbreaks.

COTS outbreaks can occur at sites without any apparent nutrient enrichment (Miller et al. 2015), but in places where upwelling may be present but not documented, and at sites with natural nutrient enrichment from ocean upwelling (e.g., in the Chagos archipelago – Roche et al. 2015) or at oceanic nutrient/productivity fronts (Houk et al. 2007; Houk and Raubani 2010). The extended COTS outbreak in the Swains reefs in the southern GBR has long been thought to be associated with the upwelling systems in that region (**Brodie et al. 2005**). Evidence of the biological effects of this upwelling and intrusive activity near the Swains and Capricorn-Bunker group reefs associated with the Capricorn Eddy (Weeks et al. 2010; Mao and Luick 2014) have recently been demonstrated via plankton blooms (Alongi et al. 2015) associated with enrichment phenomena such as manta ray feeding aggregations (**Weeks et al. 2015**). It is likely that these factors help explain the COTS outbreaks in the Swains and Capricorn-Bunker Group reefs (Miller et al. 2015).

While it has been suggested in the past (L. Zann pers. com.) that seemingly simultaneous periods of COTS outbreaks occur across the entire Indo-Pacific in response to ocean-scale phenomena such as ENSO, recent research in Polynesia suggests that COTS outbreaks can have a suite of specific local causes as well as regional-scale connectivity in populations and outbreak phenomena (Timmers et al. 2010, 2012; Kayal et al. 2012). Similarly, in Guam, COTS outbreaks seem to have elements both of a primary outbreak nature, probably with local causes, and of a secondary outbreak nature, with larval recruits possibly coming from places a great distance from Guam (Tusso et al. 2015). The occurrence of several genetically distinct sub-species of COTS in the Indo-Pacific supports the notion of the regional or local nature of outbreaks (e.g., Vogler et al. 2012).

Direct intervention to kill COTS by collection or injection of toxic chemicals has been tried in many places during COTS outbreaks without significant effects on overall population numbers. Between 1970 and 1983, almost 13 million COTS were removed from the reefs of the Ryukyu Islands, southern Japan, via a bounty for fishers, who changed from fishing to a more reliable income (Lucas 2013). Despite this huge effort, there are still large COTS populations in the Ryukyus. However, the idea of direct killing remains attractive to some and has been shown to work at the scale of a tourist site on the GBR (Great Barrier Reef Marine Park Authority 2009a). COTS can be killed by injection of sodium bisulphate, bile salts (Rivera-Posada et al. 2014) or lemon juice and vinegar (Moutardier et al. 2015). However, it is well known that such methods, while effective at keeping COTS away from a tourist reef site, cannot control populations at the population (GBR) scale. The sheer numbers of COTS larvae, their widespread distribution and the adaptability of their larvae to environmental conditions also makes the case that the success of direct killing as a population level control is unlikely (Doherty et al. 2015; MacNeil et al. 2016; Uthicke et al. 2015b; Wolfe et al. 2015b) despite claims to the contrary from the proponents of the direct killing solution in the popular press. Successful control programs have only been achieved where there was a small discrete population, which was tackled quickly with only small numbers removed – example, 225 animals in the Bos et al. (2013) case study on an isolated reef in the Philippines.

COTS outbreaks continue to be a threat to the GBR. There is some evidence that the increase in the area of no-take zones in 2004 has had significant success as COTS numbers on closed reefs are lower than on reefs open to fishing (Sweatman, 2008; McCook et al., 2010; Vanhatalo et al. 2016) (possibly due to the presence of fish predators on juvenile stages). The debate over whether more frequent COTS outbreaks in the central GBR are largely caused by nutrient runoff from agriculture in the Wet Tropics and Burdekin Regions (**Wooldridge et al. 2015**) is now reasonably settled (**Wooldridge and Brodie 2015**) but some doubts remain (Pratchett et al. 2014) and the loss of the predators on various life stages of COTS has not been ruled out as a contributing cause.

1.4.6 Debate over the importance of pesticides as a threat

During the 1980s various sampling programs for pesticide residues, primarily organochlorine insecticides (OCs), were undertaken in the GBR region. Residues were examined in GBR and Coral Sea waters during 1981 (Tanabe et al., 1982) with relatively low concentrations of hexachlorocyclohexanes (HCHs) and DDT and its breakdown products found. Lindane (c-HCH) was detected in sediments from the mouth of the Burdekin River in 1984/85 but organochlorine pesticides were not detected in sediment samples collected in Bowling Green Bay or at Lizard Island (Dyall and Johns, 1985). The authors concluded that sedimentary accumulation of organochlorines was confined to the close proximity of coastal sugarcane growing areas.

OCs were detected at low concentrations in:

- COTS from Slasher’s Reef and the Bunker Group in the southern section of the Marine Park in 1970 and 1971 (McCloskey and Duebert, 1972);
- Dugongs, with very low concentrations of lindane and dieldrin in the livers of four animals collected from Townsville in 1977 (Heinsohn and Marsh, 1978); and
- various reef animals, with low concentrations of c-lindane, heptachlor and DDT present in hard corals (*Fungia* sp. and *Acropora* sp.), liver and muscle tissue from coral trout (*Plectropoma maculatum*), surf parrotfish (*Scarus fasciatus*) and a bivalve mollusc (*Tridacna crocea*) collected from reefs between Heron and Lizard Islands in 1976 and 1977 (Olafson, 1978).

OC insecticides were detected in the Burdekin River and groundwater of the lower Burdekin floodplain in the 1970s (**Brodie et al. 1984**). Concern about OC pollution of the GBR resulted in a workshop in 1985 (focussed on a range of contaminants including OCs), which noted that the available data was insufficient to cause strong concern but that the situation needed continuing monitoring and assessment (Dutton 1985).

In 1991, after I joined GBRMPA with a “mandate” to look more closely at all water quality issues in the GBR, I made an assessment (with advice from colleagues) that OC insecticides were not a significant threat to GBR ecosystems. In addition, I determined that the pesticides in common use in 1991 (mainly herbicides and organophosphate insecticides in the sugarcane industry) were unlikely to be a threat to GBR ecosystems as their short half-lives would preclude them from being transported in significant amounts to the marine environment. In hindsight, while the assessment with respect to the OC insecticides was accurate, the assessment for herbicides was not. It took another seven years and, fortunately, the appointment of David Haynes to the Water Quality Group in GBRMPA for this assessment to be corrected, with a series of studies carried out by Haynes and his colleagues from ENTOX, led by Jochen Mueller, in the late 1990s (e.g., Haynes et al. 2000a). Our knowledge of pesticides in the GBR was summarised in a workshop in 2000 (Haynes and Michalek-Wagner 2000) and in the keynote paper of Haynes and Johnson (2000). The workshop provided the foundations for the pesticide risk assessment studies in the period from 2000 – 2015 (Devlin et al. 2015a).

Kannan et al. (1995) showed that concentrations of chlorinated organics (PCBs, DDTs, HCHs, aldrin, dieldrin and chlordanes) in muscle tissue of coastal fish species collected near Townsville between 1989 and 1993 were low compared to samples from the Brisbane region and other urbanised centres. Further analysis was carried out in 1992 and 1993 of fish livers from 142 individuals of a wide range of species collected in the central section of the GBRMP (Von Westernhagen and Klumpp, 1995). Low levels of DDE and dieldrin were detected in 8% of samples.

Lindane, dieldrin and DDT (and its breakdown product DDE) continue to be found in nearshore marine samples collected along the Queensland coast (Haynes et al. 2000a). For example, dieldrin was detected in sediments collected from the mouths of the Barron and Johnstone Rivers and in sediments from Halifax Bay. Dieldrin was a widely distributed contaminant of Queensland waterways and estuaries in the past (Clegg 1974; Kannan et al. 1995; Russell et al. 1996) and was detected in crabs (*Scylla serrata*) collected from estuaries adjacent to agricultural catchments between Moreton Bay and Cairns (Mortimer 2000; Negri et al. 2009) and in fish livers collected from the central Queensland coast adjacent to agricultural activity (von Westerhagen and Klumpp 1995).

More revealing than the studies on OCs, however, were the studies of Haynes, Mueller and colleagues over the next 15 years which showed widespread contamination with photosystem II (PSII) herbicides of GBR sediments and seagrass (Haynes et al. 2000a) and fresh, estuarine and marine waters (e.g. McMahon et al. 2005; Shaw et al. 2010; Kennedy et al. 2012b; **Kennedy et al. 2012a**; Smith et al. 2012). It was shown that during high river flows, tonnes of herbicides such as diuron and tebuthiuron could be discharged into the GBR lagoon (**Mitchell et al. 2005**; Packett et al. 2009). Herbicides (PSII and others) were found in highest concentrations in fresh and estuarine waters immediately downstream from large cropping districts (mostly sugarcane cultivation). A series of studies in the lower Burdekin cane growing district (where some other crops are grown as well) showed above-guideline concentrations of many pesticides (**Davis et al, 2008, 2012, 2013, 2014a**; Smith et al. 2012; **O'Brien et al 2016**) and high risks of ecosystem damage in some cases (**Davis et al. 2013, 2014b**). Studies over the last 4 years have confirmed similar contamination in the lower Herbert River floodplain (**O'Brien et al. 2013, 2014, 2015**).

Controversy over the impacts of herbicide pollution on mangroves arose following studies showing elevated diuron concentrations were responsible for mangroves near Mackay showing a "die-back" condition (Bell and Duke 2005; Duke et al. 2005). There was no question that diuron was present in large quantities in runoff events from the Pioneer River in Mackay (**Mitchell et al. 2005**). However, conflict arose as to whether the likely cause of the die-back was diuron (and other herbicides) or some other cause such as flooding and burial (Kirkwood and Dowling 2002; Dowling 2008). McKillup (2008) raised concerns about the statistics in the Duke et al. (2005) study; Duke (2008) responded with appropriate corrections. However, questions remained about the causes of the die-back given that the mangroves seemed to be recovering (Abbot and McKillup 2010) although diuron pollution continued. Eventually Abbot and Marohasy (2011) claimed that "*Evidence from field studies suggests burial of pneumatophores, the plant's breathing roots, following flood events is a more likely causal factor in mangrove dieback, whereas any contribution from Diuron remains unproven."* This debate has never been fully resolved.

The debate over the relative threat of pesticide pollution extended to the adequacy of management of pesticides in the GBR region and, by extension, within Australia generally. Currently, management takes place through the Federal regulatory authority the Australian

Pesticide and Veterinary Medicine Authority (e.g. APVMA 2012) with on-ground management a state responsibility. **King et al. (2013)** claim that the system is very unsatisfactory:

> *"The ad hoc, case-by-case and very slow chemical review process administered by Australia's national pesticide regulator has not effectively assessed or addressed chemical risks to the GBR. Some failures of the current system would be addressed by a systematic re-registration program of the kind in place in the European Union and United States. We conclude that to adequately protect the GBR, given its marine protected area and World Heritage status, both the special management provisions for the area already existing plus an effective national pesticide regulatory regime of the standard of the European Union are the minimum requirements."*

Holmes (2014) notes the total inadequacy of the models used by APVMA to assess and hence regulate the use of diuron in the GBR region:

> *"The environmental risk assessment process used by the APVMA utilised a runoff risk model developed and validated under European farming conditions. However, the farming conditions in the sugarcane regions of the Great Barrier Reef catchments have environmental parameters beyond the currently validated bounds of the model. The use of the model to assess environmental risk in these regions is therefore highly inappropriate, demonstrating the pitfalls of a one size fits all approach."*

Camenzuli et al. (2012) showed that a model which took into account the conditions in north Queensland (in the Tully catchment) was able to be parametised and gave diuron results in agreement with monitored data. However, even though pesticide residues far in exceedance of ANZECC guidelines continue to be found in GBR waterways (Devlin et al. 2015a), regulation through APVMA continues to be ineffective. Fortunately, other ways to manage pesticides in the GBRCA using the power of Reef Plan (Department of the Premier and Cabinet 2013) have been implemented and, as a result, pesticide loads discharged to the GBR have declined by 30.5% over the five-year period (2009 – 2014) of Reef Plan 2009 (Department of the Premier and Cabinet 2014), although the Reef Plan 2009 target of 60% has not been achieved. Effective ways to reduce herbicide loss from cane farms have now been tested (**Oliver et al. 2014;** Davis and Pradolin 2016; Melland et al. 2015). Using banded spraying, in which the diuron is only sprayed on the mound of the sugarcane and other herbicides, are sprayed in the inter-row, quantities of diuron and atrazine applied can be greatly reduced, reducing herbicide losses by 90%, without affecting cane productivity (**Oliver et al 2014**). However, banded spraying may have unforeseen consequences when the alternative herbicides (to diuron) are found to be equally or more toxic than diuron (**Davis et al. 2014a**) and hence present an equal or greater risk to aquatic ecosystems.

The significance of pesticide pollution to the GBR has been analysed by Stephen Lewis and colleagues (**Lewis et al. 2009**) and the cumulative risk of multiple pesticides analysed (**Lewis et al. 2012b; Davis et al. 2013**). These analyses and other studies have shown that due to the frequency and duration of exceedance of water quality guidelines pesticides, particularly herbicides, although continually present in ngL^{-1} concentrations throughout the GBR waters (**Shaw et al 2012**; Kennedy et al. 2012b; **Kennedy et al. 2012a**; Smith et al. 2012; **O'Brien et al. 2016**) are primarily a threat to fresh, estuarine and coastal waters, seagrass meadows and inner-shelf reefs, and only a minor threat to mid-shelf and outer-shelf reef systems (Devlin et al. 2015a).

The insecticide imidacloprid was introduced into sugarcane cultivation in the GBR catchment in the last decade to replace chlorpyrifos as the principal control of cane beetle larvae (Allsopp 2010). Imidacloprid is very effective against these larvae (Chandler 2003) and the Australian sugarcane industry relies on this insecticide in many areas (Hunt et al. 2012). Unfortunately, imidacloprid is notorious in Europe and elsewhere because of its toxicity to bees, jeopardising both crop pollination services and the honey industry (Dively et al. 2015), and in 2013 the EU restricted its use. Its effects on aquatic fauna in the GBRCA and GBR are currently unknown.

1.5 Discussion regarding water quality guidelines for GBR waters and suitable pollutant load targets for GBR rivers and the GBR generally

1.5.1 Water quality guidelines

Water quality guidelines were set for Australian waters in 1974 (Hart 1974). From this initial work the Australian and New Zealand Environment and Conservation Council developed "official" guidelines for Australian and New Zealand waters in 1992 and again in 2000 (ANZECC and ARMCANZ 2000), including guidelines for tropical marine waters but not specifically for the GBR. GBRMPA commissioned studies to develop guidelines specifically for GBR waters, which were based on an evaluation of the tolerance of corals to nutrients and related water quality variables (Greenfield et al. 1987; Hawker and Connell 1989; Bell et al 1989). However, no official guidelines were published at this time.

In 2005 **Moss et al. (2005)** produced a new set of draft guidelines for GBR marine waters, incorporating some guidelines from the ANZECC document but also devising new ones using current knowledge of GBR marine water quality. For example, a guideline of 0.6 μgL^{-1} was set for chlorophyll a, based on current knowledge of chlorophyll a from chlorophyll monitoring programs **(Brodie et al. 1997, 2007**) in less developed regions of the GBR, where chlorophyll concentrations were thought to be near natural. Subsequently a more structured program was established to set water quality guidelines resulting in the report by De'ath and Fabricius (2008). Using the large data sets available on water quality parameters in the GBR lagoon in both river discharge periods (**Devlin et al. 2001**) and non-discharge periods (De'ath and Fabricius 2008) a team of managers and scientists published the first official GBR water quality guidelines (Great Barrier Reef Marine Park Authority 2010), with the guidelines for chlorophyll a being 0.45 μgL^{-1} (annual) and 0.63 μgL^{-1} (wet season).

Currently, pesticide guidelines for marine waters of the GBR are being established or revised. New guidelines are badly needed as most of the most commonly used pesticides used in cropping and grazing in the GBRCA have no guidelines, and for those few that do, the guidelines are unsuitable. Australia's pesticide regulatory system is badly deficient in ensuring pesticide residues are of minimal danger to aquatic environments (**King et al. 2013**; Holmes 2014). The Queensland Government is now working on guidelines for a range of common pesticides (mostly herbicides), which should be incorporated into ANZECC and GBRMPA guidelines (R. Smith pers. com.).

1.5.2 Pollutant load reduction targets

1.5.2.1 Target setting in the period 2001 - 2015

The first targets for load reductions of pollutants discharged from rivers to the GBR were made in the Great Barrier Reef Water Quality Action Plan (**Brodie et al. 2001a**). Reduction targets were based on the assessed degree of anthropogenic modification of sediment, nitrogen and phosphorus inputs to individual GBR catchments. For catchments having more intensive development and hence a larger increase in delivery compared to pre-development times (circa 1850), higher targets were set – for example, 50% reductions in total load of suspended sediment. Catchments with little development were required to reduce loads by only small percentages. The loads for each river were based on use of the SedNet model as used in the National Land and Water Resources Audit (NLWRA 2001). For pragmatic and political reasons, Reef Plan 2003 did not contain numerical load reduction targets and at that stage there were no

GBR-specific marine water quality guidelines either. The ANZECC 2000 guidelines (ANZECC & ARMCANZ, 2000) were in place by 2003 and included marine water quality guidelines for nutrients and metals but were not designed to be applied in tropical waters generally or, specifically, in GBR waters.

It was not until the first revision and update of Reef Plan in 2009 following the Scientific Consensus Statement of 2008 (**Brodie et al. 2008a**) that the first load targets and land management targets were set under Reef Plan. End-of-system load targets for the major pollutants were set for the entire GBR in Reef Plan 2009 (Department of the Premier and Cabinet 2009) and load targets were set within the Reef Rescue initiative in 2008 (**Brodie et al. 2012a**) (Table 4). The two sets of targets are loosely linked although internally inconsistent. Both sets of targets were based on what could be achieved through “feasible” agricultural management change to “better” management practices of the Great Barrier Reef Catchment (GBRC) (**Brodie et al. 2012a**). End-of-system load targets for the major pollutants addressed in Reef Plan 2009 were updated in 2013 (Department of the Premier and Cabinet 2013). Targets were not established on the basis of ecological realities for the GBR although attempts to design targets of this type have been made (e.g., **Brodie et al. 2009a**). There is no guarantee that the Reef Plan 2009 or Reef Plan 2013 targets will lead to the overall Reef Plan objective of “To ensure that by 2020 the quality of water entering the reef from adjacent catchments has no detrimental impact on the health and resilience of the Great Barrier Reef”. Reef Plan 2013 includes water quality targets and land and catchment management targets to be achieved by 2018 (Table 5).

Targets at a basin scale were not set during Reef Plan 2009 or Reef Plan 2013. Thus there are no formal Reef Plan targets for the individual basins of the GBR catchment.

Table 4. Reef Plan (2009) and Reef Rescue (2009) targets. Reef Rescue targets are shaded. EOC = end of catchment.

Target	Scale (area) for reporting	Reporting frequency
50% Reduction in N load at EOC by 2013	EOC for all GBR catchments	Annual
50% Reduction in P load at EOC by 2013	EOC for all GBR catchments	Annual
Reduce the load of dissolved nutrients from agricultural lands to the GBR lagoon by 25% by 2013	EOC for all GBR catchments	Annual
Reduce the discharge of particulate nutrients from agricultural lands to the GBR lagoon by 10% by 2013	EOC for all GBR catchments	Annual
50% Reduction in pesticide load at EOC by 2013	EOC for all GBR catchments	Annual
Reduce the load of chemicals from agricultural lands to the GBR lagoon by 25% by 2013	EOC for all GBR catchments	Annual
Minimum 50% late dry season groundcover in dry tropics grazing lands by 2013	Sub catchment for Burdekin and Fitzroy	Annual
20% Reduction in sediment load by 2020	EOC for all GBR catchments	Annual
Reduce the discharge of sediment from agricultural lands to the GBR lagoon by 10% by 2013	EOC for all GBR catchments	Annual
No net loss or degradation of wetlands	Catchment for all GBR catchments	Yr 1 and 5
Condition and extent of riparian areas improved	Catchment for all GBR catchments	Yr 1 and 5
80% of landholders adopted improved practices	Sub catchment or catchment by sector	Annual
To increase the number of farmers who have adopted land management practices that will improve the quality of water reaching the reef lagoon by a further 1300 over 3 years	Sub catchment or catchment by sector	Annual progress; major report
50% of landholders adopted improved practices (grazing)	Sub catchment or catchment	Annual
To increase the number of pastoralists who have improved ground cover monitoring and management in areas where runoff from grazing is contributing significantly to sediment loads and a decline in the quality of water reaching the reef lagoon by a further 1500 over 3 years	Sub catchment or catchment	Annual progress; major report 2011

Table 5. Reef Plan 2013 Targets.

Long term goal	To ensure that by 2020 the quality of water entering the reef from broadscale land use has no detrimental impact on the health and resilience of the Great Barrier Reef.
Water quality targets (2018)	At least a 50 per cent reduction in anthropogenic end-of-catchment dissolved inorganic nitrogen loads in priority areas. At least a 20 per cent reduction in anthropogenic end-of-catchment loads of sediment and particulate nutrients in priority areas. At least a 60 per cent reduction in end-of-catchment pesticide loads in priority areas.
Land and catchment management targets (2018)	90 per cent of sugarcane, horticulture, cropping and grazing lands are managed using best management practice systems (soil, nutrient and pesticides) in priority areas. Minimum 70 per cent late dry season groundcover on grazing lands. The extent of riparian vegetation is increased.

The possibility of achieving the overall goal of Reef Plan of "no detrimental impact" is also in question given that current "Best Management Practices" may be insufficient (Kroon, 2012; Thorburn and Wilkinson, 2013). Modeling of land-use adoption scenarios across the entire GBR has shown that complete adoption of current best management practices in grazing and sugarcane would be sufficient to meet the Reef Plan targets for photosystem II herbicides, but the effects are uncertain for suspended sediment, nitrogen and phosphorus (Thorburn and Wilkinson 2013; Thorburn et al., 2013a; Waters et al. 2013) and for the desired ecological outcomes (Kroon 2012).

In March 2015 the Reef 2050 Long Term Sustainability Plan (LTSP) (Commonwealth of Australia 2015) was released (further discussed in Chapter 10). The Reef 2050 Long Term Sustainability Plan is a joint initiative between the Australian and Queensland Governments and provides an overarching strategy for management of the GBR, and contains objectives, targets and actions across several themes including: biodiversity, ecosystem health, heritage, water quality, community benefits and governance. The LTSP builds on the Reef Plan 2013 targets with the extended LTSP targets in boldface:

- at least a 50 per cent reduction in anthropogenic end-of-catchment *dissolved inorganic nitrogen* loads in priority areas, **on the way to achieving up to an 80 per cent reduction in *nitrogen* in priority areas by 2025**;
- at least a 20 per cent reduction in anthropogenic end-of-catchment loads of sediment in priority areas, on the way to achieving up to a 50 per cent reduction in priority areas by 2025;
- at least a 20 per cent reduction in anthropogenic end-of-catchment loads of particulate nutrients in priority areas; and
- at least a 60 per cent reduction in end-of-catchment pesticide loads in priority areas.

In addition, the Queensland Government announced an election commitment in 2015 that adopted and extended these targets:

- Reduce nitrogen run-off by up to 80% in key catchments such as the Wet Tropics and the Burdekin by 2025; and
- Reduce total suspended sediment run-off by up to 50% in key catchments such as the Wet Tropics and the Burdekin by 2025.

While the Reef Plan targets refer to reductions in "anthropogenic end-of-catchment" loads, and define the pollutants as "dissolved inorganic nitrogen" and "sediment and particulate nutrients", the LTSP long-term targets and the current Queensland Government targets are less specific, using the term "up to" and referring only to "nitrogen" and "sediment" and thus lend themselves to mixed interpretations. Both sets of targets refer to "priority areas" or "key catchments", which also require further definition.

1.5.2.2 Changes in the targets between 2009 and 2013

Large changes in many of the targets were made in Reef Plan 2013. Targets were greatly relaxed for nitrogen and phosphorus, remained unchanged for sediment and were marginally tightened for pesticides (from 50% to 60% reduction in loads). However, interpreting how the new targets compared to the 2009 targets was difficult as the new targets were often given in different forms of the pollutants – for example, "dissolved inorganic nitrogen" (2013) compared to "nitrogen" (2009). Best estimates of the changed nitrogen and phosphorus targets (Table 6; **Brodie et al. 2014**) involved using the percentages of PN to DIN and to DON in the Source Catchment estimates for the whole GBR discharge (Waters et al. 2014) and assumed that that a reasonable interpretation of the Reef Plan 2013 target of:

> "At least a 50 per cent reduction in anthropogenic end-of-catchment dissolved inorganic nitrogen loads in priority areas"
>
> and
>
> "At least a 20 per cent reduction in anthropogenic end-of-catchment loads of sediment and particulate nutrients in priority areas"

Meant a 50% reduction in DIN, a 20% reduction in PN and no reduction in DON, with 'priority areas' ignored (as they are not clearly defined in Reef Plan 2013) and replaced by 'all the GBR catchment (GBRC)'.

Similarly, for phosphorus the Reef Plan 2013 targets of:

> "At least a 20 per cent reduction in anthropogenic end-of-catchment loads of sediment and particulate nutrients in priority areas"

are interpreted to mean no reduction in DIP, a 20% reduction in PP and no reduction in DOP across the GBRC.

Thus, in 2009, a 50% reduction in TN load was required whereas in 2013 only a 36% reduction was required. Similarly, for TP, in 2009 a 50% reduction was required whereas in 2013 only a 16% reduction was required. These changes will have consequences in reporting progress towards targets, as the targets are now much less stringent.

1.5.2.3 Confusion over targets hinders management

The changes in the Reef Plan targets between 2009 and 2013, especially the changes from one form of "nitrogen" (possibly meaning anthropogenic nitrogen, but not made clear) in 2009 to "anthropogenic dissolved inorganic nitrogen" and "particulate nitrogen" (assumed from the descriptor "particulate nutrients") have proven an issue for interpreting progress towards the targets. This is clearly seen in the 2014 Reef Report Card (Department of the Premier and Cabinet 2014), which reports progress over the period 2008 – 2013, during which load reductions were achieved with the first tranche of Reef Plan funding, but reporting is done against the 2013 targets (which are really targets for 2018) rather than the 2009 targets, which was the original intent of the reporting process. For example, the Reef Plan 2009 target of " a 50% Reduction in N load at EOC by 2013" (Table 4), is reported against in the 2014 Reef report Card (Department of the Premier and Cabinet 2014) as a 17% reduction in DIN and a 11.5% reduction in PN. Targets for DIN and PN are set for 2018 in Reef Plan 2013 but no targets for these nitrogen forms were set in Reef Plan 2009.

This confusion over the wording and meaning of the Reef Plan (and LTSP) targets has led to a process to set “ecologically relevant targets” for Water Quality Improvement Plan (WQIP) processes as this type of target is ecologically based and clear in definition of the relevant parameters, and its can be clearly described (**Brodie et al. in press**), as shown below.

1.5.2.4 Setting Ecologically Relevant Targets

Ecologically relevant targets (ERTs) attempt to define the catchment-specific pollutant load reductions that would be required to meet the standards of the GBR Water Quality Guidelines (Great Barrier Reef Marine Park Authority 2010), which are considered to be suitable to maintain ecosystem health. Thus ERTs are required to be met to achieve the overall long-term Reef Plan goal of “To ensure that by 2020 the quality of water entering the reef from broadscale landuse has no detrimental impact on the health and resilience of the Great Barrier Reef”. The Reef Plan 2013 Targets (RPTs) are not set with a clear link to achieve this overall goal and are not based on an ecological endpoint for GBR ecosystems (or proxies like water quality).

ERTs were first set for DIN loads from the Wet Tropics rivers in 2006 (**Wooldridge et al. 2006**) and the results were incorporated into the draft Tully WQIP (Kroon 2009). Unfortunately, as the WQIP was never accepted for implementation, the use of the ERTs in this case was never tested. Methodologies for setting ERTs for other parameters and other rivers were described by **Brodie et al. (2009a)** although the term “GBR ecosystem targets” was used at the time to describe what we now call ERTs. These methodologies were used in some of the WQIPs of the period 2006 – 2008. In 2013 a decision was made to use ERTs in developing the new set of WQIPs, initially for the Burnett Mary and Wet Tropics Regions and later for the Burdekin and Fitzroy Regions. The methodology chosen followed **Wooldridge et al. (2006)** and **Brodie et al. (2009)** and, more recently, **Wooldridge et al. (2015**) **and Brodie et al. (in press)**.

Ecologically relevant targets have now been widely used in planning for the management of GBR catchments in Water Quality Improvement Plans (WQIPs). ERTs were set for fine sediment, nutrients and pesticides in the Burnett Mary WQIP (**Brodie and Lewis 2014**; Burnett Mary NRM Group 2015) and the results were used in a benefit-cost analysis of management actions for the Burnett Mary Region (Beverly et al. 2011). ERTs for the Wet Tropics Region were used similarly (Terrain NRM 2015; **Brodie et al. 2014**), as will ERTS currently being developed for the Burdekin and Fitzroy regions (**Brodie et al. 2015c, 2016;** NQ Dry Tropics, 2016).

With this type of target the load reductions needed to achieve a GBR endpoint (and restored ecosystem value) can be analysed in terms of costs of management and benefit-cost ratios (e.g. Beverly et al. 2011).

1.6 Debate over the influence of new sediment delivery on the turbidity due to benthic sediment resuspension in shallow GBR waters and associated damage to coral reefs and seagrass meadows

1.6.1 Dynamics of suspended sediments and turbidity

The GBR exists in a sedimentary setting with the shallow (0 – 20m) inner shelf dominated by silico-clastic sediments and the deeper (20 – 100m) mid and outer shelf dominated by carbonate sediments (Hopley et al. 2007). Turbidity on the inner shelf is driven by short-lived flood plumes in the wet season (**Devlin et al. 2012a**) (Figure 4) and, more importantly, by resuspension of benthic fine sediments and organic particulate material throughout the year, driven by the SE trade winds and tides (Larcombe et al. 1995; **Fabricius et al.** 2013b, **2014, 2016**) (Figure 5). However, the extent of increased turbidity on the GBR inner-shelf caused by increased sediment loads from rivers (associated with modern catchment development) has been in dispute since the early 1990s (Larcombe et al. 1995; Larcombe and Woolfe 1999a,b; **Brodie 1996**). It was postulated by a group of sedimentologists and physicists that turbidity on the inner-shelf on the “sediment wedge” was not supply limited, there being always adequate fine sediment available for resuspension during SE trade winds and strong tidal currents (Larcombe et al. 1995; Larcombe and Woolfe 1999a,b; Orpin and Ridd 2012). Hence additional sediment loads from rivers would make no difference to the turbidity regime in GBR coastal waters and have no impact on coastal ecosystems. Conversely, a group of biologists, oceanographers and other scientists claimed that river discharge introduced new, finer, “more easily resuspendable” material into the lagoon and that this was the source of the material producing increased turbidity in coastal waters, with consequent effects on light-dependent organisms (e.g. **Brodie 1996**, Fabricius and De’ath 2001a,b; Wolanski and Spagnol 2000; Wolanski et al. 2004). Conclusive evidence for this hypothesis was not produced until long-term studies on coastal photic depth (Weeks et al. 2012) and river sediment discharge (e.g., **Kuhnert et al. 2012**) were brought together to show the relationship between river fine sediment discharge and annual turbidity regimes (Fabricius et al. 2013b**; Fabricius et al. 2014, 2016**).

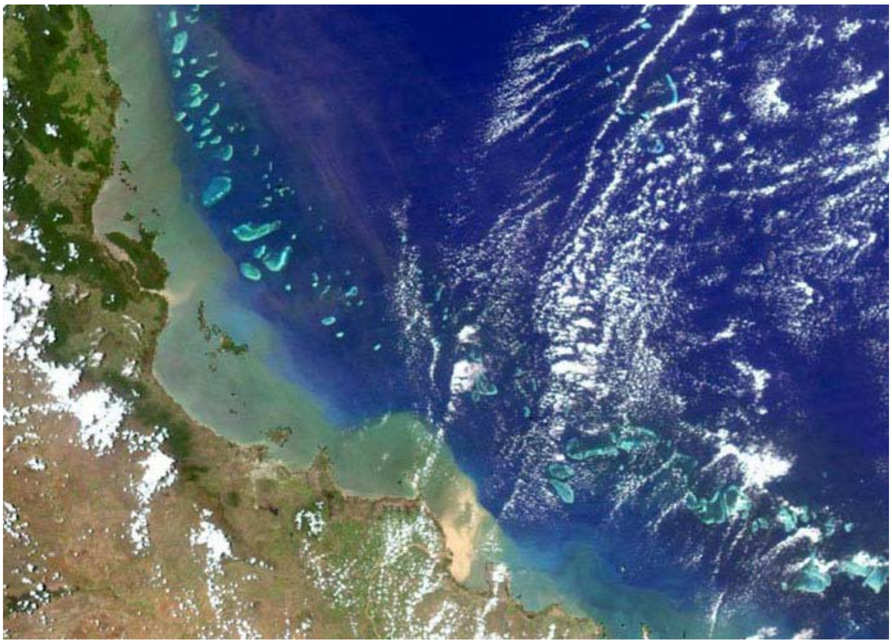


Figure 4. Flood plume turbidity: MODIS-Aqua Image of the Burdekin Region during a moderate flood discharge event (10th February 2007). Image provided by NASA and processed by Matt Slivkoff. (From Logan et al. 2013).

Figure 5. Resuspension turbidity: MODIS-Aqua Quasi-True Colour Image of the Burdekin Region, from 23 October 2008. (From Logan et al. 2013).

Understanding the impacts of sedimentation and turbidity on coral communities and seagrass meadows, and the relationships between end-of-catchment loads and turbidity in the receiving environment is critical to resolving such debates. The suspended sediment of most risk to the GBR (as it is transported furthest in flood plumes, stays in suspension longest (Storlazzi et al. 2015) and results in the greatest degree of resuspension) is the fine fraction, sometimes defined as that smaller than 15.6 µm – that is, the component containing the clay and fine silt fractions (**Bainbridge et al., 2012, 2014, 2016; Bartley et al., 2014a**; Douglas et al. 2008; **Waterhouse et al., 2013**). Of even more risk is the clay fraction (<4 µm), which carries most of the nitrogen, phosphorus and other contaminants, travels widely in flood plumes rather than depositing near the river mouth (Lewis et al., 2014, **2015a**, b; Delandmeter et al. 2015), is most effective at attenuating light when in suspension (Storlazzi et al. 2015) and drives increased turbidity on the inner and mid shelf of the GBR (**Fabricius et al.** 2013a, **2014, 2016; Logan et al. 2014**).

This increased fine sediment supply can have severe impacts on GBR organisms such as: reef fish, through effects on recruitment and feeding (e.g. Wenger et al. 2011, 2012, 2013, 2014; Hess et al. 2015; Gordon et al. 2015); corals, through sedimentation (e.g., Fabricius and Wolanski 2000; Weber et al., 2006, 2012; Flores et al., 2012; Pollock et al. 2014) and decreased light (Fabricius et al. 2013, **2014, 2016**); macro-algae and turf algae through increasing competitive advantage of over corals (Gowan et al. 2014; Goatley and Bellwood 2012, 2013); and seagrass (Collier et al., 2012a,b, Petus et al., 2014). Furthermore, suspended sediment interacts with other stressors to increase the overall impact on coral reefs (Ban et al. 2014; Risk 2014; Graham et al. 2015), and resuspension of sediment by windy conditions or strong tidal currents in shallow waters (<15 m) can bring suspended sediment concentrations above the GBR water quality guidelines (De'ath and Fabricius, 2008; Great Barrier Reef Marine Park Authority, 2010), threatening corals and seagrasses through reduced light for photosynthesis (**Bartley et al. 2014**).

Some mineral type are particularly important in driving adverse effects offshore (**Bainbridge et al. 2016**); for example, the expandable clays like smectite are very mobile in suspension in the marine environment (Smith et al. 2008) and form the organically rich flocs (**Bainbridge et al. 2012**) which are most responsible for far-field resuspension, causing loss of clarity (**Fabricius et al. 2014, 2016; Logan et al. 2014**) and adverse effects on corals when deposited on to the coral surface (Weber et al. 2006, 2014).

1.6.2 Sediment and corals

Some coral species can tolerate very high sedimentation rates and turbidity, and can recover from short-term or low levels of sedimentation (e.g., **Bartley et al. 2014a**; Schaffelke et al. 2013; **Brodie et al. 2013b**). However, most corals are reliant on autotrophy through their associated zooxanthellae and are negatively affected by smothering (sedimentation) and reduced light availability for photosynthesis due to turbidity. Turbidity (and poor water quality generally) can also increase susceptibility to ocean acidification (Uthicke et al 2014; Vogel et al. 2015).

For coral reef systems, reduced water clarity has been associated with increased macroalgal cover, reductions in coral biodiversity (De'ath and Fabricius, 2010), increased macro-bioeroder densities (LeGrand and Fabricius, 2011), shifts from communities dominated by phototrophic corals to heterotrophic filter feeders (Birkeland, 1988), reduced resilience against ocean acidification (Vogel et al. 2015) and increased presence of heterotrophic soft corals compared to autotrophic types as well as loss of soft corals in more turbid waters (Fabricius and De’ath 2001a) and loss of crustose coralline algae (Fabricius and De’ath 2001b). However, some coral reefs have developed and thrived in shallow nearshore areas with high turbidity (Browne et al., 2012; Palmer et al., 2010).

It would appear that coastal reefs like Paluma Shoals and Bramston Reef are sediment-tolerant, having existed and developed in a high-sediment environment since their development during the Holocene (Ryan et al. 2016). Reefs a little further offshore such as Middle Reef and Pandora Reef are also relatively sediment-tolerant, sufficient to be able to survive and recovery from acute damage in a high (and increasing) sediment regime (Browne et al. 2010, 2012; Done et al. 2007), although with periods of low coral cover. This is evident from the state of coral cover on Pandora Reef (**Coppo and Brodie 2015** with data from the AIMS LTMP (Australian Institute of Marine Science 2016) and MMP coral monitoring programs (e.g. Thompson et al. 2015)) with generally good (40 - 60%) cover at LTMP sites (1995 – 2012) but low (<10%) cover at MMP sites (2005 – 2014) (Figures 6 and 7) and a history of large variations in cover at different sites on the reef (Done et al. 2007). On Middle Reef coral cover has been maintained in good condition (50%) and fairly stable over 2005 – 2014 (Figure 7) (**Coppo and Brodie 2015**; Browne et al. 2010).

Further offshore again, at the inner-shelf fringing reefs in the Keppels, Whitsundays, Magnetic, Palms, Dunk islands and elsewhere, reefs may be more sensitive to an increased sediment regime, with less tolerant and adaptable coral species. At such sites coral cover varies from very poor to poor but variable – for example, at Havannah Island (Figure 6) coral cover at LTMP sites has declined from 45% to less than 5% between 1996 and 2014, but at the MMP sites (Figure 7) increased from 15% to 30% between 2005 and 2014. The reefs in the Keppel Islands group were subjected to almost annual large discharge events from the Fitzroy River, with high concentrations of suspended sediment, nutrients and pesticides over the period 2008 - 2013 (**Devlin et al. 2012b**; Wenger et al. 2016). As a result, the reefs lost resilience and coral cover has declined to very low levels (Jones and Berkelmans 2014; Wenger et al. 2016).

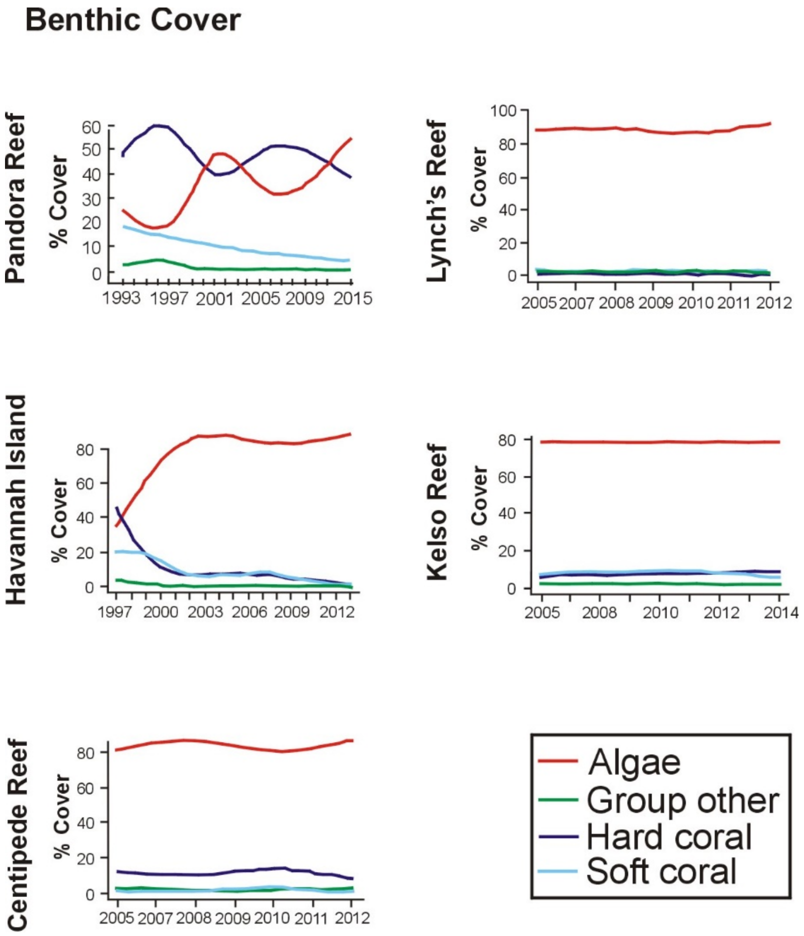


Figure 6. Coral cover, algal cover and other parameters for period 2005 – 2014 for LTMP reefs in the Burdekin marine region. Figure modified from figure and data in AIMS (2015). Note that the reefs have different time periods of the results of monitoring.

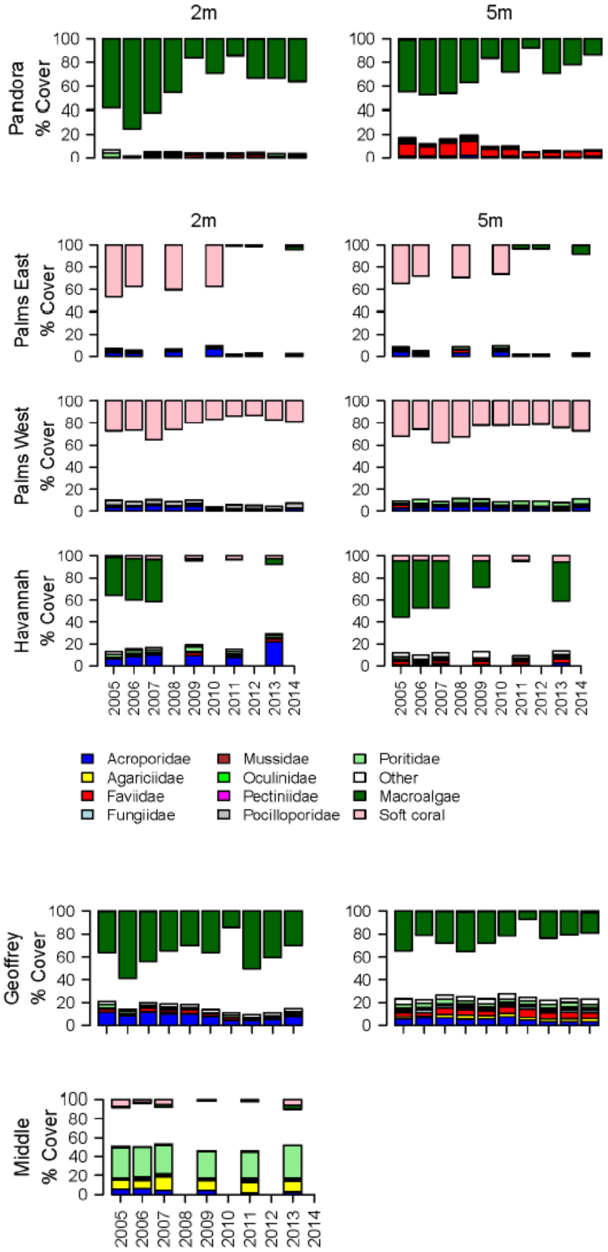


Figure 7. Coral cover by family and by depth over period 2005 – 2014 for MMP reefs in the Burdekin marine area. The colour pink shows soft coral, the white other cover, the dark green macroalgal cover while all other colours are for hard coral of different families. Cover estimates indicate regionally abundant hard coral families and the total cover for soft corals and macroalgae (hanging). Source: Modified from data and figure in Thompson et al. (2014).

1.6.3 Sediment and seagrass

Reduced water clarity may cause loss of seagrasses from deeper waters (Collier et al., 2012a,b) or, when the reduced clarity is prolonged, to seagrass mortality (Petus et al. 2014). Seagrass health and abundance is variable in space and time in the GBR (Coles et al. 2015). Recent evidence indicates that seagrass is declining in parts of the GBR (McKenzie et al 2015; Coles et al. 2015), particularly in the Townsville region (McKenzie et al., 2010; Petus et al. 2014), Cairns region (Rasheed and Unsworth 2011; McKenna et al. 2015), Abbot Point region (Rasheed et al. 2014), and several other regions, associated with a series of severe cyclones and large river flood events (McKenzie et al. 2015; Coles et al. 2015). Evidence of this decline is that 38% of sampling sites monitored regularly across the GBR are exhibiting shrinking meadow area, a large number of sites have reduced seagrass abundance, and many sites have limited or no sexual reproduction and so are not producing seeds that would enable rapid recovery (McKenzie et al. 2015). Degraded light regimes from increased suspended sediment are the cause of reduced seagrass abundance in many sites. The 2011 major river discharge events from many of the GBR rivers associated with the strong La Nina and the effects of Category 5 Tropical Cyclone Yasi have had devastating effects on large areas of GBR seagrass (Devlin et al., 2012b; McKenzie et al. 2015).

Port dredging may have severe but more short-term effects on seagrass in the GBR (although the potential for spoil dumping to damage seagrass is a hotly debated topic), such as at Hay Point (York et al. 2015), where turbidity from dredging is believed to have prevented seasonal re- establishment of deep-water seagrass, although recovery occurred after the dredging ceased.

1.7 Debate over prioritisation for management across the GBR among regions, catchments, land uses and industries, and within catchments

Assessments to prioritise catchments and land uses for management on the GBR catchment began formally with the prioritisation by **Greiner et al. (2003, 2005),** based on a multi-criteria analysis tool for assessing the relative impact of diffuse-source pollution from the river basins draining into the GBR lagoon. The assessment integrated biophysical and ecological data with socio-economic information pertaining to non-point-source pollution and (potential) pollutant impact. The analysis generated scores for each river basin against four criteria, thus profiling the basins and enabling prioritization of management alternatives between and within basins. The criteria were: (1) (Potential) ecological impact of diffuse-source pollution; (2) (Potential) social impact of pollution prevention; (3) (Potential) economic impact of pollution; (4) Development pressures.

The analysis was advanced in that it included offshore GBR asset values, and the capacity of catchment communities to manage natural resources, which were factors not included in subsequent assessments until the most recent Water Quality Improvement Plans (WQIPs) (e.g., Burnett Mary NRM 2015). No single ranking of basin priorities across the 35 GBR Basins was produced due to conceptual difficulties in combining scores from the four criteria. All subsequent prioritisation analyses followed similar methodology to **Greiner et al. (2003, 2005)**.

In response to the needs of the Australian Government's Reef Rescue funding allocation in 2008, a new multiple-criteria prioritisation assessment was carried out (Cotsell et al. 2009), which was further developed at a workshop at which scientists supplied weights for each criterion to generate a multiple-criteria score for each NRM region. The outcomes of the workshop were presented at stakeholder forums to inform proposal development for Reef Rescue Water Quality Grants and Partnerships funds. This prioritisation process proved useful for the logical and transparent treatment of a wide range of data sets and facilitated the structured engagement of Reef Rescue implementers with Reef scientists and stakeholders. However, a major limitation of the decision support model was the lack of adequate data sets for solvability criteria.

In 2009 the Queensland Government introduced regulatory action to ensure management of the catchments delivering the greatest impact on the GBR. The Barrier Reef Protection Amendment Act (2009) attempted to ensure that farmers adopt management practices that reduce the levels of farm pesticides, fertiliser nutrients and sediment harming the GBR (see **Brodie et al. 2012a**). It was announced that the package of regulations aimed to reduce pesticide and fertiliser pollution of Reef waters by 50% by 2013 and sediment pollution by 20% by 2020. These "targets" were based on estimates of the quantity of land-based contaminants discharged from the region, the proximity of the catchment to vulnerable reef ecosystems, the existing condition of the reef ecosystems and the nature of the industries contributing contaminant loads. The targets derived from another prioritisation MCA based on a relative risk assessment, but restricted to pre-determined regions of the GBR – the Wet Tropics, the Burdekin and the Mackay Whitsunday regions (**Brodie et al. 2009b; Brodie and Waterhouse 2009).** In this analysis it was recognised that previous prioritisations of management response between different pollutants, different land uses/industries and different regions using MCA methods were valuable but had been carried out with limited input data (Cotsell et al., 2009; **Greiner et al., 2005**). More sophisticated analyses with better input data were needed to confidently prioritise between pollutants. The study of **Waterhouse et al. (2012**), which extended the analysis of **Brodie and Waterhouse (2009)** to include five regions of the GBR (Wet Tropics, Burdekin, Mackay Whitsunday, Fitzroy and Burnett-Mary but excluding Cape York), aimed to address previous assessment deficiencies by using improved input data and assessing the reliability of the data.

The assessment showed that the Wet Tropics and Mackay Whitsunday regions rank the highest priority (ranked high), with Burdekin and Fitzroy catchments relatively high priority (medium–high) and the Burnett Mary catchments of moderate priority in terms of the contribution and influence of land-based pollutants (**Waterhouse et al. 2012**). This assessment concurs with several principles of the current understanding of priority contaminants and land uses in the GBR:

1. Sugar cane and horticultural land uses that generate substantial runoff of DIN and PSII herbicides are dominant in the coastal areas of the Wet Tropics, Burdekin, Mackay-Whitsunday and Burnett-Mary catchments.
2. The predominantly coastal location of intensive agriculture in the GBR catchment results in efficient delivery of contaminants to the GBR.
3. Many reefs are located close to the coast in the northern parts of the GBR, particularly in the Wet Tropics, while most southern reefs are located further offshore.
4. The assessment reflects the importance of dry tropics grazing activities and the contribution of sediment by erosion to receiving waters. A large proportion of the reefs in the dominant grazing areas of the Fitzroy and Burdekin catchments are located further offshore and thus may present a lower risk. However, suspended-sediment risk to other important GBR ecosystems such as seagrass beds has not been included in this assessment; if this was done, the importance of the Burdekin and Fitzroy regions might be enhanced.

To assist in the development of Reef Plan 2013 and the SCS of 2013, a risk-assessment method was developed and applied (**Brodie et al. 2013a**), **Brodie et al (2013b**) and **Waterhouse et al. (2013**). It aimed to inform policy makers and catchment managers on the land-based pollutants of greatest risk to the health of coral reefs and seagrass meadows. The approach used a combination of qualitative and semi-quantitative information about the influence on these ecosystems of individual catchments, in the 6 relevant natural resource management (NRM) regions. The method used a multiple-criteria approach with the application of a spatial tool, Multi-Criteria Analysis Shell for Spatial Decision Support (MCAS-S). The combined assessment of water quality variables was used to identify the areas where coral reefs and seagrass are at highest relative risk of impact of degraded water quality in the GBR. The relative risk was estimated from the areas of coral reefs and seagrass meadows exposed to a combination of defined pollutant thresholds (observed or modelled). The results indicated that the risk was greatest for coral reefs in the Fitzroy and Mackay Whitsunday regions, and for seagrass in the

Burdekin and Fitzroy regions. The combined assessment of these results with inclusion of information on end-of-catchment pollutant loads allowed conclusions to be drawn about the overall risk of pollutants to the GBR (which differ from the assessment when loads are not considered). In summary, from this overall assessment, the greatest risk to coral reefs and seagrass meadows is in the Wet Tropics region, followed by the Fitzroy and Burdekin regions.

A similar analysis with additional data layers was carried out during 2013-14 to support and inform discussion and decisions on funding priorities for investment, particularly through Reef Water Quality Grants (part of the Australian Government Reef Programme) (Barson et al. 2014). The results showed that investments in improving practices in the sugar cane and grazing industries could be expected to give the biggest water quality improvements. In the Wet Tropics NRM region the priority is to improve the management of nutrients (fertiliser use) in the Johnstone, Russell-Mulgrave, Tully, Herbert and Daintree Basins, and in improving herbicide management in the Herbert and Johnstone catchments. In the Burdekin NRM region, investments in improved cane nutrient and herbicide management are expected to give the biggest returns in the Haughton catchment. In the Mackay Whitsunday NRM region, investment in improving cane herbicide management practices is likely to deliver the biggest water quality improvements. For the grazing industry, the biggest returns on investment in reducing sediment loss will come from the Burdekin and Fitzroy catchments.

The prioritisations from **Greiner et al. (2005**) through to Barson et al. (2014) have given generally consistent results with priorities given to fertiliser and pesticide management in the sugarcane cultivation industry and erosion management in the beef grazing industry. However, confusion is still present in the government response to these priorities, through misinterpretation of the science and caveats in the results, such that the Queensland election commitment by the incoming Palaszczuk government (see Section 4.7.1.1 above), as an addition to the LTSP, stated:

> *"Reduce total suspended sediment run-off by up to 50% in key catchments such as the Wet Tropics and the Burdekin by 2025."*

Unfortunately, the Wet Tropics has never been seen as a priority region for sediment (erosion) management, although it may be for particulate nutrient management (which is also related to erosion rates). The catchments that are identified for sediment management in our latest analyses are actually the Mary, Fitzroy, Burdekin and Normanby, none of which are in the Wet Tropics (**Brodie et al. 2013b**).

One important issue is still not resolved in the current prioritisation assessments. The current prioritisation methodologies focus on identifying the most impacted marine environments and correlating them to investment in management actions within the most disturbed sections of the GBR catchment. As a result, the limited resources for management action change have been invested in Reef regions with the largest disturbance in an effort to arrest the decline in Reef water quality. Through this approach only the most degraded sections of the Reef (e.g. central GBR) receive large-scale funding while the areas of the Reef still in good condition (e.g. Cape York) receive little funding. As a result, perhaps, the current investment prioritisation method, coupled to the current level of on-ground investment and lack of commitment to meaningful Reef regulation, is doing little to arrest the decline in GBR water quality and ecosystem health (**Brodie and Waterhouse 2012;** Great Barrier Reef Marine Park Authority 2014; **Hughes et al. 2015**).

Given this issue of too little funding ploughed into areas of high catchment degradation with little hope of major success in reducing pollutant loads, a triage approach through a conservation biology framework is now being suggested as an important addition to current management thinking (Will Higham pers. com.). Through this approach, regions such as Cape York, where we know reefs, seagrass and dugong populations are in good condition (**Coppo et al. 2016**), would be prioritised for protective management – for example, agricultural development to only be allowed with immediate adoption of A class practices. Similarly, given the good status of seagrass and dugongs in Hervey Bay (**Coppo et al. 2014**), the river most influencing Hervey Bay, the Mary (Burnett Mary NRM Group 2015; **Brodie and Lewis 2014**; **Waterhouse et al. 2014**), would be prioritised for erosion management (as it already is following these principles in the Burnett-Mary WQIP – Burnett Mary NRM Group 2015). These conclusions are discussed in more detail in Chapter 10.

1.8 Consensus

The above issues have never been fully resolved, as might be expected for such complex systems and processes, and continue to be debated vigorously. However, various syntheses, scientific consensus statements, review papers, books and technical reviews have attempted to resolve the issues over the last 25 years such that management could be prioritised on the basis of the best understanding of the issue at the time (e.g. **Williams 2002**; Furnas 2003; **Brodie et al. 2001b**; Productivity Commission 2003; **Haynes et al. 2001**). The progress towards a consensus view by 2003 allowed development of the Reef Water Quality Protection Plan ("Reef Plan”), described below.

The first scientific consensus statement on the issue (**Williams et al. 2001**) concluded that:

- available evidence indicates that post-European land use has significantly increased runoff and sediment, associated nutrient and contaminant delivery to near-shore regions of the GBRHWA;
- runoff has had clear detrimental impacts on freshwater aquatic systems; and
- there is significant risk that this impact is currently or may in future damage areas of high exposure along the wet tropical and central Queensland coasts of the GBRWHA, and there is a continued urgency to work towards a reduction in the runoff of sediments, nutrients, herbicides and other pollutants into the Great Barrier Reef World Heritage Area

Similarly, the Productivity Commission report (Productivity Commission 2003) concluded that:

- Water quality in rivers entering the Great Barrier Reef (GBR) lagoon has declined because of diffuse pollutants, especially sediments, nutrients and chemicals from cropping and grazing lands in relatively small areas of the adjacent catchments. This diffuse pollution threatens inshore reefs and associated ecosystems.
- Because of the World Heritage values at risk, a strategy to identify, prioritise and manage risks is warranted, notwithstanding remaining scientific uncertainty about the condition of reefs and the effectiveness of remedial actions.
- Existing water quality policies largely ignore diffuse pollution and involve prescriptive end-of-pipe controls. Prescription is not the answer. Because of the complexity, heterogeneity and dispersion of the diffuse sources, and the inability to monitor them, governments cannot prescribe land management practices that are both viable and cost-effective.
- Solutions will have to be built up from local knowledge and insights, within a general framework set by the Commonwealth and Queensland Governments.
- Some primary producers (from each industry) have already demonstrated that it is possible and viable to reduce land and water degradation on their own lands. The challenge is for these practices to be more widely adopted or adapted.
- No single solution will control diffuse pollution entering the GBR lagoon. Various combinations of measures — tailored to particular land uses, locations, and pollutants

— will be necessary, giving land users flexibility to choose abatement actions best suited to their property.

- Local groups have an important role in designing and delivering programs and monitoring outcomes, but serious questions remain about the structure, transparency and accountability of proposed regional groups.
- Regional groups should not create an additional layer of complexity but instead be part of a simplified approach that is integrated with the actions of other parties, notably the Commonwealth and Queensland Governments.
- Improving downstream water quality in rivers and estuaries flowing into the GBR lagoon will generate benefits apart from reducing the threat to the Reef. But zero discharge is unnecessary and, if possible at all, would be at prohibitive cost.

1.9 Science to management- Reef Plan 2003

By 2001, the large amount of research and monitoring carried out over the previous 20 year on the GBR, and its synthesis into a coherent body of knowledge through the processes described above, was sufficient to, in the appropriate political and governance environment (see below), begin formulating a plan to manage terrestrial pollutant runoff to the GBR.

However, it still required the intervention of Senator Robert Hill, Minister for the Environment (and Heritage) 1996 – 2001 in the Australian Government and a powerful political figure within the Liberal Party, to initiate action. His decision, at a GBR Ministerial Council meeting in Cairns in early 2001, to ask for a report setting out calculated targets for pollutant reduction for the rivers of the GBR Catchment led to a group, which I led, being tasked with the target-setting process at the meeting. The group proceeded over the next few months to prepare the target report (Great Barrier Reef Catchment Water Quality Action Plan) (**Brodie et al. 2001a**) with the best available knowledge at that time. Rod Welford was the Minister for Environment & Heritage and Minister for Natural Resources in the Queensland Government from 1998 to 2001 and also contributed greatly to the subsequent agreement between the Australian and Queensland Governments over Reef Plan 2003.

This critical conjunction of the Federal Coalition Government and Queensland Labor Government in 2001 at the time that much of the science had come together (see above), and Minsters for the Environment in both governments convinced by the science and willing to act, was crucial in the formulation of the Reef Water Quality Protection Plan (Reef Plan 2003). Following this Ministerial Council meeting in 2001, through the efforts of many government scientists and environmental and natural resource managers, agricultural industry, university and research agency scientists, conservation organisations, and of particular mention, Sheriden Morris (Director, Water Quality and Coastal Development, GBRMPA) and Helen Ringrose (Queensland Government), the Reef Plan was formalised in 2003.

1.10 From Plan to action

While Reef Plan 2003 was more about a “Plan to develop a Plan” than an actual implementable Plan for on-ground actions, its symbolic importance was huge and led to substantial funding in 2008 to implement on-ground actions (**Brodie et al. 2012a**). From 2001 to the present, our knowledge of the water quality issues of the GBR and potential solutions have improved greatly through research, evaluation and monitoring. To facilitate use of this new knowledge, two further Scientific Consensus Statements were prepared in 2008 (**Brodie et al. 2008a, b**) and in 2013 (**Brodie et al. 2013a**). The statements were used to produce revised Reef Plans (Reef Plan 2009 and Reef Plan 2013). The improved knowledge brought together in 2008 can be summarised in the conclusions of the 2008 SCS as follows:

- Water discharged from rivers to the GBR continues to be of poor quality in many locations.
- Land derived contaminants, including suspended sediments, nutrients and pesticides are present in the GBR at concentrations likely to cause environmental harm.
- There is strengthened evidence of the causal relationship between water quality and coastal and marine ecosystem health.
- The health of freshwater ecosystems is impaired by agricultural land use, hydrological change, riparian degradation and weed infestation.
- Current management interventions are not effectively solving the problem.
- Climate change and major land use change will have confounding influences on GBR health.
- Effective science coordination to collate, synthesise and integrate disparate knowledge across disciplines is urgently needed.

Similarly, the 2013 SCS concluded:

- Overall the overarching consensus is that key Great Barrier Reef ecosystems are showing declining trends in condition due to continuing poor water quality, cumulative impacts of climate change and increasing intensity of extreme events. (Brodie et al. 2013a).

- The decline of marine water quality associated with terrestrial runoff from the adjacent catchments is a major cause of the current poor state of many of the key marine ecosystems of the Great Barrier Reef (Schaffelke et al. 2013).
- 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 reduces the light available to seagrass ecosystems and inshore coral reefs. Pesticides pose a risk to freshwater and some inshore and coastal habitats (Brodie et al. 2013b).
- Recent extreme weather—heavy rainfall, floods and tropical cyclones—have severely impacted marine water quality and Great Barrier Reef ecosystems. Climate change is predicted to increase the intensity of extreme weather events (Johnson et al. 2013).
- The main source of excess nutrients, fine sediments and pesticides from Great Barrier Reef catchments is diffuse source pollution from agriculture (Kroon et al. 2013).
- Improved land and agricultural management practices are proven to reduce the runoff of suspended sediment, nutrients and pesticides at the paddock scale (Thorburn et al. 2013b).

Following the allocation of large-scale funding from both the Australian and Queensland Governments in 2008 (**Brodie et al. 2012a**), on-ground management action improvements began in earnest. They included fencing in grazing lands to restrict cattle access to waterways and maintain pasture cover, and fertiliser management in sugarcane cultivation to match crop needs to fertiliser application rates to reduce fertiliser loss from the paddock to waterways. The success of these interventions and of Reef Plan in general is assessed in Chapter 10.

1.11 Thesis Plan

The following chapters of this thesis comprise 8 chapters that represent my research over the period 1984 to 2016, and a concluding chapter, as follows:

Chapter 2. Paper 1. State of knowledge in 2001.

Brodie, J., Christie, C., Devlin, M., Haynes, D., Morris, S., Ramsay, M., Waterhouse, J., Yorkston, H. 2001. Catchment management and the Great Barrier Reef. Water Science and Technology, 43 (9), 203-211.

Link to paper: http://wst.iwaponline.com/content/43/9/203.abstract

Chapter 3. Paper 2. Link between nutrient discharge and crown of thorns starfish

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

Link to paper: http://www.sciencedirect.com/science/article/pii/S0025326X04003868

Chapter 4. Paper 3. Discharge and flood plume dynamics

Brodie, J., Schroeder, T., Rohde, K., Faithful, J., Masters, B., Dekker, A., Brando, V., Maughan, M. 2010. Dispersal of suspended sediments and nutrients in the Great Barrier Reef lagoon during river-discharge events: Conclusions from satellite remote sensing and concurrent flood-plume sampling. Marine and Freshwater Research, 61 (6), 651-664.

Link to paper: http://www.publish.csiro.au/?paper=MF0803

Chapter 5. Paper 4. Linking nutrient discharges to phytoplankton dynamics

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Chapter 6. Paper 5. GBR eutrophication

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Chapter 7. Paper 6. Target setting

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Chapter 10. Here, I synthesise our current knowledge of water quality, its impacts and its management in the GBR region, the likely future of the GBR, and my contribution to the management of the water quality issue. A paper largely drawn from Chapter 10 entitled:

“Ecosystem health of the Great Barrier Reef: time for effective management action based on evidence” **(Brodie and Pearson 2016)** is now published.

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Chapter 2. Catchment management and the Great Barrier Reef. (Brodie et al. 2001b)

Abstract: Pollution of coastal regions of the Great Barrier Reef is dominated by runoff from the adjacent catchment. Catchment land-use is dominated by beef grazing and cropping, largely sugarcane cultivation, with relatively minor urban development. Runoff of sediment, nutrients and pesticides is increasing and for nitrogen is now four times the natural amount discharged 150 years ago. Significant effects and potential threats are now evident on inshore reefs, seagrasses and marine animals. There is no effective legislation or processes in place to manage agricultural pollution. The Great Barrier Reef Marine Park Act does not provide effective jurisdiction on the catchment. Queensland legislation relies on voluntary codes and there is no assessment of the effectiveness of the codes. Integrated catchment management strategies, also voluntary, provide some positive outcomes but are of limited success. Pollutant loads are predicted to continue to increase and it is unlikely that current management regimes will prevent this. New mechanisms to prevent continued degradation of inshore ecosystems of the Great Barrier Reef World Heritage Area are urgently needed.

Link to paper: http://wst.iwaponline.com/content/43/9/203.abstract

Chapter 3. Are increased nutrient inputs responsible for more outbreaks of crown-of-thorns starfish? An appraisal of the evidence (Brodie et al. 2005)

Abstract: The cause(s) of primary outbreaks of the coral-eating crown-of-thorns starfish (*Acanthaster planci*) are still subject to scientific controversy. The possibility of primary outbreaks being linked to terrestrial runoff has been postulated a number of times, suggesting that enhanced nutrient supply is critical for enhanced *A. planci* larval development. This paper examines the evidence for such a cause, focussing particularly on the Great Barrier Reef (GBR). Nutrient discharges from rivers have increased at least four-fold in the central GBR over the last century, and concentrations of large phytoplankton (>2μm) of the inshore central GBR shelf in the wet season when *A. planci* larvae develop, is double that of other places and times. Larval development, growth and survival increase almost ten-fold with doubled concentrations of large

phytoplankton. This and other lines of evidence suggest that frequent *A. planci* outbreaks on the GBR may indeed be a result of increased nutrient delivery from the land.

Link to paper: http://www.sciencedirect.com/science/article/pii/S0025326X04003868

Chapter 4. Dispersal of suspended sediments and nutrients in the Great Barrier Reef lagoon during river-discharge events: Conclusions from satellite remote sensing and concurrent flood-plume sampling (Brodie et al. 2010)

Abstract: Intense wet-season rainfall in January 2005 caused rivers in the Mackay–Whitsunday region of Queensland, Australia, to produce large discharges to the Great Barrier Reef (GBR) lagoon. The regional land use is dominated by sugarcane cultivation, beef grazing and urban uses. The high nutrient (nitrogen and phosphorus) fluxes from these land uses via river runoff produced a massive phytoplankton bloom in the GBR lagoon, which, after 9 days, had spread 150 km offshore. The plume and algal bloom surrounded inner-shelf reefs of the GBR such as Brampton Island Reef and its spread was tracked with a variety of satellite sensors including MODIS, SeaWiFS and Landsat over the 9-day period. The ability to be able to access imagery from a large number of satellite sensors allowed almost daily estimates of the extent of plume to be made, despite periods of cloud. Analysis of water samples from the plume revealed elevated (2–50 times higher) concentrations of Chlorophyll a (and hence phytoplankton biomass), up to 50 times higher than in non-flood conditions, nutrients (2–100 times higher) and herbicide residues (10–100 times higher) compared with GBR lagoon waters in nondischarge conditions. The concentration data from the samples and estimated exposure periods from the satellite images allowed estimates of the exposure of GBR marine ecosystems (coral reefs, the pelagic community, seagrass beds and mangrove forests) to the terrestrial contaminants to be made.

Link to paper: http://www.publish.csiro.au/?paper=MF0803

Chapter 5. Spatial and temporal patterns of near-surface chlorophyll a in the Great Barrier Reef lagoon (Brodie et al. 2007)

Abstract: Surface chlorophyll *a* concentrations in the Great Barrier Reef (GBR) lagoon were monitored at individual stations for periods of 6 to 12 years. The monitoring program was established to detect spatial and temporal changes in water quality resulting from increased loads of nutrients exported from the catchments adjoining the GBR. Sampling occurred monthly at up to 86 sites that were located in transects across the width of the continental shelf. In the central and southern GBR (16–21^0 S), there was a persistent cross-shelf chlorophyll *a* gradient, with higher concentrations near the coast. No cross-shelf gradient was observed in the far northern GBR (12–15^0 S). Mean chlorophyll *a* concentrations in the far northern GBR (0.23µgL^{-1}) were less than half those in the south and central GBR (0.54µgL^{-1}). Chlorophyll *a* varied seasonally within regions, with mean summer-wet season (December–April) concentrations ~50% greater than those in the winter-dry season (May–November). Sub-annual, inter-annual and event-related variations in chlorophyll *a* concentrations were observed in several zones. Multi-year patterns in concentrations suggest that relatively short (5–8 years) time series may give spurious estimates of secular trends. Higher chlorophyll *a* concentrations in inshore waters south of 16^0 S were most likely related to the levels of river nutrient delivery associated with agricultural development on adjacent catchments.

Link to paper: http://www.publish.csiro.au/?paper=MF06236

Chapter 6. Assessment of the eutrophication status of the Great Barrier Reef lagoon (Australia) (Brodie et al. 2011)

Abstract: Current scientific consensus is that inshore regions of the central and southern Great Barrier Reef, Australia, are at risk of impacts from increased nutrient (as well as sediment and pesticide) loads delivered to Reef waters. Increases in the discharge of water quality contaminants to the Reef are largely a consequence of the expansion of agricultural practices in northern Queensland catchments following European settlement in the 1850s. In particular, the presence of elevated chlorophyll a and nutrient concentrations in many parts of the inshore Great Barrier Reef together with intense and extensive phytoplankton blooms following the discharge of nutrient-rich river flood waters suggest that the central and southern inshore area of the Great Barrier Reef is likely to be significantly impacted by elevated nutrient loads. The biological consequences of this are not fully quantified, but are likely to include changes in reef condition including hard and soft coral biodiversity, macroalgal abundance, hard coral cover and coral recruitment, as well as change in seagrass distribution and tissue nutrient status. Contemporary government policy is centred around promotion and funding of better catchment management practices to minimize the loss of catchment nutrients (both applied and natural) and the maintenance of a Reef wide water quality and ecosystem monitoring program. The monitoring program is designed to assess trends in uptake of management practice improvements and their associated impacts on water quality and ecosystem status over the next 10 years. A draft set of quantitative criteria to assess the eutrophication status of Great Barrier Reef waters is outlined for further discussion and refinement.

Link to paper: http://link.springer.com/article/10.1007/s10533-010-9542-2

Chapter 7. Target setting for pollutant discharge management of rivers in the Great Barrier Reef catchment area (Brodie et al. 2009)

Abstract: Water Quality Improvement Plans (WQIPs) are being developed for individual river basins on the Great Barrier Reef (GBR) catchment associated with the GBR Water Quality Protection Plan. Within each WQIP, marine ecosystem targets are linked to end-of-river pollutant (suspended sediments, nutrients and pesticides) load targets and to farm level management practice targets. The targets are linked through quantitative models; e.g. one model connects GBR chlorophyll concentrations (marine target) to end-of-river nitrate loads, a second connects the end-of-river nitrate loads to fertiliser management targets in the catchment, whereas a third model links fertiliser application to nitrate loss at the farm scale. The difficulties of applying these linked models to derive credible and practical management targets are great, given the high degree of uncertainty in each model. Our understanding of the generation of suspended sediments, nutrients and pesticides in catchments and the relationship to on-farm management, the transport of these materials to the ocean, their transport in coastal waters and their effects on marine ecosystems is incomplete. The challenge is to produce estimates from the models, with known levels of uncertainty, but robust enough for management purposes. Case studies from the Tully–Murray basin and the Burdekin basin in north Queensland are discussed.

Link to paper: http://www.publish.csiro.au/?paper=MF08339

Chapter 8. Terrestrial pollutant runoff to the Great Barrier Reef: An update of issues, priorities and management responses (Brodie et al. 2012)

Abstract: The Great Barrier Reef (GBR) is a World Heritage Area and contains extensive areas of coral reef, seagrass meadows and fisheries resources. From adjacent catchments, numerous rivers discharge pollutants from agricultural, urban, mining and industrial activity. Pollutant sources have been identified and include suspended sediment from erosion in cattle grazing areas; nitrate from fertiliser application on crop lands; and herbicides from various land uses. The fate and effects of these pollutants in the receiving marine environment are relatively well understood. The Australian and Queensland Governments responded to the concerns of pollution of the GBR from catchment runoff with a plan to address this issue in 2003 (Reef Plan; updated 2009), incentive-based voluntary management initiatives in 2007 (Reef Rescue) and a State regulatory approach in 2009, the Reef Protection Package. This paper reviews new research relevant to the catchment to GBR continuum and evaluates the appropriateness of current management responses.

Link to paper: http://www.sciencedirect.com/science/article/pii/S0025326X11006503

Chapter 9. A critical review of environmental management of the 'not so Great' Barrier Reef (Brodie and Waterhouse 2012)

Abstract: Recent estimates put average coral cover across the Great Barrier Reef (GBR) at about 20-30%. This is estimated to be a large reduction since the 1960s. The Great Barrier Reef Marine Park Act was enacted in 1975 and the Great Barrier Reef Marine Park Authority (GBRMPA) set up shortly afterwards. So the question is: why has coral cover continued to decline when the GBR is being managed with a management regime often recognised as 'the best managed coral reef system in the world', based on a strong science-for-management ethic. The stressors which are known to be most responsible for the loss of coral cover (and general 'reef health') are terrestrial pollution including the link to outbreaks of crown of thorns starfish, fishing impacts and climate change. These have been established through a long and intensive research effort over the last 30 years. However the management response of the GBRMPA after 1975, while based on a strong science-for-management program, did not concentrate on these issues but instead on managing access through zoning with restrictions on fishing in very limited areas and tourism management. Significant action on fishing, including trawling, did not occur until the Trawl Management Plan of 2000 and the rezoning of the GBR Marine Park in 2004. Effective action on terrestrial pollution did not occur until the Australian Government Reef Rescue initiative which commenced in 2008. Effective action on climate change has yet to begin either nationally or globally. Thus it is not surprising that coral cover on the GBR has reduced to values similar to those seen in other coral reef areas in the world such as Indonesia and the Philippines. Science has always required long periods to acquire sufficient evidence to drive management action and hence there is a considerable time lag between the establishment of scientific evidence and the introduction of effective management. It can still be credibly claimed that the GBR is the best managed coral reef system in the world but it must be realised that this is a relative assessment against other reef systems and management regimes and not an absolute claim for effective management.

Link to paper: http://www.sciencedirect.com/science/article/pii/S0272771412000856

Chapter 10. Ecosystem health of the Great Barrier Reef: time for effective management action based on evidence.

10.1 Introduction

As I demonstrated in Chapter 1, in the eight papers included as Chapters 2 to 9 and in appendices 1 and 2 [publication lists], I have had a major role in research on land-based water quality deterioration on the Great Barrier Reef, in development of management guidelines, and in management application. The papers that make up the main body of this thesis provide a sample of that involvement. Briefly, their content is as follows.

Chapter 2, Paper 1. *State of knowledge in 2001 (**Brodie et al. 2001a**)*

In this paper we reviewed the state of knowledge and progress in catchment management for the GBRCA as a contribution to the development of the Reef water Quality Protection Plan. My presentation to the GBR Ministerial Council, including Senator Robert Hill, the Federal Minister for the Environment, on the substance of this paper led to the decision to set the first targets for river pollutant discharge to the GBR (**Brodie et al. 2001b**) and eventually to Reef Plan 2003.

Chapter 3, Paper 2. *Link between nutrient discharge and crown-of-thorns starfish (**Brodie et al. 2005**)*

In this paper we built on my analysis of the links between crown-of-thorns starfish (COTS) outbreaks on the GBR and nutrient enrichment of the GBR lagoon (**Brodie 1992**) using a "weight of evidence approach" to show that this hypothesis best explained the increased frequency of COTS outbreaks observed since 1962. The hypothesis was further validated given the occurrence of the fourth wave of COTS outbreaks on the GBR in 2010 (**Wooldridge and Brodie 2015**) as predicted. This work was a key element in supporting the need for nutrient management on the GBRCA including fertiliser management and erosion control.

Chapter 4, Paper 3. *Discharge and flood plume dynamics (**Brodie et al. 2010**)*

In this paper we analysed the distribution of flood plumes in the Mackay Whitsunday region of the GBR and the processes occurring within plumes that contribute to the exposure of Reef ecosystems to terrestrial pollutants. This work, in association with many other flood plume studies in which I was involved (**Brodie and Mitchell 1992; Brodie 1996; Brodie and Furnas 1996; Brodie et al. 1997; Devlin et al. 2001, 2003; Devlin and Brodie 2005; Devlin et al. 2012, 2013,**

2015; Schroeder et al. 2012; Alvarez-Romero et al. 2013), has quantified the extent of influence (and possible impacts) of river discharged pollutants in the GBR.

Chapter 5, Paper 4. *Linking nutrient discharges to phytoplankton dynamics (**Brodie et al. 2007**)*

Chlorophyll is a well-recognised indicator of phytoplankton biomass in both fresh and marine water bodies. In association with scientists from the Australian Institute of Marine Science (AIMS), tourism operators, Marine Parks staff and community volunteers I organised and initiated a GBR-wide chlorophyll monitoring program in 1991 while running the water quality program of GBRMPA. Initial results from the monitoring program were published in 1997 (**Brodie et al. 1997**) and the complete results and interpretation of the spatial trends in chlorophyll from 1991 – 2006 were published in this paper. The results were then used to assess the relationships between water quality parameters such as chlorophyll and coral biodiversity and macroalgae on the Great Barrier Reef (De'ath and Fabricius 2010). The results were also crucial in the setting of water quality guidelines for the waters of the GBR (**Moss et al. 2005**; De'ath and Fabricius 2008; Great Barrier Reef Marine Park Authority 2010).

Chapter 6, Paper 5. *GBR eutrophication (**Brodie et al. 2011**)*

Anthropogenic eutrophication is a somewhat loaded term used to describe aquatic systems in which the functioning of ecosystems has been degraded by increased nutrient input. The criteria used to decide whether a marine system is eutrophic derive from studies in temperate seas and are less relevant in a tropical coral reef system. In this paper we designed a set of eutrophication criteria more suited to assessment of tropical coral reef systems and applied the criteria to the GBR. In summary, we concluded that the GBR is eutrophic at certain times and places. However, conflicting views as to the state of eutrophication of the GBR continue (Bell et al. 2014a,b; Furnas et al. 2014).

Chapter 7, Paper 6. *Target setting (**Brodie et al. 2009**)*

While targets for river pollutant discharge to the GBR have been set previously (Brodie et al. 2001b; Queensland Department of Premiers and Cabinet 2009, 2013), they have mostly not taken into account the desired ecological status of the focus of pollution controls – the GBR. In this paper we began the process of designing ecologically relevant targets for individual drainage basins of the GBR (see also **Wooldridge et al. 2006**). This study has been used subsequently to set targets for regional Water Quality Improvement Plans (**Brodie and Lewis 2014; Brodie et al.**

2014a, 2015, 2016), for nutrient targets in the Wet Tropics (**Wooldridge et al. 2015**) and as a general methodology developed for use across the GBR (**Brodie et al. in press**).

Chapter 8, Paper 7. *State of knowledge in 2012 (cf. Chapter 2) (**Brodie et al. 2012**)*

This paper comprised a review of our knowledge of the water quality issues and their management for the GBR in 2012. It reprised the similar analysis carried out in 2001 (**Brodie et al. 2001a**) – Chapter 2 of this thesis – and to some extent was a precursor to the 2013 Scientific Consensus Statement of water quality and the GBR (**Brodie et al. 2013a**). To a large extent the message across all three publications was consistent, as explained in Chapter 1.

Chapter 9, Paper 8. *Management of the GBR (**Brodie and Waterhouse 2012**)*

In this paper we analysed the success of management of the GBR, focussing on water quality, but also examining the record of fisheries management and climate change. Given the poor state of the GBR shown in the 2014 Outlook Report (Great Barrier Reef Marine Park Authority 2014) the paper was prophetic in demonstrating that management had largely failed, despite the management regime being regarded as world's best practice.

Chapter 10

In this final chapter I review how my contributions and those of the rest of the research community have been progressively rolled out to improve management of the GBR. I assess progress in water quality management under Reef Plan from its development in 2003 through to 2016, likely progress over the period of the Reef 2050 Long Term Sustainability Plan (LTSP) from 2015 – 2025 and whether this progress (and other management actions) are likely to provide adequate resilience for the GBR in the face of the overwhelming effects of climate change which will become evident after about 2025. The main body of this chapter is now published (**Brodie and Pearson 2016**).

10.2 Status of selected species and ecosystems of the GBR

10.2.1 Key World Heritage value species and ecosystems

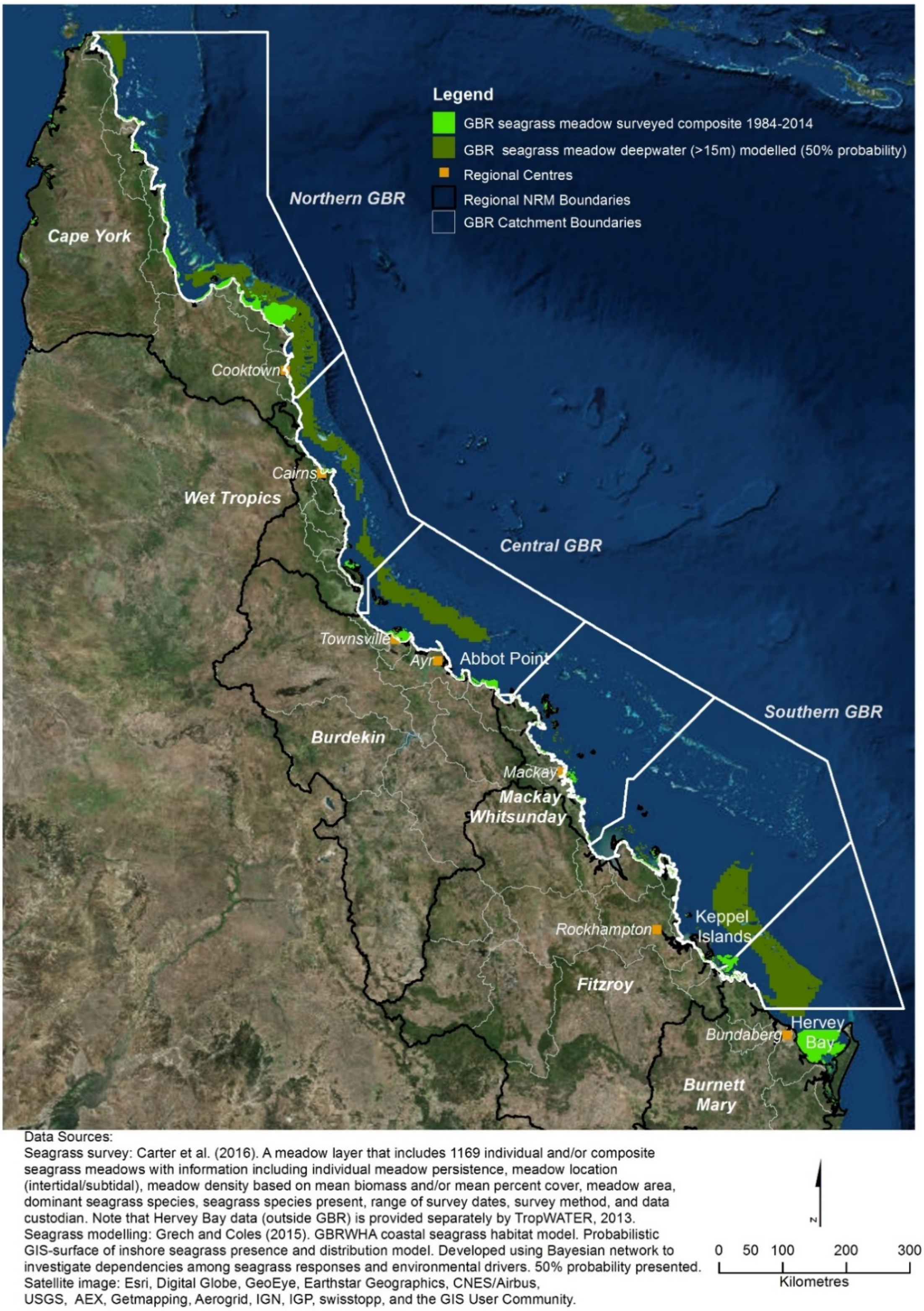
Here I use five "iconic" species groups to assess the status of the GBR and the success of the current GBR management regime: the corals themselves, the seagrass meadows, the dugongs, the mangroves and the turtles (Day 2011) (Figure 1).

10.2.2 Coral reefs

Coral cover (an indicator of coral reef status) on the GBR has declined markedly in the period since the 1960s from values near 45 - 55 percent on mid and outer shelf reefs in the 1960s (**Hughes et al. 2011**), to 28 percent in 1986 (Sweatman et al. 2011) and 14 percent in 2011 (De'ath et al., 2012). On the inner-shelf reefs, although our record is shorter (8 years), similar declines have been recorded (Thompson et al. 2014). Coral decline has been minor in the Torres Strait section of the GBR with cover remaining in the 40 – 50% range (Sweatman et al. 2015) and on northern Cape York, where coral cover remains above 30% (**Coppo et al. 2016**), although the recent major coral bleaching in these areas will have reduced coral cover (Normile 2016). This contrasts with coral cover on monitored reefs south of Cape York being approximately 11% (De'ath et al. 2012). In addition, calcification rates have declined across the central GBR as a result of thermal stress and some ocean acidification on mid- and outer-shelf reefs (De'ath et al. 2009), but on inner-shelf reefs terrestrial runoff also plays a part (D'Olivo et al. 2013). There are many causes of the decline of coral cover, often quite reef-specific, including: terrestrial runoff of fine sediment (with associated nutrients) causing more turbid conditions on the inner shelf and reducing light availability for coral growth (**Fabricius et al. 2014, 2016**); nutrient runoff from soil erosion and fertiliser loss causing crown-of-thorns starfish outbreaks (**Brodie et al. 2005**; Fabricius et al. 2010; **Wooldridge and Brodie 2015**), excess algal growth (De'ath and Fabricius 2010), enhanced sensitivity to coral bleaching (Wooldridge and Done 2009), and coral diseases (Haapkyla et al. 2011); coral bleaching and mortality associated with climate change (Hughes et al. 2007; Normile 2016); and increasing incidence of category 4 and 5 cyclones, which appears to have occurred over the last decade and is predicted to continue under climate change (Walsh et al. 2016). Rainfall extremes – and more frequent and larger river discharge events – are also predicted to increase with an increase in the frequency of La Nina periods (Cai et al. 2015), potentially casing further severe impacts on GBR ecosystems.

10.2.3 Seagrass

Seagrass health and abundance is very variable in space and time in the GBR (Coles et al. 2007). This variability constrains our knowledge of the extent and biomass of seagrass in the GBR at any fixed time, in contrast to coral reefs, which are much more structurally stable. Analysis of areas of the GBR suitable for seagrass has been carried out by Grech and Coles (2010) and these



Data Sources:
Seagrass survey: Carter et al. (2016). A meadow layer that includes 1169 individual and/or composite seagrass meadows with information including individual meadow persistence, meadow location (intertidal/subtidal), meadow density based on mean biomass and/or mean percent cover, meadow area, dominant seagrass species, seagrass species present, range of survey dates, survey method, and data custodian. Note that Hervey Bay data (outside GBR) is provided separately by TropWATER, 2013.
Seagrass modelling: Grech and Coles (2015). GBRWHA coastal seagrass habitat model. Probabilistic GIS-surface of inshore seagrass presence and distribution model. Developed using Bayesian network to investigate dependencies among seagrass responses and environmental drivers. 50% probability presented.
Satellite image: Esri, Digital Globe, GeoEye, Earthstar Geographics, CNES/Airbus, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopp, and the GIS User Community.

Figure 1. The Great Barrier Reef showing the mapped extent of potential seagrass meadows from monitoring (Carter et al. 2016) and modelled as 50% probability of occurrence (Grech and Coles 2015) and coral reefs in the Great Barrier Reef World Heritage Area, catchments and major rivers and major cities and towns. Satellite image supplied by ESRI.

modelled results at 50% occurrence probability have been combined with in-situ survey results (Carter et al. 2016) to produce the combined seagrass extent seen in Figure 1.

Recently, there is strong evidence that seagrass is declining in parts of the GBR (McKenzie et al. 2015; Coles et al. 2015), particularly in the Townsville region (McKenzie et al. 2010; Petus et al. 2014); Cairns region (Rasheed and Unsworth 2011; McKenna et al. 2015); Abbot Point region (Rasheed et al. 2014) and several other locations, associated with a series of severe cyclones and large river flood events (Coles et al. 2015). Degraded light regimes from increased turbidity are the driver of declining seagrass abundance in many sites (e.g. Petus et al. 2014). For example, the 2011 major river discharge events from many of the GBR rivers associated with the strong La Nina and the effects of Category 5 Tropical Cyclone Yasi have had devastating effects on large areas of GBR seagrass (**Devlin et al. 2012**). However, seagrass is now recovering along many parts of the coast as there has been a series of low-discharge years during the El Nino conditions. For example, in Cleveland bay/Townsville (Davies and Rasheed 2016) seagrass meadow area has increased each year since 2011. Port dredging may have severe but shorter-term effects on seagrass in locations in the GBR such as at Hay Point near Mackay, where turbidity from dredging is believed to have prevented seasonal re-establishment of deep-water seagrass, although recovery occurred in later years after the dredging ceased (York et al. 2015). Seagrass is also in decline on southern Cape York as a result of damage from Cyclone Nathan (Category 5) (**Coppo et al. 2016**). In contrast, seagrass in Hervey Bay to the south of the GBRWHA boundary is still in fair condition despite major discharge events in 2011 and 2013 from the Mary and Burnett Rivers (**Coppo et al. 2014**).

10.2.4 Mangroves

While mangrove forests worldwide are under increasing pressure from a range of anthropogenic threats (Duke 2014), mangroves along the whole GBR coast are generally in excellent condition and relatively stable, with only small losses reported, mostly associated with port and urban development (Great Barrier Reef Marine Park Authority 2009). Mangrove and saltmarsh habitats cover an area of approximately 3,800 km^2 along the GBR coast (Goudkamp and Chin 2006). Given their importance to so many commercial fisheries (Sheaves et al. 2012), it is vital to maintain protection of this asset.

10.2.5 Dugongs

Dugong numbers have declined precipitously over recent decades, at a rate of 8.7 percent a year between 1962 and 1999, from about 72,000 to 4,000 animals, across the central and southern GBR (16.5 to 28 ^{0}S) (Marsh et al. 2005) with a further decline to 600 animals in this same area following the severe weather events of 2011 (Sobtzick et al. 2012). Causes of mortality include incidental netting in fish and shark nets, loss of seagrass habitat due to water quality impacts and coastal development, and legal hunting (Marsh et al. 2005, 2007). Severe weather events in 2011 (**Devlin et al. 2012**) also increased dugong mortality, but the long-term effects of these events combined with existing stresses are not yet known.

Dugong populations are in best condition in Hervey Bay beyond the southern end of the GBR (**Coppo et al. 2014**) and in the northern GBR (north of 17°S) and the Torres Strait (Sobtzick et al. 2014), while there are much smaller populations remaining in the central and southern GBR (Grech et al. 2011). The Torres Strait region between mainland Australia and Papua New Guinea (Figure 2) supports the largest recorded single continuous seagrass meadow in Australia (Carter et al. 2014) and is the most important dugong habitat in the world (Marsh et al. 2011). Dugongs primarily occur in a large, central area that extends south of Boigu Island to north of Badu and Moa Islands; and west of Badu and Muralug Islands (Grech et al. 2011; Sobtzick et al. 2014).

10.2.6 Turtles

The population structure, distribution, range and status of the six species of marine turtles found in the region have been well documented (Hamann et al. 2007). All six species are listed as threatened under Queensland and Federal legislation and the International Union for Conservation of Nature and Natural Resources (IUCN) Red List. Long-term census data on Green turtle (*Chelonia mydas*) populations indicate that although significant declines in population size are not apparent, other biological factors such as declining annual average size of breeding females, increasing remigration interval and declining proportion of older adult turtles in the population may indicate populations at the beginning of a decline (Limpus et al. 2003). In Queensland, the population of Loggerhead turtles, *Caretta caretta*, has been monitored annually since the late 1960s and has undergone a substantial and well documented decline in the order of 85 percent in the last three decades (Limpus and Limpus 2003). Long-term monitoring data collected for the eastern Australian population of Flatback turtle (*Natator depressus*) show no signs of a declining population (Limpus et al. 2000). No Leatherback turtle (*Dermochelys coriacea*) nests have been reported in Queensland since 1996, despite annual nesting surveys for Loggerhead turtles that use the same beaches (Hamann et al. 2006). Data on Hawksbill turtles (*Eretmochelys imbricate*) in Queensland waters is limited but currently it is known that large declines in the population have occurred in recent years (I. Bell pers. com.). Mortality of Green turtles increased greatly in the year after the large flood and cyclone events of 2011 (**Devlin et al. 2012**) with many turtles appearing to be starved. Fibropapilloma virus is also present in GBR Green turtle populations, the causes of which is being investigated (**Brodie et al. 2014b**).

10.2.7 Overall assessment

The joint Australian and Queensland governments' water quality report card on the health of the GBR in relation to contaminant runoff from rivers found most aspects of marine condition (water quality, seagrass and coral) to be in very poor to moderate condition (Queensland Department of the Premier and Cabinet, 2014). This assessment confirms the Great Barrier Reef Marine Park Authority's five-yearly Outlook Report (Great Barrier Reef Marine Park Authority 2014a) which found with respect to species and ecosystems:

> "The assessments of biodiversity and ecosystem health show that the northern third of the Great Barrier Reef Region has good water quality and its ecosystem is in good condition. In contrast, key habitats, species and ecosystem processes in central and southern inshore areas have continued to deteriorate from the cumulative effects of impacts. For example, the population of the iconic and culturally important dugong, which was already at very low levels compared with a century ago, has declined further in this part of the Region. There are good examples of species continuing to show recovery after past significant declines. Populations of humpback whales, estuarine crocodiles, loggerhead turtles and the southern stock of green turtles are all increasing."

From these and other assessments of the status of the GBR, it can be concluded that many of the key species and ecosystems inside the central and southern GBRWHA – particularly corals, seagrasses and dugongs – are in poor condition and on a generally declining trend, whereas most of these same species and ecosystems are in good condition in the Torres Strait, northern GBRWHA and, for seagrass, dugongs and turtles, in Hervey Bay (**Chapter 1; Brodie and Waterhouse 2012; Coppo et al. 2014, 2016**; Great Barrier Reef Marine Park Authority 2014a; Marsh et al. 2015; Sweatman et al. 2014, 2015).

10.3 Issues and stressors for the GBR

The GBR's diverse array of ecosystems is being affected by the cumulative impacts of multiple human stressors (summarised in **Chapter 1**). The Great Barrier Reef Marine Park Authority (2014a) has identified the primary stressors as unsustainable fishing, agricultural and urban pollutant runoff, coastal development including urban, tourism and large port development, and rapid climate change causing sea-level rise, increasing seawater temperatures and ocean acidification. These stressors are steadily increasing and set to grow rapidly in the future under current global carbon-management and energy policies. They operate via various mechanisms (**Brodie et al. 2012, 2013a**; Great Barrier Reef Marine Park Authority 2014a; **Hughes et al. 2015; Waterhouse et al. 2016**) including: land-sourced pollution of sediment (**Fabricius et al. 2014, 2016**), nutrients (with the associated crown-of-thorns starfish outbreaks), (**Brodie et al. 2005 , 2011** ; De'ath and Fabricius 2010 ; Fabricius et al. 2005 , 2010) and pesticides (**Lewis et al. 2009**); coral bleaching/mortality and physical damage associated with climate change including increasing incidence of severe storms (cyclones) (Osborne et al. 2011 ; De'ath et al. 2012; Beeden et al. 2015); ocean acidification (Cooper et al. 2008 ; De'ath et al. 2009; 2013); and coral diseases (Haapkylä et al. 2011). Several recent large river discharge events have caused acute mortality to coastal reefs through low salinity and polluted water ((Jones and Berkelmans 2014; Butler et al. 2013, 2015; **Devlin et al. 2012**).

Seagrass health and abundance is also under anthropogenic threat (Grech et al. 2011), with recent declines associated with large river discharges of polluted water (Petus et al. 2014) and severe cyclones (Rasheed et al. 2014). The 2010/11 major river discharge events from GBR rivers associated with the strong La Nina and Tropical Cyclone Tasha intense rainfall, and the physical effects of Category 5 cyclones (e.g. Tropical Cyclone Yasi), have had devastating effects on large areas of GBR seagrass (**Devlin et al. 2012**) and subsequent increased mortality of dugongs and turtles, which depend on the seagrass for food.

10.4 Management of the GBR

10.4.1 Zoning

Zoning of the GBRMP was one of the initial primary means of management of activities within the Park (Day 2011). By the late 1990s it was realised that the area of the Park closed to extractive activities (in particular fishing) was likely inadequate for the stated "long-term protection" component of the overall aims for the management of the Park: *"The long-term protection, ecologically sustainable use, understanding and enjoyment of the Great Barrier Reef for all Australians and the international community, through the care and development of the Marine Park"* (http://www.gbrmpa.gov.au/about-us/strategic-plans/statement-of-expectations). To remedy this perceived deficiency in management approach the GBR was re-zoned in 2004 so as to include a much larger area of "no-take" zones where extractive activities were forbidden (Fernandes et al. 2005). It was also considered that there were insufficient "highly protected areas" to represent the full biodiversity of the GBR and so the re-zoning was specifically based on the 70 bioregions of the GBR developed during the re-zoning process. The re-zoning was seen as a primary biodiversity conservation measure as well as being a means to manage fishing (McCook et al. 2010; Kenchington and Day 2011).

10.4.2 Water quality plans at GBR scale

Reef Plan 2003 (Queensland Department of the Premier and Cabinet, 2003) aimed to halt and reverse the decline in water quality entering the Reef within 10 years, and strictly focused on diffuse pollution from agriculture. To achieve its aim, the Plan stated two objectives: (i) Reduce the load of pollutants from diffuse sources in the water entering the Reef, and (ii) Rehabilitate and conserve areas of the Reef catchment that have a role in removing water borne pollutants. The plan outlines a set of activities to be carried out by multiple participants that would lead to a schedule of on-ground activities.

Following the establishment of Reef Plan in 2003 a series of research, monitoring, planning, communication and agricultural extension actions were initiated (or continued) but no funding for major on-ground works was committed before 2008 (**Brodie et al. 2012**).

In 2007, the new Federal Labor Government implemented Reef Rescue, an AU $200 million investment for on-ground works, monitoring, research and partnerships over 5 years (Australian Government, 2007). The objective was to improve the water quality of the GBR lagoon by increasing the voluntary adoption of land management practices that reduce the run-off of nutrients, pesticides and sediments from agricultural land. Reef Rescue was developed following an initiative by the Reef Water Quality Partnership, which included agricultural industries, regional NRM bodies and natural resource and environment managers. It built on key activities conducted under Reef Plan, including the development of local and regional Water Quality Improvement Plans (e.g. Dight, 2009), and the Nutrient Management Zones process (**Brodie, 2007**).

In 2009, Reef Plan 2003 was revised and updated (Queensland Department of the Premier and Cabinet, 2009) following a new Scientific Consensus Statement (**Brodie et al. 2008a, b**), with GBR-wide pollutant load targets (see Chapter 1) and better defined management actions in line with Reef Rescue. In addition to Reef Plan's 2003 aims, Reef Plan 2009 also aimed to ensure that by 2020 the quality of water entering the GBR from adjacent catchments would have no detrimental impact on the health and resilience of the GBR. Reef Plan 2009 included targets and goals for water quality improvement and management practice change by 2013 and 2020.

In 2009, the Queensland Government introduced the Great Barrier Reef Protection Amendment Act 2009 (also known as the Reef Protection Package – **Brodie et al 2012**). The Act includes regulations to improve the quality of water entering the GBR, and applies to sugarcane-growing and cattle-grazing properties in the Burdekin Dry Tropics, Wet Tropics and Mackay-Whitsunday Regions in northern Queensland. In these areas, the Act provides for the implementation of (i) Farm Environmental Risk Management Plans in sugarcane cultivation and beef grazing, (ii) Fertiliser management in sugarcane through a "calculator" for sustainable fertiliser rates, (iii) Erosion management in grazing through managing pasture cover, and (iv) Pesticide management through application management and buffer strips. The Act and its regulations were implemented during 2010 and 2011.

Under a new policy framework of the Queensland Government in 2012, implementation of the Act's regulations was largely suspended, although the Act was not repealed, and policy shifted to promoting a voluntary industry-led Best Management Practice (BMP) approach known as Smartcane BMP in sugarcane cultivation and Grazing BMP in beef grazing –

https://www.qld.gov.au/environment/agriculture/sustainable-farming/best-practice/

Under a new Queensland Government, beginning in 2015, the BMP approach is still in place, although moves to reintroduce enforcement of the Act and its regulations are under consideration.

A further update of Reef Plan, following the 2013 Scientific Consensus Statement **(Brodie et al. 2013a)**, led to Reef Plan 2013 (Queensland Department of the Premier and Cabinet, 2013). For Reef Plan reporting purposes, new targets were set for anthropogenic loads (i.e., current loads minus pre-European loads). The Reef Plan 2013 load targets, to be achieved by 2018, are as follows:

i) At least a 50 per cent reduction in anthropogenic end-of-catchment dissolved inorganic nitrogen loads in priority areas.

ii) At least a 20 per cent reduction in anthropogenic end-of-catchment loads of sediment and particulate nutrients in priority areas.

iii) At least a 60 per cent reduction in end-of-catchment pesticide loads in priority areas.

The pesticide regulations are of particular interest in that the Queensland Government has largely moved ahead of the Australian Government pesticide regulatory regime by introducing strong management measures for the GBR which have not been enforced in other parts of Australia (see **Chapter 1**) (**King et al. 2013**).

10.5 Progress under the current management plans

10.5.1 Overall condition

Despite the impressive management system in place for the GBR, the success of the management regime in halting the decline of many species and ecosystems in the GBR is mixed (summarised in **Brodie and Waterhouse 2012**; Great Barrier Reef Marine Park Authority 2014a).

Recent data indicates that turtle population are declining, particularly after recent large-scale flooding. Whales (humpbacks in particular) are slowly increasing in numbers after the cessation of most commercial whaling. There has been little loss of mangroves because of strong prohibitions on damaging marine plants under the Queensland Fisheries legislation. However, saltmarsh has not been so well protected (Wegscheidl et al. 2014) and coastal wetlands in general are in need of further protection and restoration (Sheaves et al. 2014; **Waterhouse et al. 2015**).

Sewage effluent discharges from resort islands and mainland cities and towns have been improved greatly. Strong action on shipping management for compulsory pilotage and navigation equipment may have prevented many shipping accidents but ships still run on to the reef every decade or so. Water quality may have started to improve with the very recent programs under the Reef Plan policy addressing river pollutant discharges (**Brodie et al. 2012, 2013a**), but the success of the Reef Plan is still uncertain and there will be no real proof of this for some time, mainly due to the scale of the management area and associated resource implications, and time lags in the system response to land management change. Current progress under the Reef Plan is summarised in an annual report card (e.g. Queensland Department of the Premier and Cabinet 2014). Over this period, the modelling, which removes the time lags in management practice effectiveness, indicates that the adoption of improved land management practices reduced loads of suspended sediment by 11%, total phosphorus by 13%, total nitrogen by 10% and PSII-inhibiting herbicides by 28% to the GBR lagoon (Waters et al. 2014). Despite these efforts, a large proportion of agricultural land in priority areas (up to 75–80% in some regions) is still managed below best management practice standards (Queensland Department of the Premier and Cabinet 2014).

Conversely, coral cover has declined greatly (De'ath et al., 2012; Thompson et al. 2014), seagrass health in the central GBR is mostly in poor condition, dugong numbers have declined precipitously, shark populations are in serious decline (although perhaps recent management has reduced the rate of decline), many other large fish on the GBR have had large population declines (although data on many are incomplete) and the fourth wave of crown-of-thorns starfish outbreaks is in progress (**Wooldridge and Brodie 2015**). Most notably, coral bleaching has become more frequent, widespread and damaging (Great Barrier Reef Marine Park Authority 2014a; Normile 2016) and coral calcification has started to decline due to ocean acidification (e.g. De'ath et al. 2009). Rapid port expansion with dredging of entry channels (**Grech et al. 2013**) and associated increases in shipping traffic linked to the growth of the mining industry in Australia raise significant concerns for the long-term health of the GBR (**Hughes et al. 2015**), with increased potential for fauna strikes and a greater risk of major shipping incidents occurring in the GBR.

The reasons for this apparent failure of effective management are complex but include the need for reasonably 'certain' science before management action occurs (Chapter 1), and the long time needed to achieve this (**Brodie and Waterhouse 2012**). Time lags in recovery after management action are long. For a slow-breeding animal like a dugong (one calf every few years), population recovery is a very slow process. Catchment management activities such as reafforestation of riparian areas or rehabilitation of degraded land take decades to reduce erosion and river sediment loads. The likelihood of effective reduction in global greenhouse gas emissions such that temperature change associated with climate change can be limited to a maximum of two degrees also seems remote although the recent Paris agreements (http://www.cop21.gouv.fr/en/), if implemented, may limit temperature rises to less than a catastrophic four degrees.

10.5.2 Zoning

There have been notable successes in recent times after the major rezoning of 2004 (Fernandes et al. 2005), which increased the percentage of "no-take zones" from 5% of reefs to 30%, with new no-take zones showing increased fish populations (Emslie et al. 2015; Williamson et al. 2014) but also apparent effects on crown-of-thorns starfish populations (McCook et al. 2010; Sweatman 2008) with fewer starfish in no-take zones. However, major floods have removed much of the positive effect on coral health in the no-take zones in the Keppel Island regions (Wenger et al. 2016), showing that integrated management of fishing, terrestrial pollution and other stresses is needed to maintain healthy reef condition (Almany 2015). Recent analyses show little effect of no-take zones on reef biodiversity, as opposed to particular fish populations (Emslie et al. 2015; Sweatman et al. 2015). No-take zones can have positive benefits in reducing the incidence of coral diseases and in providing resilience against even major disturbances such as Cyclone Yasi (Lamb et al. 2016), but poor water quality associated with major flooding removed this resilience. Therefore, while the major rezoning program of 2004 (Fernandes et al. 2005) has had major successes in increasing coral trout populations, it has had little positive effects on coral cover and some limited effects on general reef biodiversity and reef resilience (Mellin et al. 2016). The effects of the zoning associated with restrictions on prawn trawling are likely to be greater for general biodiversity (Pears et al. 2012) than the no-take zones in the line fisheries.

As the zoning has only been in place for 11 years, further positive effects on biodiversity may yet be demonstrated. Hence it is important to continue monitoring the effects of the zoning and enforcement of the plans.

10.5.3 Water quality

The effectiveness of Reef Plan, Reef Rescue and the Reef Protection Package is being assessed using an integrated monitoring, assessment and reporting program – the Paddock to Reef Program (Carroll et al., 2012; Waters et al. 2014). The program commenced in 2009 and the first report card was released in 2011 with regular updates through to 2014 (Queensland Department of the Premier and Cabinet 2014). The program is built around a number of components including (a) monitoring and auditing of management practice adoption; (b) paddock monitoring and modelling, involving collecting runoff during rainfall events and rainfall simulation (modelling is used to extend results to situations that are not part of the monitoring scheme); (c) catchment monitoring (Turner et al 2013; Wallace et al. 2014; Garzon-Garcia et al. 2015) and modelling (Waters et al. 2014) to assess the water quality entering the GBR lagoon and to determine trends in water quality over time; identifying potential source areas of contaminants; linking plot to paddock to river scales; and validating and calibrating the catchment models being used (e.g. Source Catchments); (d) marine monitoring including biological monitoring of inshore coral reefs (Thompson et al. 2014) and intertidal seagrass meadows (McKenzie et al. 2015), and inshore water quality and flood plume monitoring focussing on total suspended solids, nutrients, chlorophyll a, salinity, pesticides, temperature, turbidity and light conditions (Queensland Department of the Premier and Cabinet 2014).

The latest Report Card for 2013/14 (Queensland Department of the Premier and Cabinet 2014) shows the following progress. As at June 2014 the area of land managed using best management practice systems for each industry across the Great Barrier Reef was:

- Sugarcane—approximately 13 per cent for nutrients (60,000 hectares), 30 per cent for pesticides (123,000 hectares) and 23 per cent for soil (101,000 hectares).
- Grazing erosion—approximately 28 per cent for pastures (8.6 million hectares), 47 per cent for streambanks (14.5 million hectares) and 24 per cent for gullies (7.4 million hectares).
- Horticulture—approximately 23 per cent for nutrients (20,000 hectares), 45 per cent for pesticides (39,000 hectares) and 71 per cent for soil (61,000 hectares).

Other changes were as follows:

- The grains pesticide reduction target was exceeded (91 per cent) in the Burdekin region.
- Overall loss of wetlands continued between 2009 and 2013 (330 hectares, less than 0.1 per cent), although the rate of loss was lower than in the previous periods.
- Overall forest loss in riparian areas continued between 2009 and 2013 (31,000 hectares, 0.4 per cent), with an increased rate of loss compared to the previous periods.
- The ground cover target was exceeded across all regions in 2013–2014. However, there were significant areas of low cover, which pose a high risk for sediment loss, particularly in areas of the Burdekin and Fitzroy regions that were drought declared.
- Modelled annual average load reductions across the Great Barrier Reef from 2009 to 2014 were:
    - sediment, 12 per cent
    - particulate nitrogen, 11.5 per cent
    - particulate phosphorus, 14.5 per cent
    - dissolved inorganic nitrogen, 17 per cent
    - pesticides, 30.5 per cent
    - particulate phosphorus – the target was exceeded (20.5 per cent) in the Wet Tropics region.

The load reductions were largely driven by funding for management practice change from the Australian Government's Reef Rescue program and associated extension and regulatory approaches from the Queensland Government (see **Brodie et al. 2012**). However, many farmers are not taking up best management practices even when funding is available. Motivation and risk factors are key reasons for differences in adoption rates in the pastoral industry (Greiner and Gregg 2011; Rolfe and Gregg 2015) as well as limited or negative financial benefits for landholders (Rolfe and Gregg 2015).

Progress towards other targets (proportion of farmers using best management practices, wetland extent, riparian vegetation extent, and the status of a series of marine indicators) are also reported in the 2014 Report Card (Queensland Department of the Premier and Cabinet 2014).

10.5.4 Climate change

Direct solutions to climate change issues, such as emissions controls in Australia or globally, are not under the control of the any of the legislation applying to the GBR. However global action on climate change is now well under way with the global achievement of the Paris agreements in 2015 (COP21 2015) to which Australia is a signatory. However, greenhouse gas emissions and climate change are seen as some of the most important issues facing the GBR over the next 50 years (Great Barrier Reef Marine Park Authority 2014a). Effects of climate change are already causing impacts on the GBR (Great Barrier Reef Marine Park Authority 2014a), through unprecedented broad-scale bleaching events in 1998 and 2002 (Berkelmans et al. 2004; Hoegh-Guldberg et al. 2007), and 2016 (Great Barrier Reef Marine Park Authority 2016; Normile 2016); reduced thermal tolerance of corals to bleaching (Ainsworth et al. 2016); and, possibly, a period of extreme weather from 2006 to 2014 with a series of category 4 and 5 cyclones contributing to extensive coral loss (De'ath et al. 2012), polluted flood waters discharging into the GBR causing extensive loss of coral cover on inner-shelf reefs (e.g., Wenger et al. 2016) and loss of seagrass meadows and the dugongs, which feed on the seagrass (Devlin et al. 2012; McKenzie et al. 2015). The year 2015 was the hottest on record globally (Tollefson 2016) following the previous record set in 2014, and the month of February 2016 was the hottest February on record globally (NASA 2016). These temperature extremes associated with climate change, combined with the current (2016) El Nino conditions, are causing mass coral bleaching across the tropical Pacific Ocean and the GBR (Normile 2016), with current (February-April 2016) bleaching categorised as Very Serious from Cairns north to Torres Strait on the GBR, and Severe in the Torres Strait (Normile 2016); Severe in the Far Northern GBR; Moderate to Severe in the Cairns/Cooktown region; Minor to Severe from Townsville to the Whitsunday Islands; and Minor in the Mackay/ Capricorn region (Great Barrier Reef Marine Park Authority 2016).

The effects of climate change (bleaching, ocean acidification, stronger cyclones and larger river floods) are also predicted to impact many other species and ecosystems of the GBR, including coral trout (*Plectropomus sp*.) (Johansen et al. 2015); turtles (Hawkes et al. 2014); seabirds (Great Barrier Reef Marine Park Authority 2014a); and plankton assemblages (Mongin et al. 2016).

A number of recent papers have documented global increases in the proportion of very intense cyclones (summarised in Walsh et al. 2015). Assessments of global and regional projections of future tropical cyclone climatology by 2081-2100 relative to 2000-2019 for a mid-range emissions scenario conclude that, globally, the consensus projection was for a reduction in the number of tropical cyclones by approximately 5-30%, an increase in the frequency of categories 4 and 5 storms by 0-25%, an increase of a few percent in typical lifetime maximum intensity, and increases in rainfall amounts by 5-20% (Christensen et al. 2013). Haig et al. (2014) noted a reduction in the frequency of cyclones in Queensland in recent times without commenting on changed strength. However, there is a large uncertainty in these projections (Walsh et al. 2015). Rainfall extremes are also predicted to increase with a greater frequency of La Nina periods (Cai et al. 2015), resulting in more frequent and larger river discharge events.

Other recent studies show that the world may reach dangerous levels of global warming much sooner than expected due to the implications of rising energy demand. For example, Wagner et al. (2016), in new models using long-term average projections on economic growth, population growth and energy use per person, predict that average world temperatures could rise by 1.5 ^{0}C above pre-industrial levels by 2020 and by 2 ^{0}C by 2030.

10.6 Water quality management outlook

10.6.1 The development of the Reef 2050 Long Term Sustainability Plan (LTSP)

In 2011 the United Nations Educational, Scientific and Cultural Organization (UNESCO) expressed concern over the decline of the outstanding universal value of the GBRWHA, because of the rapid industrialisation of the Queensland coastline for port, urban and industrial development (see Waltham and Sheaves 2015), and the recent proposals for expanded development of ports for export of unprecedented amounts of fossil fuels (**Grech et al. 2013**). As a result of these concerns, in 2012, UNESCO explored placing the GBR on the "World Heritage in Danger" list. In 2012 a team from the UNESCO World Heritage Centre and IUCN visited the GBRWHA to assess the status of the WHA (Douvere and Badman 2012; McGrath 2012). In response, the Australian government undertook a strategic assessment of management in the GBR World Heritage Area (Hockings et al 2014; Great Barrier Reef Marine Park Authority 2014b) and the Queensland government undertook a strategic assessment of management of the GBR coast and catchments (Queensland Department of State Development, Infrastructure and Planning 2014; Jacobs, 2014). These assessments culminated in the Australian and Queensland governments drafting the Reef 2050 Long-term Sustainability Plan (LTSP) in 2014 (Commonwealth of Australia 2015a) (hereafter the LTSP). The preparation of the LTSP caused UNESCO to delay taking immediate action but it called for substantive effort to safeguard the GBR's World Heritage values (UNESCO 2015).

10.6.2 Adequacy of the LTSP

The Australian Academy of Science (AAS) review of the LTSP concluded that the draft plan was inadequate to achieve the goal of restoring or even maintaining the diminished outstanding universal value of the GBR (Australian Academy of Science 2014). The AAS noted (https://www.science.org.au/files/userfiles/support/position-statements/response-to-the-draft-reef-2050-long-term-sustainability-plan.pdf):

> *"While the draft Reef 2050 Long-Term Sustainability Plan contains many positive elements, based on overwhelming scientific evidence the Academy concludes that, in its present state, the draft plan is inadequate to achieve the goal of restoring or even maintaining the diminished Outstanding Universal Value of the reef. While the draft plan acknowledges the greatest risks to the reef are "climate change, poor water quality from land-based run off, impacts from coastal development and some fishing activities", it fails to effectively address any of these pressures. Rather, the draft 2050 plan represents business-as-usual in terms of how escalating pressures on the reef are adequately regulated (or not), when much bolder action is required to restore the values of the reef and prevent further degradation.*
>
> *1. The draft plan proposes to 'maintain' the values for the reef, when it should instead provide a pathway for restoring OUV*
>
> *2. The draft plan advocates for targets that are specific, measurable, achievable, realistic, and time-bound (SMART), but many important targets are not quantified, nor are they connected to any mechanisms through which they can be achieved*
>
> *3. The draft plan does not resolve the issue of cumulative impacts, rather it permits new impacts that will be superimposed on those already causing loss of OUV*

4. In its current form, the mechanisms and level of funding for implementation of the draft plan are inadequate for achieving its goals: the draft plan is missing targets for key attributes of the reef, and mechanisms to avoid real and perceived conflicts of interest are not yet in place.

5. There is no adequate recognition in the draft plan of the importance of preventing damaging climate change for the future trajectory of the reef."

The final Plan, released in March 2015, remains short-sighted given its aspiration to provide an overarching framework for the next 35 years (**Hughes et al. 2015**). Critically, the revised plan lacks any action on climate change (Great Barrier Reef Marine Park Authority 2014a; Scheffer et al. 2015). However, much of the damage to coral, seagrass and dugong populations up to now has been driven by water quality issues and not climate change. This damage includes crown-of-thorns starfish predation on coral being enhanced by nutrient runoff (e.g., Fabricius et al. 2010); reduced coral growth because of the reduction in light caused by sediment and nutrient runoff (e.g., **Fabricius et al. 2016**); damage to seagrass via reduced light associated with sediment and nutrient runoff (e.g. **Fabricius et al. 2014**; Petus et al. 2014); and dugong mortality associated with loss of seagrass (**Devlin et al. 2012**). Hence, the identification of climate change as the key threat to the GBR does not preclude efforts to manage water quality as a worthwhile objective to provide the GBR with resilience against climate change (e.g. Anthony et al. 2015).

The inadequacy of the LTSP appears to be due at least partly to its preparation over a short timeframe, with little direct input from active scientists and its lack of review by independent experts in GBR science or environmental management.

10.6.3 The need for a comprehensive water quality management plan for the GBR

Proposals to develop a detailed water quality management plan for the GBR beyond the existing Reef Plan 2013 have been made but not funded (J. Waterhouse pers. com.). However, better understanding of the cost effectiveness of improved management practices (e.g., Van Grieken et al., 2014, Poggio et al., 2014; Star et al., 2013), combined with more spatially specific information about pollutant generation, can now be used to target future investment in management practice changes. We also now have a set of detailed Water Quality Improvement Plans (WQIPs) for the individual Natural Resource Management (NRM) Regions of the GBR Catchment, developed over the last three years – for Cape York (Cape York NRM and South Cape York Catchments, 2016), Wet Tropics (Terrain NRM 2015), Burdekin (NQ Dry Tropics 2016), Mackay Whitsunday (Folkers et al. 2014), Fitzroy (Fitzroy Basin Association 2015 http://riverhealth.org.au/projects/fba-wqip/), and Burnett-Mary (Burnett Mary NRM Group 2015). These WQIPs bring the best, most relevant and most up-to-date science and economics together such that the final plan documented the most cost-effective measures needed to reduce water pollution to ecologically satisfactory levels.

Many of the WQIPs (Wet Tropics, Burdekin, Fitzroy, Burnett Mary) used sophisticated benefit-cost analysis methods such as, for example in the Burnett Mary, INFFER™ (Investment Framework for Environmental Resources – Pannell et al. 2012), with economic models (Van Grieken et al. 2014; Beverley et al. 2015), such that the real cost of achieving ecologically relevant pollutant load targets could be estimated. The end point of the benefit–cost analysis is the value of the asset, in this case the value of the regional marine zone (e.g. for the Burdekin see **Thomas and Brodie 2015**). The needed ecologically relevant targets (**Brodie et al. in press**), which address the Reef Plan 2013 overall objective of: "To ensure that by 2020 the quality of water entering the reef from adjacent catchments has no detrimental impact on the health and resilience of the Great Barrier Reef" were developed for the Burnett Mary WQIP (**Brodie and Lewis 2014**); Fitzroy WQIP (**Brodie et al. 2015a**); Burdekin WQIP (**Brodie et al. 2016**); and the Wet Tropics WQIP (**Brodie et al. 2014a**).

The WQIPs provide excellent robust guidance for prioritising policy approaches, assessing the true costs of management to achieve targets and prioritising expenditure to reduce pollution within regions. However, they do not provide a means to prioritise across regions at the scale of the whole of the GBR. Thus the current WQIPs form a useful basis on which to develop a water quality management plan for the GBR but are not sufficient by themselves without a comprehensive overall plan. Currently, approximately $500 million has been spent on water quality management across the GBR from 2009 to 2016 without a robust management plan.

10.7 Required geographical scale for GBR management

10.7.1 The Greater GBR

While the GBRWHA encompasses most of the area of the GBR, large areas of contiguous ecosystems that are ecologically connected to the GBR, such as parts of Torres Strait and Hervey Bay, are not included. Inclusion of these sub-regions is important for appropriate holistic management of the GBR. But holistic management should also include contiguous terrestrial and freshwater environments that form the catchment of the GBR and influence it through inputs of fresh water and suspended or dissolved materials (Figure 2). The link between catchment land use and the sea (the GBR) is a basic principle of ecohydrology (Wolanski and Elliott 2015), and the need for management on the basis of land-sea connectivity, ecohydrology and holistic management of the Great Barrier Reef and its catchments has been evaluated by **Waterhouse et al. (2016)**.

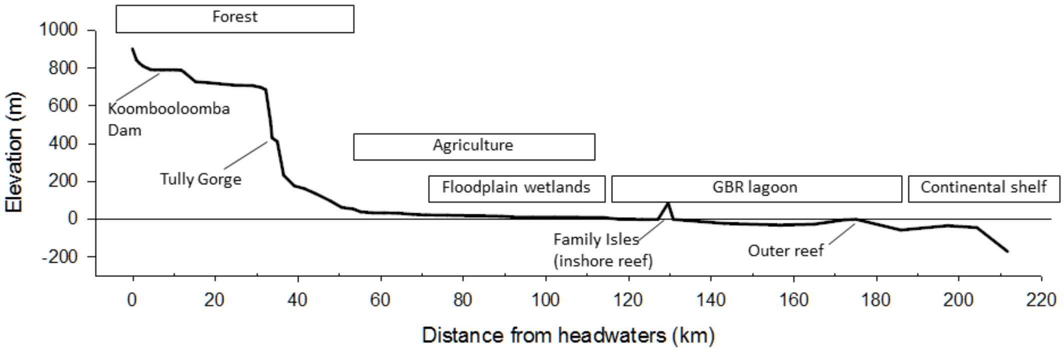


Figure 2. Connectivity, catchment to reef. This example, for the Tully River, illustrates a typical Wet Tropics river-to-reef profile, from the forested headwater streams of the coastal ranges, through the floodplain with its remnant wetlands and extensive agriculture to the very shallow waters of the GBR lagoon and finally the continental shelf. The profile of rivers of the dry tropics (e.g., the Burdekin and Fitzroy) would be greatly extended to the landward side, with little forest and extensive woodland grazing country. Thus the Tully River catchment (1 683 km^2) and Burdekin River catchment (136 000 km^2) include, respectively, about 350 km^2 vs. 130 000 km^2 of pastoral land, 135 km^2 vs. 2 700 km^2 of crops, and 1 200 km^2 vs. 2 700 km^2 of conservation lands (QDPI 1993; QDNRM 2002).

The current legislation includes catchment influences as being under the auspices of GBRMPA (see Section 10.8.2 below) although the relevant powers have been little used. However, the importance of the catchment is well recognised by the programs aimed at improving water quality, outlined above. Natural and anthropogenic processes on the land generate sediments, nutrients and other contaminants that are transported through fresh waters to the GBR lagoon, with loads greatly increased by intense activity such as agriculture or widespread activity such as pastoralism. Less well recognised is the importance of freshwater ecosystems as a component of the GBR system. They provide essential habitat during the ontogeny of some species (e.g., prawns, Barramundi), and supplementary habitat for many others (e.g., Mangrove jack). Thus, at least 27 fish species are currently known to move between fresh and saline waters in the GBR catchment area (Pearson et al. 2010), some of which use GBR estuaries and coastal waters for reproduction (e.g., Jungle perch) or passage to their breeding grounds (e.g., eels and cling gobies). The health of these freshwater systems is very dependent on appropriate land management, although the critical periods for fresh waters and the marine environment differ: it is the loading of contaminants during floods that has greatest effect on the marine environment, whereas it is the concentrations of contaminants during inter-flood periods that most seriously affect fresh waters (**Davis et al. 2016**). Therefore, management goals for fresh and marine water may differ. However, these considerations mean that a more comprehensive "area in need of management" or "management province" for the GBR needs to be developed. We recommend that this management province include not only the GBRWA and the GBRC but also Torres Strait and Hervey Bay, and the overall catchment of this region. Suggested boundaries of this "Greater GBR" management province are shown in Figure 3.

The Greater GBR comprises the major ecologically connected areas of the GBR. Management should now be prioritised across the Greater GBR, not just within the GBRWHA, including Torres Strait, Hervey Bay and the GBR Catchment in prioritisation analysis, such as the previous risk assessments and regional prioritisation (e.g. **Waterhouse et al. 2012, 2013a**).

Figure 3. Proposed boundaries of the Greater GBR. The area inside the red line is the GBRWHA while the shaded area is the proposed Greater GBR management area, including the GBR catchment area, the GBRWHA, Torres Strait and Hervey Bay. Map prepared by J. Waterhouse, JCU. Data for the GBR provided by the Great Barrier Reef Marine Park Authority.

10.7.2 Reprioritising management on the basis of current ecosystem health

The regions of the Greater GBR where ecosystems/species populations are still in good condition – including Torres Strait (coral reefs, seagrass meadows, dugong populations); northern Cape York (coral reefs, dugong populations, freshwater wetlands, estuaries); Hervey Bay (seagrass meadows, dugong populations) – are currently ranked as "low risk" in terms of anthropogenic threats (e.g., **Brodie et al. 2013b; Waterhouse et al. 2013a, b**) and hence receive low priority for restorative management funding. The ecological intactness of these regions and their potential roles as refuges against climate change and the possibility that they may act as "seeding centres" for the rest of the Greater GBR gives them a greater importance than one based on current risk profiles. Therefore, assuming that resources will always be inadequate to tackle the whole GBR, we need to strengthen management in the areas of the Greater GBR with ecosystems in good condition – Torres Strait, northern Cape York and Hervey Bay – and give them prime attention. Next in line might be more southerly outer reefs (south of Cairns), with inshore southerly reefs the last to receive special attention. At the same time, continuing improvement of land and water management across the GBR catchment, based on a more comprehensive Water Quality Management Plan (Section 10.6.3), is required.

10.8 Management needs for the future of the GBR

10.8.1 Future state of the GBR

Given the concerns outlined above, the long-term viability of the GBR even in its current state is in doubt (**Hughes et al. 2015**). Many species and ecosystems are in decline and only a few are stable or recovering from past degradation. In addition, the heavy cyclone and flood damage of 2009 – 2015, the commencement of the fourth wave of crown-of-thorns starfish outbreaks and the current severe bleaching on the northern GBR (Normile 2016) further raises concern for the long-term health of the GBR (Great Barrier Reef Marine Park Authority 2014a). It could be argued that the system has gained some resilience through the current management interventions in water quality management (**Brodie et al., 2012**; Queensland Department of Premier and Cabinet 2014) and the GBRMP rezoning in 2004 (McCook et al. 2010). However, it is unlikely that this management response is adequate to prevent either a large-scale phase shift in the system (e.g., Hughes et al. 2010) or even the continuing slow decline (Fung et al. 2011). Even successful interventions are unlikely to return the GBR to some pristine or pre-disturbance state as has been shown from experience in restoration through management in other systems. For example, Duarte et al. (2009) examined four systems (the Helgoland ecosystem, Odense fjord, Gulf of Riga and Marsdiep ecosystem) where large increases in nutrient loadings had occurred in the past and which were considered to be eutrophic as a result. After management intervention and large reductions in nutrient loading, all four ecosystems displayed convoluted trajectories that failed to return to the reference status following nutrient reduction .

Predictions that the GBR would come to the current disastrous state unless strong action was taken on managing terrestrial pollutant runoff and climate change were made over the last two decades (e.g., **Brodie et al. 2001a**; Wolanski and De'ath 2005; Bohensky et al. 2011; Hughes et al. 2007). The studies now appear prophetic given the current condition of the GBR (**Brodie and Waterhouse 2012**; Great Barrier Reef Marine Park Authority 2014a) and the extensive and serious current bleaching on the GBR (Normile 2016).

Overall, issues such as the continuing effects of climate change, including ocean warming and ocean acidification (Pandolfi et al. 2011), more frequent extreme events (Min et al. 2011), continued crown-of-thorns starfish outbreaks (**Wooldridge and Brodie 2015**), further agricultural development on the GBRCA (Commonwealth of Australia 2015b), and accelerating coastal development associated with greatly expanded port and urban developments that are not managed in any strategic way (Sheaves et al. 2015), raise serious concerns regarding the likelihood of recovery of many of the key species and ecosystems of the GBR (**Brodie and Waterhouse 2012; Waterhouse et al. 2016**; Kroon et al. 2016). This outcome is despite the fact that the GBR remains one of the best managed coral reef systems in the world (**Brodie and Waterhouse 2012**).

Building resilience to the impacts of changing climate patterns through water quality management and other local management (e.g., fishing) is recognised and accepted globally within the scientific and management communities as the key management strategy for long-term health of coral reefs globally (Anthony et al. 2015). This approach involves the management of cumulative impacts. However, the interaction of water quality stressors and climate change through direct and indirect effects (Ban et al. 2014; Cinner et al. 2015; Witt et al. 2012; Mumby et al. 2014) highlights the needed for all-of-stressors management. Recent studies point the way to understanding relative and differential effects of stressors including cyclones, river discharge, bleaching and pH changes on reefs across the shelf and the decline of reefs from multiple causes (e.g., Wenger et al. 2016).

10.8.2 The need for a regulatory approach in conjunction with other non-regulatory policy approaches

Reviews of the use of voluntary mechanisms to implement catchment management so as to reduce pollutant loadings to downstream waterbodies consistently show that such mechanisms are not effective when used without a regulatory component (e.g. Kroon et al. 2014; Roberts and Craig 2014). In a global review of the nature of successful examples of reducing agricultural pollution, Kroon et al. (2014) note that "management approaches that have resulted in reduced agricultural pollution to coastal ecosystems have all been non-voluntary, indicating that voluntary approaches alone may not be sufficient to achieve improvements". In more recent studies Kroon et al. (2016) and **Waterhouse et al. (2015)** recommend a number of initiatives that will be needed to reduce GBR pollutant loading to levels that meet the Reef Plan vision of ensuring "that by 2020 the quality of water entering the GBR from adjacent catchments would have no detrimental impact on the health and resilience of the GBR". These include (Kroon et al. 2016):

1. The use of a mix of policy instruments including both voluntary and regulatory approaches;
2. Hydrological restoration of landscapes; and
3. Land retirement.

The Queensland Government introduced a regulatory approach in 2009 – the *Great Barrier Reef Protection Amendment Act 2009* – which required pastoralists and sugarcane farmers to have farm management plans to govern, for example, fertiliser use (Queensland Department of Environment and Heritage Protection 2015). As enforcement of the regulations was largely suspended in 2012 with the election of new Queensland Government it is difficult to assess whether use of this regulatory approach was successful (Harvey et al. 2014). In addition, land clearing legislation introduced in 2009 by the Queensland Government had a large effect in reducing clearing (Kroon et al. 2016), and hence avoiding further erosion, but was reduced in effectiveness by legislative changes in 2013 (Kroon et al. 2016; **Hughes et al. 2015**). Further changes to the legislation to once again make it an effective control over unnecessary land (tree) clearing are currently before the Queensland parliament (March 2016) but it is uncertain they will be supported and passed.

The Commonwealth Government enacted two pieces of legislation that are fully available for use in managing catchment activities that are likely to impact adversely on the GBR – the *Great Barrier Reef Marine Park Act 1975* (GBRMP Act) and the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act). The *Great Barrier Reef Marine Park Act 1975* Section 66 (2) (e) states that:

> *GREAT BARRIER REEF MARINE PARK ACT 1975 - SECT* ***66***
>
> *Regulations*
>
> *(1) The Governor-General may make regulations, not inconsistent with this Act or with a zoning plan, prescribing all matters required or permitted by this Act to be prescribed or necessary or convenient to be prescribed for carrying out or giving effect to this Act.*
>
> *(2) Without limiting the generality of subsection (1), regulations to do any or all of the following may be made:*
>
> > *(e) regulating or prohibiting acts (whether in the Marine Park or elsewhere) that may pollute water in a manner harmful to animals and plants in the Marine Park;*
>
> This Section relates directly to pollution and, notably, to acts which may occur "in the Marine Park or elsewhere" – thus, actions upstream of the GBR on the GBR Catchment are covered.

In Australia's national environmental legislation (EPBC) matters of national environmental significance (MNES) are defined under Part 3 of the EPBC Act as namely:

1. World Heritage properties (sections 12 and 15A).
2. National Heritage places (sections 15B and 15C).
3. Wetlands of international importance (sections 16 and 17B).
4. Listed threatened species and communities (sections 18 and 18A).
5. Listed migratory species (sections 20 and 20A).
6. Protection of the environment from nuclear actions (sections 21 and 22A).
7. Commonwealth marine environment (sections 23 and 24A) – includes listed marine species.
8. Great Barrier Reef Marine Park (sections 24B and 24C).
9. A water resource, in relation to coal seam gas development and large coal mining development (sections 24D and 24E).

Many of the MNESs listed here are relevant to the downstream effects of GBRCA pollution and runoff including (1) the GBRWHA; (3) Ramsar sites such as Bowling Green Bay in the estuaries of the Burdekin and Haughton rivers; (4) GBR threatened species; (5) listed migratory seabirds and shorebirds of the GBR coasts and islands; (7) and (8) evidently.

Section 12 of the EPBC Act specifies that a person must not take an action that will have a significant effect upon the values of a declared World Heritage property. In a similar way to the

GBRMP Act, prohibited actions may include those that take place within or outside the boundaries of the World Heritage property.

Given these aspects of the GBRMP Act and the EPBC Act it is entirely within the powers of the Australian Government to strictly regulate activities on the GBRCA in order to prevent pollution of the GBRMP and GBRWHA and thus avoid damage to species and ecosystems within the GBR. It may be understandable, if not reasonable, that such powers have only been used rarely.

10.8.3 Funding requirements

Funding of \$375 million to implement the 2009 – 2013 reductions was provided by government with additional farmer in-kind investment. Future funding for water quality management for 2014– 2018 comes from the Reef Trust (~ \$140 million) and from the Queensland Reef Protection Program (~\$100 million). Thus the total appears to be much less than for the 2008 – 2013 period. Some estimates of the real amount needed to manage river pollutant loads are close to \$800 million (Reef Regions GBR Natural Resource Management Organisations 2015). The recent WQIPs (see section 10.6.3) estimate the costs to reach ecologically relevant targets for their regions and can be added to get an approximate combined cost. While some of the estimates are still preliminary, the best estimate of the combined cost to get pollutant loads to meet ERTs across the GBR is in the range \$8 – 10 billion over ten years (by 2025) (**Alluvium 2016**).

The value of the GBR asset has been estimated using a number of techniques and for different purposes. A range of ecosystems services values were assessed by Stoeckl et al. (2011), who notes the paucity of information available to assess such values and the restricted nature of previous studies. The GBR supports a successful tourism industry, which injects AUS\$5 billion into the economy and generates around 64,000 full-time equivalent jobs (Deloitte Access Economics, 2013). Overall Stoeckl et al. (2014) estimate that the collective monetary value of a broad range of services provided by the GBR is likely to be between AUS \$15 billion and \$20 billion per annum.

To ensure a viable tourism industry, a destination such as the GBR must maintain or improve its natural, physical, and social assets such that the destination’s competitiveness is retained (especially internationally for assets such as coral reefs). This is especially important, given observed stagnation in several destinations, including the GBR (Deloitte Access Economics, 2013). A destination must not only ensure its overall attractiveness, but it must also ensure that the integrity of the experiences it delivers to tourists must equal or surpass that of alternative destinations (Esparon et al. 2015). In the case of the GBR, management of agriculture is essential to preserve the desired environmental values (**Brodie et al. 2015**). The clear message from studies such as Esparon et al. (2015) is that environmental values of the GBRWHA are more important relative to market factors such as changes in prices, and their consequential decline will severely impact on the entire Reef and its catchment's economy.

Given a collective monetary value of A$15-20 billion per year (Stoeckl et al. 2014), spending 10% of this amount on research, monitoring, management and enforcement for the GBR seems appropriate by international standards (Watson et al. 2014). Spending A$ 0.5-1 billion annually (A$5-10 billion over 10 years) to manage agriculture in the catchment as part of this investment would thus appear to be reasonable. Further, assuming that investment is in sustainable long-term solutions, required subsequent annual expenditure after the initial 10-year period should be much reduced.

10.8.4 Governance reform

Dale et al. (2013) point out serious weaknesses that are evident in the governance structures that should allow effective management of the GBRCA to protect the GBR, and identify governance subdomains that present high, medium, or low risk of failure. The critical Long Term Sustainability Plan (LTSP) Subdomain presents the highest risk as it represents the primary institutional arrangements for coordinated GBR management. This finding is consistent with the Australian Academy of Science's view that the LTSP is inadequate (see above).

Given expanding coastal urban and industrial development in the coastal zone of the GBRWHA there is a critical need for coordinated planning and policy (Waltham and Sheaves 2015). However, our current environmental impact assessment/statement processes are seriously flawed (Sheaves et al. 2015; **Brodie 2014**) with poor use of the existing science and often, at best, token efforts to compare the available developmental options with respect to their potential environmental impacts versus the costs of management and remediation. Offsets are often used as the first option to "manage" environmental impacts rather than the last in the hierarchy after avoid and mitigate (Bos et al. 2014; **Dutson et al. 2015**).

As many of the freshwater, terrestrial and marine ecosystems in the Greater GBR have been damaged by agricultural, mining and urban developmental activities, it is also important in a governance sense to investigate methods of cross-boundary management to achieve simultaneous cost-effective terrestrial, freshwater and marine ecosystem protection in the Greater GBR (e.g. Alvarez-Romero et al. 2011).

10.9 Conclusions

Given the parlous state of the GBR, a complete refocus and strengthening of management is required. The LTSP should have provided this focus and vision but failed to do so. My recommendations for the way forward are to:

1. Refocus management to the Greater GBR – that is, include management of Torres Strait, Hervey Bay and the GBR Catchment as priorities along with the GBRWHA.
2. Strengthen management in the areas of the Greater GBR with ecosystems in good condition, with Torres Strait, northern Cape York and Hervey Bay being the systems with highest current integrity.
3. Investigate methods of cross-boundary management to achieve simultaneous cost-effective terrestrial, freshwater and marine ecosystem protection in the Greater GBR.
4. Develop a detailed, comprehensive, costed water quality management plan for the Greater GBR.
5. Use the GBRMP Act and the EPBC Act to regulate catchment activities that lead to damage to the Greater GBR, in conjunction with the relevant Queensland legislation.
6. Fund catchment and coastal management to the required level to largely solve the pollution issues for the Greater GBR by 2025, before climate change impacts become overwhelming for the Greater GBR ecosystems.
7. Australia to show commitment to protecting the Greater GBR through greenhouse gas emissions control, of a scale to be relevant to protecting the GBR, by 2025.
8. Continue enforcement of the zoning plans.
9. Fund strategic research to address important knowledge gaps that hinder our ability to prioritise management actions and assess their success. We need to better understand: pollutant transport processes (e.g. overbank flow, groundwater transport and residence times); processes taking place during transport (e.g. denitrification, flood-plain deposition, plume flocculation, biological uptake, pesticide half-lives); the effects of contaminants in the short term (e.g. during flood plumes) versus the long term (e.g. chronic effects over years of low level pollution); the long-term effectiveness of many of our recommended management practices in reducing pollution (e.g. constructed wetlands to trap contaminants from cropping or better pasture cover to reduce erosion in rangelands); the effects of removal of vegetation from catchments and reduced infiltration and increased water runoff (but see Thornton et al., 2007); and the effects of pollutants at ecosystem scale versus single species response.

10.10 Postscript

This thesis demonstrates that I have produced a coherent body of research that has contributed substantially to our deeper understanding of the science of the Great Barrier Reef and hence the management needs for this system. The selected research papers (Chapters 2 to 9) indicate diverse initiatives over a number of years, reflecting the greater body of my research and advisory output (Appendices 1 and 2). Chapters 1 and 10 place this work in the broader context of research and initiatives by many people, but I think effectively demonstrate the extent of my contribution.

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Appendix 2. A selection of conference papers, technical reports, books and book chapters

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