National Environmental Research Program

TROPICAL ECOSYSTEMS hub

Water Quality

Synthesis of NERP Tropical Ecosystems Hub GBR Water Quality Research Outputs 2011-2014

Compiled by RRRC

Australian Government

Department of the Environment

Reef & Rainforest RESEARCH CENTRE

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Synthesis of NERP Tropical Ecosystems Hub Water Quality Research Outputs 2011-2014

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The Tropical Ecosystems Hub is part of the Australian Government's National Environmental Research Program. The NERP TE Hub is administered in North Queensland by the Reef and Rainforest Research Centre Limited (RRRC). The NERP Tropical Ecosystem Hub addresses issues of concern for the management, conservation and sustainable use of the World Heritage listed Great Barrier Reef (GBR) and its catchments, tropical rainforests including the Wet Tropics World Heritage Area (WTWHA), and the terrestrial and marine assets underpinning resilient communities in the Torres Strait, through the generation and transfer of world-class research and shared knowledge.

Cover photograph: K. Fabricius

This report is available for download from the NERP Tropical Ecosystems Hub website:
www.nerptropical.edu.au

February 2015

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Acronyms Used In This Report

AFMA	Australian Fisheries Management Authority
AIMS	Australian Institute of Marine Science
BoM	[Australian] Bureau of Meteorology
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DoE	[Australian] Department of Environment
DEHP	Queensland] Department of Environment and Heritage Protection
DFAT	[Australian] Department of Foreign Affairs and Trade
DNRM	[Queensland] Department of Natural Resources and Mines
DSDIP	[Queensland] Department of State Development, Infrastructure and Planning
DSITIA	[Queensland] Department of Science, Information Technology, Innovation & Arts
EMQ	Emergency Management Queensland
GBR	Great Barrier Reef
GBRMPA	Great Barrier Reef Marine Park Authority
IPCC	Intergovernmental Panel on Climate Change
JCU	James Cook University
MTSRF	Marine and Tropical Sciences Research Facility
QDAFF	Queensland Department of Agriculture, Fisheries and Forestry
RRRC	Reef and Rainforest Research Centre Limited
TSC	Torres Shire Council
TSIRC	Torres Strait Island Regional Council
TSRA	Torres Strait Regional Authority
WTMA	Wet Tropics Management Authority
WTWHA	Wet Tropics World Heritage Area

Abbreviations Used In This Report

abbrev.	abbreviated
A&P	analysis and prediction
approx..	approximate
AR4	IPCC Fourth Assessment Report
AR5	IPCC Fifth Assessment Report
assoc.	association
Chl a	cholophyll a
CPUE	catch per unit effort
DIN	dissolved inorganic nitrogen
DIP	dissolved inorganic phosphorus
DON	dissolved organic nitrogen
LRE	loads regression estimator
NRM	natural resource management
PN	particular nitrogen
PP	particular phosphorus
PSII	photosystem II
RCP	representative concentration pathways
SST	sea surface temperature
TSS	total suspended solids
WQ	water quality

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About this Report

This report provides an overview and synthesis of the key findings of research conducted under the Australian Government's National Environmental Research Program (NERP) Tropical Ecosystems Hub relevant to water quality related research in the region. The NERP research theme water quality was comprised of 9 projects undertaken collaboratively by researchers from the Australian Institute of Marine Science, James Cook University, CSIRO and University of Queensland.

The intent of the NERP-funded water quality research was to assess the risks to biodiversity from current water quality in the inshore GBR and to assess the impacts of cumulative pressures on coastal biodiversity in the GBR. There has been a strong focus on priority pollutants, cumulative pressures on key ecosystems, identifying priority areas or actions for managers and monitoring and evaluation of long term historical water quality.

This report presents a synthesis of the highlights of the NERP Tropical Ecosystems Hub Water Quality and an overview of key project acheivements within the theme. The report provides an introduction to water quality associated research carried out across the GBR and, a synthesis of key ecological project highlights for the regions (including status and trends), future pressures and threats, how research has informed policy and management, and future research priorities.

This report provides a synthesis of projects across all three themes in the NERP Tropical Ecosystems Hub, and is one of several such reports in a series of information products that summarise NERP research findings relevant to policy and management in tropical North Queensland. Other products include:

- GBR
- Torres Strait
- Rainforests

1. Introduction to the Water Quality Projects

1.1 Background to NERP

On 13 September 2011, the federal Minister for Sustainability, Environment, Water, Population and Communities (DSEWPaC), Tony Burke, approved research plans for five research hubs funded by the department, under the National Environmental Research Program (NERP). Funding of $68.5 million over four years has been allocated to the NERP program, which aims to provide the first-class science essential for managing Australia's environments – applied, 'public good' research. The NERP program's five Hubs are: Tropical Ecosystems (QLD), Northern Australia (NT), Landscapes and Policy (TAS), Environmental Decisions (QLD) and Marine Biodiversity (TAS). The NERP Tropical Ecosystems Hub is the largest of the five Hubs with over 240 researchers undertaking 38 projects across north and far north Queensland and the Torres Strait.

The NERP TE Hub, administered by the Reef & Rainforest Research Centre (RRRC) addressed issues of concern for the management, conservation and sustainable use of the Great Barrier Reef and its catchments; tropical rainforests including the Wet Tropics World Heritage Area; and the land and water assets supporting communities in the Torres Strait.

The NERP Tropical Ecosystems Hub research program had three themes, twelve research programs and 38 research projects. The research concentrates on three geographic areas: the Great Barrier Reef and its catchments, Torres Strait, and the Wet Tropics Rainforests. This synthesis focuses on projects that delivered information about Great Barrier Reef Water Quality. Projects within the water quality research spectrum are across all three themes and linked to programs 4, 5, 9 and 10. These water quality related projects haveincreased the understanding of ecosystem function and the impact of synergistic and cumulative pressures on the system.

These research projects cover various components of water quality and climate effects in the GBR and Torres Strait, pesticides and fine sediments and their potential impacts on GBR ecosystems, cumulative impacts on coral and seagrass communities, long term historical records of change in the GBR and revised spatially complex risk assessment of terrestrial inputs and coastal development.

Table 1-1. NERP TE themes, programs and projects that are relevant to Water Quality Reseach. Projects discussed in this synthesis report are highlighted in bold. Projects that are related to water quality projects through direct linkages of outcomes and information are highlighted in blue.

Theme	*Theme Title*	*Program*	*Project*
1	Assessing Ecosystem Condition and Trends	Program 1: Historical and Current Condition of the Great Barrier Reef	Project 1.3: Characterising the cumulative impacts of global, regional and local stressors on the present and past biodiversity of the GBR
2	Understanding Ecosystem Function and Cumulative Pressures	Program 4: Water quality of the Great Barrier Reef and Torres Strait	Project 4.1: Tracking coastal turbidity over time and demonstrating the effects of river discharge events on regional turbidity in the GBR
			Project 4.2: The chronic effects of pesticides and their persistence in tropical waters
			Project 4.3: Ecological risk assessment of pesticides, nutrients and sediments on water quality and ecosystem health
			Project 4.4: Water Quality in the Torres Strait
		Program 5 Cumulative Impacts on Benthic Biodiversity	Project 5.1: Understanding Diversity of the GBR: Spatial and Temporal Dynamics and Environmental Drivers
			Project 5.2: Experimental and field investigations of combined water quality and climate effects on corals and other reef organisms
			Project 5.3: Vulnerability of seagrass habitats in the GBR to flood plume impacts: light, nutrients, salinity
3	Theme 3: Managing for Resilient Tropical Systems	Program 9: Decision support systems for GBR managers	Project 9.1: Dynamic Vulnerability Maps and Decision Support Tools for the Great Barrier Reef
			Project 9.2: Design and implementation of Management Strategy Evaluation for the Great Barrier Reef inshore (MSE-GBR
			Project 9.4: Conservation planning for a changing coastal zone
		Program 10: Socio-economic value of GBR goods and services	Project 10.1: Social and Economic Long Term Monitoring Programme (SELTMP)
			Project 10.2: Socio-economic systems and reef resilience
		Program 13: Knowledge Brokering and Communications	Project 13.1: e-Atlas

Projects in program 4 have assessed the risks to biodiversity from current water quality in the inshore GBR. Project 4.1 measured the transport and settlement of fine sediments carried by river plumes and subsequently resuspended by winds. A second project (Project 4.2) established the half-lives of common agricultural chemicals in the marine environment and quantified the impacts of acute and chronic low-level exposure to these pollutants. Information from both these projects has contributed to the Reef Water Quality Protection Plan (Reef Plan) and was designed in consultation with the outcomes of the Reef Rescue Program (Lewis et al., 2014). A third project (Project 4.3) was a methodological pilot study recommending how to conduct a formal risk analysis of the threats from multiple stressors in water quality that has been used to prioritise future investment decisions in the catchments (i.e. what is the relative risk from sediments, excess nutrients, and contaminants). This spatial analysis approach was also explored in project 9.4 which developed eight spatially-explicit scenarios of coastal development for 2035, covering land uses and related marine activities using Geographic Information Systems. The range of 2035 scenarios incorporated uncertainty around demand for food, mineral resources, tourism, and environmental services.

Projects in Program 5 were designed to assess the impacts of cumulative pressures on coastal biodiversity in the GBR. Project 5.1 is a synthesis and analysis of spatial and temporal patterns of inshore biodiversity seeking to partition the influence of different environmental drivers (water quality, crown of thorns seastar, cyclones, and connectivity and identify synergistic interactions between stressors (refer to Donnelly et al., 2015). The other two projects are both multi-factorial laboratory experiments and field experiments exposing corals and seagrasses to different combinations of stressors in order to incorporate cumulative hazards into quantitative descriptors and thresholds. Project 5.2 assessed the effects of nutrients, salinity, turbidity/light/sedimentation, in combination with elevated temperature and OA induced stress on a range of organisms and project 5.3 focused on the development of thresholds around seagrass communities across different scales. This focus on cumulative impacts is further explored in a Program 1 project that incorporates a strong water quality focus by characterising the cumulative impacts of global, regional and local stressors broad temporal and spatial scales using a range of novel methods for collecting long term historical data.

This report provides a synthesis of one key theme in the NERP Tropical Ecosystems Hub, and is one of several such reports in a series of information products that summarise NERP research findings relevant to policy and management in tropical North Queensland. Other NERP synthesis products include:

- Carmody, J., Murphy, H., Hill, R., Catterall, C., Goosem, S., Dale, A., Westcott, D., Welbergen, J., Shoo, L., Stoeckl, N., Esparon, M. (2015) The Importance of Protecting and Conserving the Wet Tropics: A synthesis of NERP Tropical Ecosystems Hub Tropical Rainforest Outputs 2011-2014. Report to the National Environmental Research Program. Reef and Rainforest Research Centre Limited, Cairns (64pp.).
- Donnelly, R., Sweatman, H., Emslie, M., Russ, G., Williamson, D., Jones, G., Harrison, H. (2015) Effects of Management Zoning on Coral Trout Populations in the Great Barrier Reef Marine Park. Report to the National Environmental Research Program. Reef and Rainforest Research Centre Limited, Cairns (12pp.).

- Donnelly, R., Yates, P., Schlaff, A., Espinoza, M., Matley, J., Ledee, E., Currey, L., de Faria, F., Moore, S. (2015) Spatial Management and Sharks on the Great Barrier Reef. Report to the National Environmental Research Program. Reef and Rainforest Research Centre Limited, Cairns (10pp.).
- Johnson, J.E., Marsh, H., Hamann, M., Duke, N., Burrows, D., Bainbridge, S., Sweatman, H., Brodie, J., Bohensky, E., Butler, J., Laurance, S. (2015) Tropical Research in Australia's Torres Strait region. Report to the National Environmental Research Program. Reef and Rainforest Research Centre Limited, Cairns (33pp.).

1.2 Water Quality issues

Water quality in the Great Barrier Reef has been recognized as being a state of decline, with rapid expansion of agriculture and urbanization in the GBR catchment as the primary cause of this decline. River discharge carrying land-based pollutants results in both acute and chronic stress on coral reefs and seagrass beds due to the changes in water quality conditions driven by the increase in pollutant load. Acute stresses on marine ecosystems are usually associated with wet season weather conditions resulting in prolonged exposure to low salinity, river plumes, decreased light availability (due to suspended fine material) and the exposure of systems to direct impacts from pollutants, including nutrients, fine sediments and pesticides (Alvarez-Romero et al., 2012; Devlin et al., 2012. Chronic stresses associated with increased levels of nutrients and turbidity (reduction in light) can affect corals, seagrass and fish species susceptible to long-term changes in ambient (dry season) environmental conditions such as the found in the GBR (De'ath and Fabricius, 2010; Brodie et al., 2014, Fabricius et al., 2014; Wenger et al., 2014).

Despite the protected status and World Heritage listing, the GBR is under stress from three main threats associated with anthropogenic activities: over-harvesting of marine resources, climate change and land-based pollution. 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., 2014). Exposure to the land-sourced pollution has been identified as an important factor in the decline in coral reef and seagrass condition in the GBR. Different rates of exposure to land-sourced pollutants have important consequences for the degree of degradation that habitats such as coral reefs and seagrass meadows may suffer as a result of land-sourced pollution. Since European settlement, loads of pollutants delivered to the GBR have escalated, with recent estimates indicating increases by around 5.5, 6 and 9 times when compared to annual pre- European loads of total suspended particulate matter, total nitrogen, and total phosphorus, respectively. Discharge of pollutants to the GBR occurs mainly during the high-flow events associated with the north Queensland wet season between the months of December to April.

Early adopters of best practice land management have reduced total pollutant loads—a significant step towards the goal of halting and reversing the decline in water quality to the reef (http://www.reefplan.qld.gov.au/measuring-success/methods/assets/gbr-report-card-2012-and-2013-catchment-pollutant-loads-methods.pdf). The latest scientific consensus statement on the

Great Barrier Reef (Brodie et al., 2013a) identifies that while the current management interventions are starting to address water quality in the Great Barrier Reef, a greater effort will be required to achieve the ultimate goal of no detrimental impact on the health and resilience of the reef. In addition to continuous improvement, transformational and innovative changes in some farming technologies may be necessary to reach some targets that are currently required under Reef Plan targets.

NERP Water Quality projects have set out to advance the understanding of both catchment and marine processes that impact on GBR Water Quality and impacts on the resilience and health of key GBR ecosystems. This information is vital for managers to make the best informed decisions on how to continue to move towards a goal of reversing the decline in water quality.This understanding is essential in developing effective management responses that promote ecosystem resilience.

2. Research highlights

2.1 NERP WQ research projects

NERP WQ projects have delivered across several themes and programs with a summary of the main outcomes listed below.

- The characteristics of cumulative impacts of global, regional and local stressors on the present and past biodiversity of the GBR
- Improved understanding of coastal turbidity over time and quantifying the impacts of of river discharge events on regional turbidity.
- The conclusion that runoff only affects the inshore of the GBR has to be revised for the Central and Northern GBR.
- The chronic effects of pesticides and their persistence in tropical waters
- The risk assessment of changing water quality on the ecological systems of the GBR
- Combined water quality-climate effects on coral and other reef organisms
- Identifying drivers for lack of recovery is just as important as identifying timing and drivers of change.
- Palaeoecological studies can provide a quick assay to determine timing of ecological change at sites on individual GBR reefs.
- The vulnerability of seagrass habitats in the GBR to changing coastal environments
- How spatial planning of coastal development in the GBR region can provide information to direct management decisions by identifying future scenarios**.**

2.2 NERP WQ research outcomes

NERP Water Quality was delivered on several key research areas, including priority pollutants (Projects 4.1, 4.2), cumulative pressures (and development of ecologically relevant thresholds) (Projects 5.2, 5.3), priority areas for management (Projects 4.4, 9.4), and the monitoring and evaluation of key ecosystems over historical time scales (Project 1.3) (Figure 4-1). Several other projects also contribute to water quality research (Figure 3-1) but these will be reported on in corresponding synthesis reports including a GBR report (Project 5.1, 9.1, 9.2, 10.1, and 10.2; see Ryan et al., 2015) and in the Torres Strait report (Project 4.4, see Johnson et al., 2015)

Projects focusing on priority pollutants utilised both laboratory and field data to evaluate the impacts of sediments and pesticides on GBR ecosystems. Pesticides are considered one of the key priority pollutants discharging into the GBR, particularly for the nearshore ecosystems. A water quality project under NERP (Project 4.2) focused specifically on pesticides resulting in improved paramaterisation for models and risk assessment. Project 4.1 utilised remote sensing data and complex statistical modeling to provide long term information of change in the delivery and potential impacts of fine sediment into the GBR, considered another priority pollutant for impacting GBR ecosystems.

Two research projects focused on delivering improved spatial assessments of water quality risk across the GBR and future scenarios for the GBR based on changes in the coastal development trajectory. Project 4.3 finalised a scoping study to determine the most effective approach for assessing risks to biodiversity in the inshore Great Barrier Reef (GBR) from declining water quality. Results from Project 9.4 Results to date have informed management on changing baselines by the assessment of potential scenarios of coastal development and their cumulative impacts on marine species and ecosystems.

Project 5.2 focused on cumulative pressures and the development of ecologically relevant thresholds using a series of laboratory based and field experiments to assess the impacts of multiple pressures on GBR ecosystems. Project 5.3 reported on the level of exposure that seagrass meadows experience over broad scale and long-term changes in water quality. The main water quality influence is associated with the onset, duration and impact of flood plumes in coastal regions of the GBR and these short-term changes in light, nutrients and salinity (simulating flood plumes) on seagrass condition.

In addition, water quality projects that provide new and novel information in the continuing monitoring and evaluation of the GBR were also completed. Project 1.3 provided comprehensive paeleoecological information over several sub-projects to ascertain the link between terrestrial discharge, water quality, global warming, ocean acidification on the GBR over decades – centuries – millennia

Managers need information on the areas or ecosystems at risk to prioritise actions that needs to be taken. Projects 4.4 and 9.4 provided novel spatial assessments of GBR risks and pressures and have provided this information to GBR managers for prioritizing of risk in relation to different water quality issues and possible trajectories of the development of the GBR coastline.

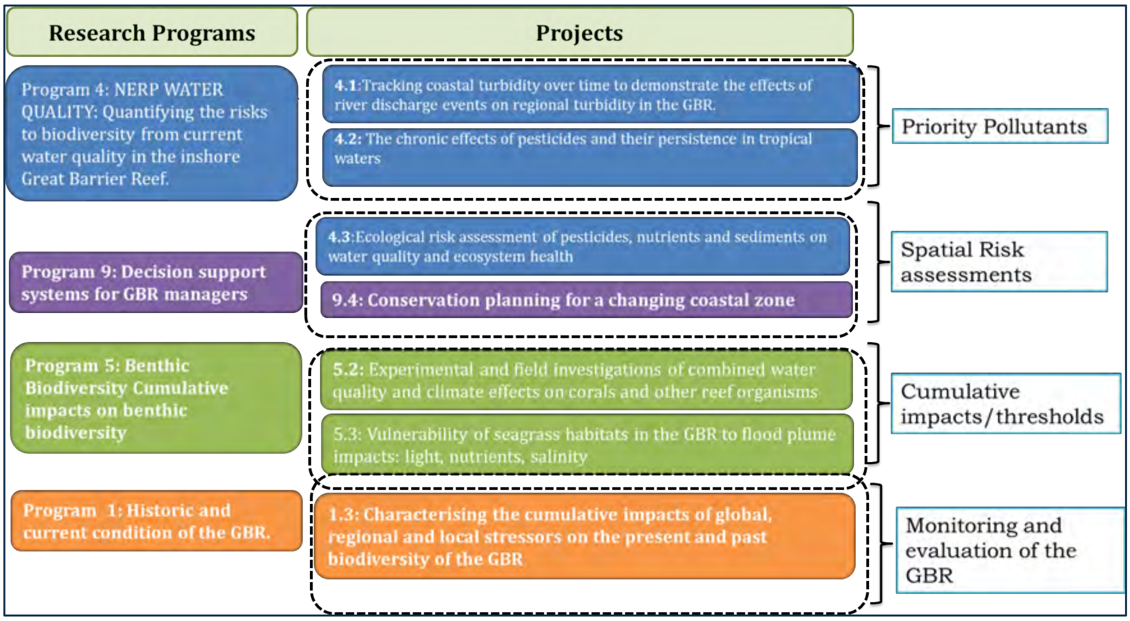


Figure 2-1. Research program and projects delivering research for the NERP Water Quality Program.

2.3 Priority Pollutants

2.3.1 Issues

Two projects dealt specifically with the extent and possible impacts of two priority pollutants on GBR ecosystems with project 4.1 reporting on the extent and influence fine sediment through the modelling of light attenuation and water clarity in response to the delivery of fine sediment into the GBR. Project 4.2 investigated the impact of PSII herbicdes through multi-factorial experiments simulating water quality through flood plume conditions.

Turbidity is a fundamental environmental property of coastal marine ecosystems, because suspended particles reduce irradiance for primary producers, alter trophic structures, and can be vectors for nutrients, pollutants and diseases. On the Great Barrier Reef, increasing turbidity has been related to a five-fold increase in macroalgal cover and a 30% reduction in coral biodiversity [De'ath and Fabricius, 2010]. Due to its relevance, both levels of turbidity and changes in turbidity are used as indicators for environmental reporting of the condition of estuarine and coastal waters [ANZECC, 2000]. An initial study had investigated the spatial and temporal variation in turbidity at 14 inshore reefs in four regions of the Australian Great Barrier Reef (GBR) over ~3 years. The data show that significant intra-annual changes in turbidity on the inshore GBR are related to variation in terrestrial runoff. The study suggested that a reduction in the river loads of fine sediments and nutrients through improved land management should lead to measurably improved inshore water clarity. Whilst this study provided the strongest indication yet that inshore water quality is affected by terrestrial runoff, and hence amenable to improvement through improved land management, the study was too short to investigate inter-annual variation in turbidity (e.g. differences between relatively wet and dry years), and the 14 points spatially too limited for providing specific information in relation to differences between the different NRM Regions (Fabricius et al., 2011). The NERP project focused on the determination of NRM region specific quantitative relationships between changed terrestrial runoff to the GBR and intra- and inter-annual variation in coastal water clarity.

Pesticides, and particularly herbicides from agricultural sources (Lewis et al., 2009), have been detected in nearshore sites of the Great Barrier Reef (GBR) all year round (Shaw et al., 2010). The actual impacts from these concentrations of herbicides remain uncertain and information on cumulative impacts is required. A key policy to minimise the effects of climate change on tropical marine organisms (e.g. coral bleaching and loss of seagrass cover) is to improve water quality, thereby reducing the potential for pollution to exacerbate the effects of thermal stress (Reef Plan, 2009). While pesticides are thought to contribute to the stress on nearshore habitats, little is known of their chronic effects on tropical species or their persistence in tropical waters. The most commonly detected herbicides inhibit photosynthesis, thereby reducing primary productivity and calcification in key marine species. When plants and corals are stressed from increased sea surface temperatures (SST), additional stresses from reduced salinity and at high irradiance the impact of secondary chronic pollution such as herbicides exposure can become additive or synergistic (Negri et al., 2011). There is little data to explain to what extent chronic exposure to herbicides might interact with climate change to negatively affect sensitive tropical organisms such as corals and especially seagrass (Haynes et al., 2000; Ralph, 2000; Jones and Kerswell, 2003). Furthermore, little is known of the fate and persistence of agricultural herbicides that have been detected in the lagoon of the GBR. Understanding the half lives of these compounds and the toxicity of their breakdown products in the tropical marine environment is also a critical data-gap required to develop realistic ecological risk models for sensitive coastal organisms and communities of the GBR.

To address this, a series of experiments were conducted as part of Project 4.2 to examining how seagrass are affected by herbicides in conjunction with other stressors such as temperature and low light. An important source of herbicides in coastal waters is flood plumes from river runoff. By creating experimental conditions similar to GBR flood plumes this project determined how long herbicides persist and how they are transformed as they travel into coastal waters and identify the herbicide concentrations that cause chronic stress in marine biota and use this information to refine pollution targets for the GBR.

2.3.2 Research outcomes

NERP research has now delivered an improved understanding of the quantitative relationships between Queensland Rivers and changes in the coastal water clarity within their region. Project 4.1 investigated the relationship between discharges of major rivers and the water clarity in the GBR waters of the Fitzroy, Whitsundays, Burdekin, Wet Tropics and Cape York NRM Regions by using daily 11-years (2002-2013) MODIS-Aqua remote sensing data at 1 km^2 resolution, to investigate time scales and processes affecting water clarity in these regions. This resolution of data allowed the project to investigate affecting water clarity in these regions across relevant time scales. In the first year, the studies showed that mean annual water clarity in the central GBR is strongly related to discharges by the large Burdekin River. That study was based on 10 years of remote sensing and environmental data (2002–2012), a new GBR-validated photic depth algorithm for MODIS-Aqua data (Weeks et al. 2012, Logan et al., 2013) and statistical models. The study then assessed the spatial extent (inshore to offshore) and duration of reduction in water clarity beyond the duration of the flood plumes. The results suggest that reductions in the sediment and nutrient loads of the Burdekin River will likely result in significantly improved water clarity downstream of the river mouth and across much of the central GBR, both during the wet season and throughout the following dry season (Logan et al. 2013,Fabricius et al. 2014)

In the second year, the project extended the methods developed by Logan et al. (2013), and applied them to the other four large NRM Regions of the GBR, namely the Fitzroy and Whitsundays regions in the south, and the Cape York and Wet Tropics regions in the north. For all coastal, inshore and lagoonal regions except for Cape York, photic depth was strongly negatively related to the freshwater discharge of the main rivers (Figure 2.2). The declines started with the onset of river floods, and water clarity typically took 150– 260 days until complete recovery. The relationship between photic depth and rivers was strongest in the Northern Wet Tropics, the initiation area of outbreaks of crown-of-thorns starfish, where effects were strong even on the outer shelf. Previous conclusions that river runoff predominantly affects the inshore of the GBR have therefore to be revised for the Central and Northern GBR. The results were used in the setting of regional ecologically relevant targets for fine sediment in the Burnett-Mary and Wet Tropics WQIPs, and will likely be used for other WQIPs.

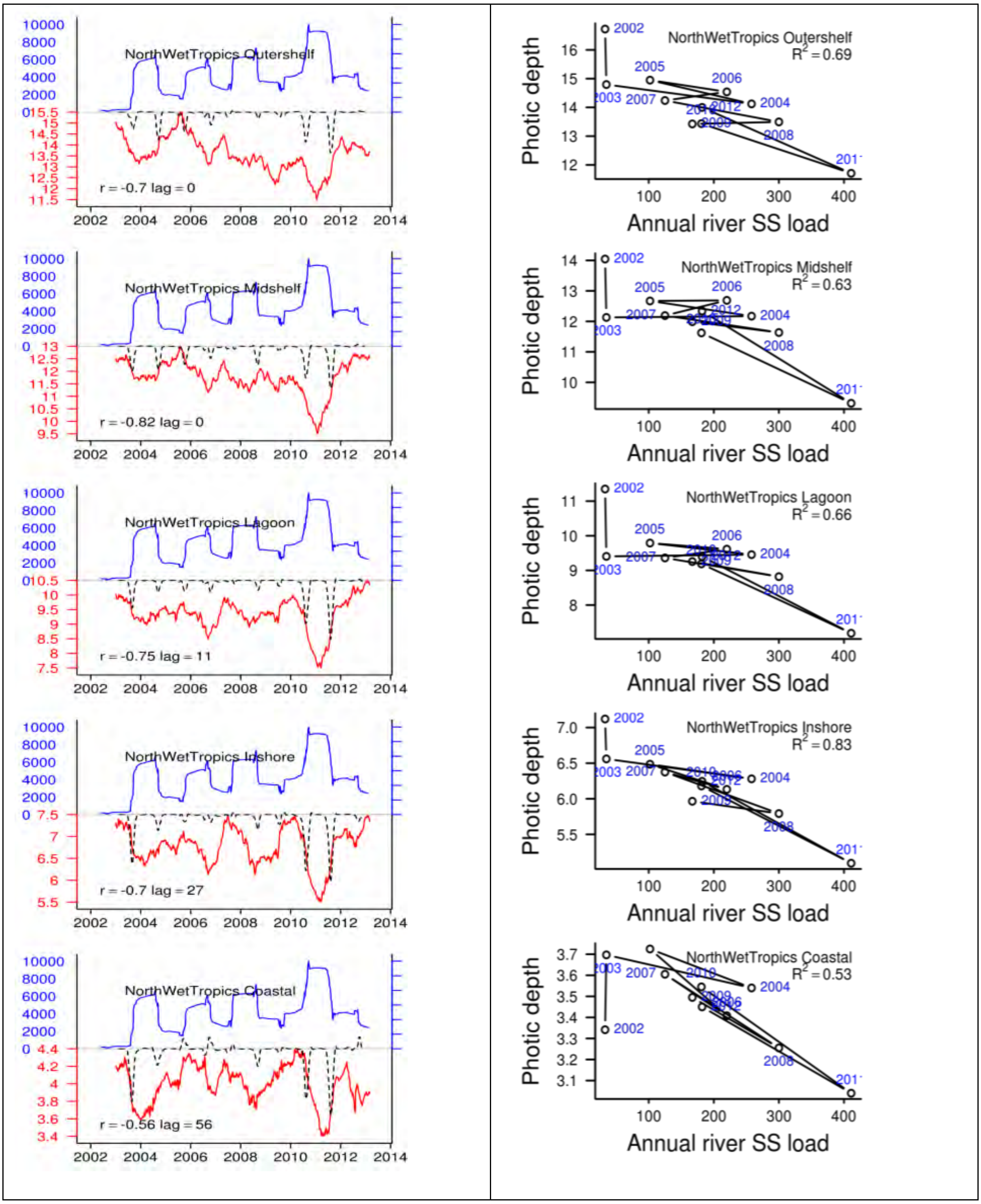


Figure 2-2. Standardized photic depth (left panel: red lines) strongly declines with increasing river flows (blue lines), and with annual sediment and nutrient loads (right panel, black lines) in all GBR regions except Cape York. Of all GBR regions, the Northern Wet Tropics (Cairns to Lizard Island, the initiation area of outbreaks of crown-of-thorns starfish) had the strongest correlation between photic depth and rivers. In this region, the relationship was strong across the whole shelf, including the Mid- and Outershelf Zone, and only slightly weaker in the turbid Coastal Zone.

Pesticides, and particularly herbicides from agricultural sources, have been detected in nearshore sites of the Great Barrier Reef (GBR) all year round. The actual impacts from these concentrations of herbicides remain unclear with little information on the impacts of cumulative pressures on GBR ecosystems, with a particular focus on seagrasses. The identified herbicide concentrations that cause chronic stress in marine biota can be used to refine pollution targets for the GBR. When combined with the herbicide persistence data (determined here), water quality and climate data this will contribute to cumulative risk models and thus to policy development to protect the GBR from the effects of pollution and climate change.

This project has examined the effects of 8 PSII herbicides on up to 5 species of seagrass. The effects of the herbicides on photosynthesis were performed in standard acute tests (Flores et al., 2013), chronic flow-through tests and finally, in miniature assays were developed by the project for rapid toxicity assessment (Wilkinson et al., 2015). These phytotoxicity data will contribute to the development of new water quality guidelines and to assess the protection afforded to seagrass by the current guidelines. Results indicate that combinations of high light and Diuron are additive in their impacts on photosynthesis and damage to photosystem II within the leaves. Diuron was shown to have least impact on the plants at their thermal optima (PSII efficiency optima) of ~33°C but was more potent at low temperatures.

The sensitivity of seagrass to herbicide exposures increased at both high and low temperatures and high and low light levels (Wilkinson et al., 2015), indicating that the cumulative effects of multiple pressures may increase risks posed by herbicide exposure under certain flood-plume conditions. In addition, this project developed a new method to accurately measure seagrass growth and successfully applied this method to chronic herbicide-exposed plants (Figure 2.3).

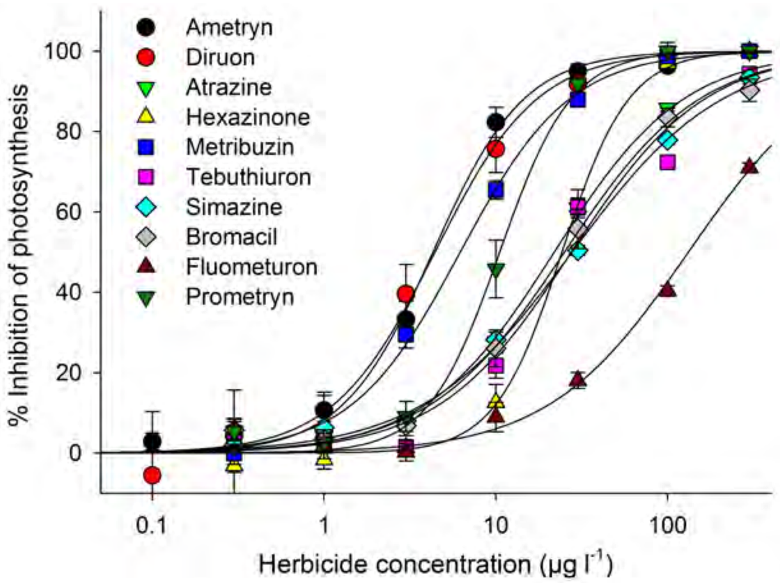


Figure 2-3. Example of inhibition of photosynthesis presented for ten common herbicides used on the GBR catchment.

A series of OECD "simulation tests" for herbicide degradation were performed for up to a year in incubated flasks. The half-lives of 6 PSII herbicides and 3 non-PSII herbicides (2,4-D, Glyphosate and Metolachlor) were examined in these standard tests in conditions that included 2 light conditions and 2 temperatures. The experiments which ran for a year revealed long half-lives for the PSII herbicides (over 550 days) and that temperature and light affected degradation, likely due to shifts in microbial communities. The non-PSII herbicides 2,4-D, Glyphosate (Mercurio et al., 2014) and Metolachlor were less persistent. The persistence of herbicides in the standard flask experiments was longer than the persistence in the open pond experiments (NERP/Caring for our Country) which included higher light conditions and treatments with coastal sediments.

This project has generated the first relevant persistence data for herbicides to tropical marine conditions. While the flask experiments performed under standard conditions follow internationally recognised protocols and provide suitable persistence data for comparative studies, the pond experiments provide the most environmentally relevant data which can be directly applied to spatial risk assessments for herbicides in flood plumes. Little degradation of herbicides would be expected during the weeks-months duration of flood plumes.

The final long-term herbicide degradation experiment was yielded samples for determining the potential toxicity of the degraded herbicide products to coral symbionts, coral larvae and prawn larvae. The toxicity experiments have so far not identified unexpected toxicity that may be due to the breakdown products. The acute toxicity of Atrazine and Diuron (including commercial formulations) and other PSII herbicides to coral larvae were also conducted in separate experiments. Although toxicity was observed, this was not significant at environmental concentrations.

2.3.3 Management outcomes

Project 4.1 and 4.2 have both successfully communicated outcomes into management applications. Project 4.1 has delivered an improved understanding of the quantitative relationships between Queensland Rivers and changes in the coastal water clarity within the downstream environment. The relationship between discharges of major rivers and the water clarity in the GBR waters of the Fitzroy, Whitsundays, Burdekin, Wet Tropics and Cape York NRM Region have been investigated through daily 11-years (2002-2013) MODIS-Aqua remote sensing data at 1 km^2 resolution. This resolution of data allowed the project to investigate affecting water clarity in these regions across relevant time scales. In all coastal, inshore and lagoonal regions except for Cape York, photic depth was strongly negatively related to the freshwater discharge of the main rivers. The declines started with the onset of river floods, and water clarity typically took 150– 260 days until complete recovery. The relationship between photic depth and rivers was strongest in the Northern Wet Tropics, the initiation area of outbreaks of crown-of-thorns starfish, where effects were strong even on the outer shelf. Previous conclusions that river runoff predominantly affects the inshore of the GBR have therefore to be revised for the Central and Northern GBR. The results were used in the setting of regional ecologically relevant targets for fine sediment in the Burnett-Mary and Wet Tropics WQIPs, and will likely be used for other WQIPs.

Project 4.2 adapted experimental procedures and directions in line with ongoing communication between researchers and research users. For example, it became apparent during acute toxicity investigations that all of the PSII herbicides under investigation act on seagrass in the same way but have different potencies. Therefore, following discussion with end users (DoE Chemical Assessments, GBRMPA, APVMA) the focus of the experiments has shifted towards (i) developing techniques to facilitate the rapid and reliable acute toxicity of multiple PSII herbicides, including emerging herbicides, (ii) developing new techniques to link effects on photosynthesis with whole plant effects. Strong communication outputs have continued to be facilitated with NERP Project 4 hosting a series of workshops on Pesticides and the Great Barrier Reef (Pesticide Working Group). The fourth workshop was held in Townsville in November, 2014 included presentations outlining the current synthesis report on Pesticides being compiled for QLD state government.

2.4 Cumulative pressures

2.4.1 Issues

Two projects build on research undertaken through the Marine and Tropical Science Research Facility (MTSRF) and other programs that have identified many of the primary risks and threats to the environmental assets of North Queensland. However, these pressures do not occur in isolation to each other (Figure 2-4) and it is clear that a greater understanding of the cumulative and synergistic impact of these pressures was required for improved management. Managers require information on the type of cumulative pressure, and how to prioritise the approach to dealing with multiple stressors impacting on vulnerable ecosystems over different time periods and at different scales (Figure 2-5)

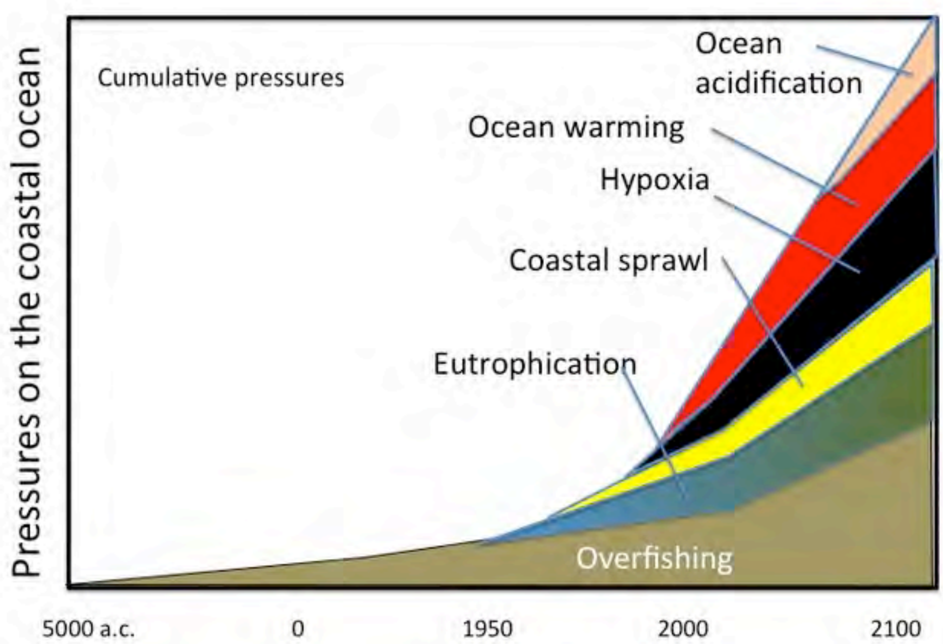


Figure 2-4. Conceptual diagram of six pressures that can add cumulatively on our coastal oceans Figure extracted from Duarte, 2013 ((http://theconversation.com/auditing-the-seven-plagues-of-coastal-ecosystems-13637). Habitat alteration and pollutant input are combined under “coastal spawl”.

Increasing temperatures, ocean acidification (OA) and decreasing water quality from terrestrial runoff are likely to significantly alter ocean and coastal ecosystems over the next few decades. These issues have normally been considered as individual threats to tropical systems, but their interactions are as yet poorly understood and likely to be more damaging than the threats in isolation. Local stressors include water quality affected by terrestrial runoff, which have significantly altered Great Barrier Reef ecosystems, especially on inshore reefs (Brodie et al., 2014). Global stressors such as increasing temperatures and OA have and will continue to increase pressure on reefs over the coming decades. As one outcome of Project 5.2 it was suggested that increased CO_2 and land runoff OA could already particularily impact on GBR inshore reefs Cumulative effects of these global and local stressors are poorly understood and difficult to apply appropriate management actions to deal with them (Uthicke et al., 2014).

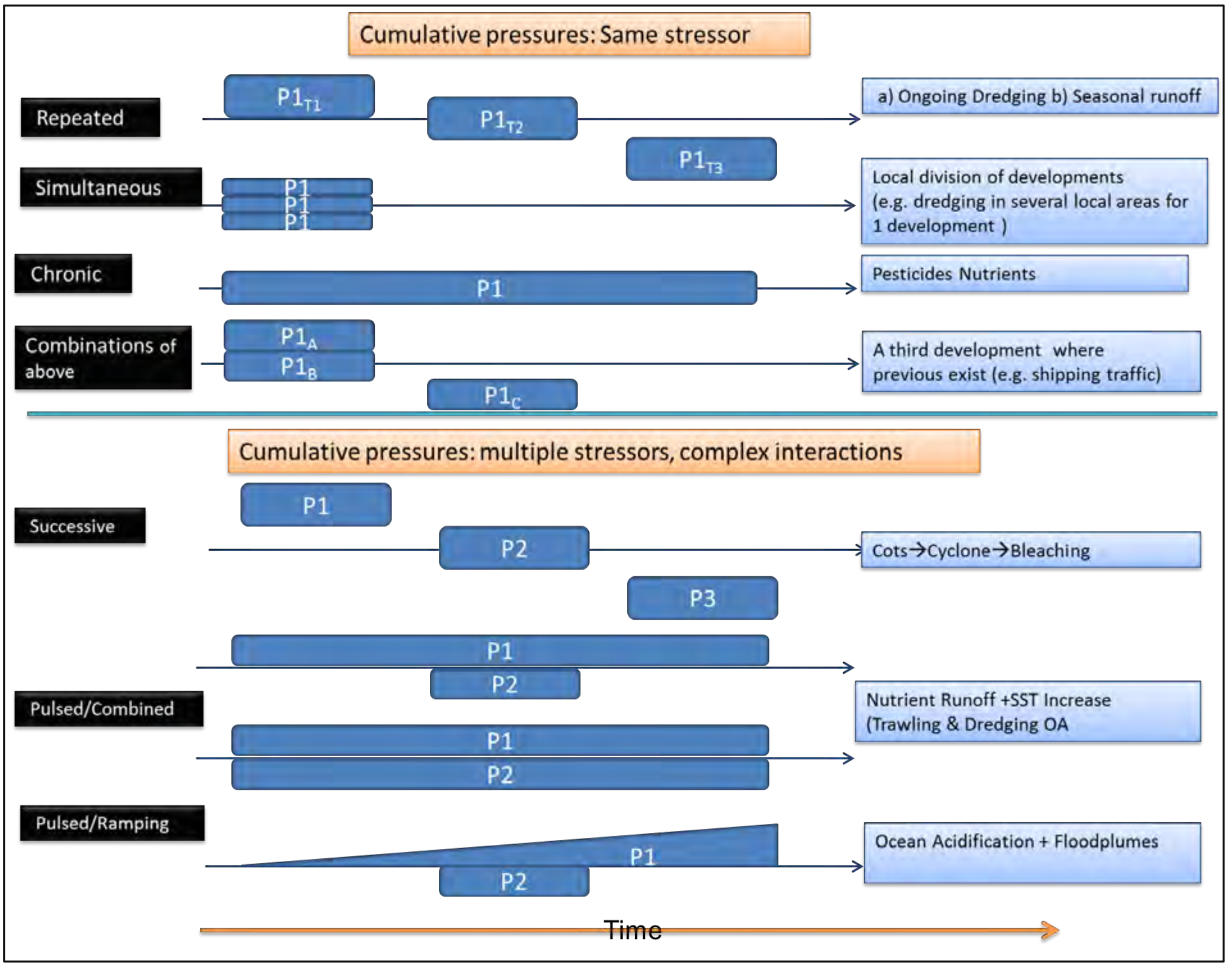


Figure 2-5. Types of cumulative pressures from same stressor (repated, simultaneous, chronic) and multiple stressors with complex interactions (Successive, pulsed/combined, pulsed/ramping). Examples of each type of cumulative pressure are presented.

Increased ocean temperatures negatively affect symbiotic relationships (e.g. coral bleaching) and atmospheric carbon pollution is reducing the ability of tropical marine organisms to calcify. Inshore coral reefs are an important model system to predict whether and how the calcification of reef organisms in general may respond to lower carbonate saturation states and increased temperatures. Freshwater and organic matter from terrestrial runoff may also affect benthic calcification on inshore reefs, by influencing pH, oxygen saturation and carbonate saturation, particularly in the boundary layers of terrigenous siliciclastic and carbonate sediments on coastal reefs. Particular attention needs to be directed toward water quality - OA interactions affecting coral reef organisms that grow within the sediment boundary layers.

Physiological studies are needed to understand the impact of changes in the finely tuned balance between symbiotic relationships and on calcification and metabolism resulting from enhanced carbon (through OA) and enhanced nitrogen (from land runoff). The proposed research project will conduct a series of integrated and complementary laboratory and field experimental studies to assess causal association between the interactions of water quality, ocean warming and ocean acidification.

Seagrass meadows are a vital habitat in tropical coastal ecosystems: they support biodiversity of estuarine, coastal and reef communities, including fisheries species, and they are a direct food source for obligate seagrass feeders such as dugongs. Seagrass meadows in the coastal zone also form a buffer between the catchment and the reef, trapping sediments and absorbing nutrients, with their high productivity rates facilitating rapid nutrient cycling. The Reef Rescue Marine Monitoring Program has identified that seagrass meadows along the GBR are in a state of decline (McKenzie et al. 2010). The Reef Rescue Marine Monitoring Program has established that seagrass meadows along the GBR were in decline in the years leading up to 2011 (McKenzie et al., 2012). The indicators of this decline were: 73% of sites declined in abundance (below the seagrass guidelines) from 2010-2011 and 80% showed a declining long-term trend (5-10 years); 55% of sites exhibited shrinking meadow area, majority of sites had few seeds that would enable recovery. The trends in seagrass decline were the result of changing water quality, particularly caused by flood plumes, as well as the direct impacts of cyclones in localized areas. The decline in seagrass meadow abundance and area was also associated with record dugong and turtle mortality in 2011 (Meager and Limpus, 2012).

One of the biggest threats to seagrass meadow health in the GBR is low light levels, both chronic low light levels, and pulsed acute low light that occurs as a result of flood plumes (Collier & Waycott 2009, Waycott et al. 2009). As such, the impacts of low light has, and is continuing to be, the focus of considerable research and monitoring. The NERP project explored the exposure of seagrass meadows to light, nutrients and salinity, seagrass responses to the interactive effects of these water quality impacts and contributed to the development of thresholds, the establishment of fundamental biological traits for input into modelling exercises and to biodiversity assessments.

2.4.2 Research Outcomes

The two NERP projects looking at the impacts of water quality on GBR ecosystems took different approaches to investigating that impact. Project 5.2 tested pressure conditions on a range of key species including corals, seagrasses, calcifying algae, foraminifera and echinoderms, with project 5.3 focusing on the impacts of deteriorating water quality on GBR seagrasses. Both projects focused on a mix of laboratory based experiments with field work outcomes incorporated in the laboratory design. Project 5.2 investigated the vulnerability of organisms and ecosystems on nearshore reefs of the GBR to increased water temperatures and Ocean Acidification (OA) and tested these vulnerabilities on a range of cumulative impacts and intereactions across several key species. Project 5.3 focused on the vulnerability of seagrasses to declining water quality, in particular, changes associated with flooding and the exposure of seagrass to flood plume conditions.

In collaboration with other projects of the NERP, Project 5.2 focused on multi-factorial laboratory studies and field research, quantifying effects of different water quality parameters (specifically nutrients, reduced light, increased sediment load and reduced salinity) in combination with increased temperature or ocean acidification on keystone species groups and ecosystem processes on nearshore areas of the GBR. This was done through an advanced experimental aquarium system (ATOS), access by research vessels to the whole GBR, and controlled flow-through seawater facilities that allow manipulation of nutrients, carbonate saturation, light and temperature. Similarly, and in collaboration, Project 5.3 focused on multi-factorial laboratory studies and field research, quantifying effects of different water quality parameters (specifically nutrients, reduced light simulations, increased sediment load and reduced salinity) in combination with seasonally variable water temperatures. This was done through experimental aquarium facilities.

Project 5.2 examined climate and WQ interactions and modeled these changes in thresholds and consequences of improved land management by conducting over 15 experiments to assess individual and cumulative impacts of water quality, ocean warming and OA (see summary of all experiments in Table 2-1). In many cases, the combination of stressors showed additive effects, thus clearly suggesting that land-management can ameliorate impacts of climate change. Benthic foraminifera were tested under different temperatures and OA scenarios, and showed that stress resulting from OA and temperature was additive, but also strongly depended on the species investigated. Similar results were found for a keystone echinoid species (rock boring sea urching, Echinometra sp.), with subtle additive responses of OA and temperature increase on adult metabolism. That paper (Uthicke et al., 2014) also strengthens previous conclusions from this project that effects on reproduction and larval stages are more distinct and important for population size maintenance that those on adults. Other studies included interactive effects of OA, light and nutrients on seagrasses, corals and calcifying algae, and of temperature nutrients and OA on corals. The results will assist to better define the threshold of concern for several stressors in combination

This project also investigated carbon chemistry on inshore reefs and compared this to historical data. pCO_2 concentrations in GBR inshore reefs ranged from 340 to 554 µatm, with higher values during the wet seasons and pCO^2 on inshore reefs distinctly above atmospheric values. Aragonite saturation on inshore reefs was consistently lower and pCO^2 higher than on GBR reefs further offshore. Compared to surveys 18 and 30 years ago, pCO^2 levels on inshore reefs have disproportionately increased compared to atmospheric levels. That study suggests that inshore GBR reefs are more vulnerable to OA and have less buffering capacity compared to offshore reefs. This may be caused by anthropogenically induced trophic changes in the water column and benthos of inshore reefs subjected to land runoff.

As an ad hoc response to recent COTS outbreaks North of Cairns, Project 5.2 researchers also conducted a series of experiments to investigate single effects of temperature or combined effects of temperature and food (microalgal) increase on larvae of this coral predator (Lamare et al., 2014; Uthicke et al., 2013). A surprise result of this was that temperature was a strong modulator of larval response to algal increase: A slight increase in temperature as expected under global change and which already has occurred over the last 100 yrs can amplify the larval response to increased food and enhance survivorship and development of the larvae (Uthicke et al., in press). Thus it cannot be excluded that temperature increase has qaggravated COTS outbreaks.

Table 2-1. Summary table of Interactive/cumulative effects of Global and Local stressors on Coral Reef organisms. This is the summary of all previous MTSRF work and the outcomes from NERP project 5.3. Note that *unpublished is denoted with *, interactive effects denoted with # and TBA identifies experiments have been conducted, data "to be analysed". Abbreviation: ex: experiment, MQY: maximum quantum yield of photosystem II, P: Production/Photosynthesis, ↓: reducing effect on respective parameter, ↑: enhancing effect, - no effect, blank field: not measured.

Global	Local	Organism	Calcification/growth	Production	General Effects/Other parameters	Comment/Species	Literature
Temp X	Nutrients	Corals			Organic enrichment reduced bleaching threshold, DIN alone not	Outcomes depend on trophic status	(Fabricius et al. 2013)
	Organic nutrients	Coral			Fertilisation T↓ N↓#		Humanes et al*
					Embryogenesis T↓ N↓#	abnormalities	Humanes et al*
					Larvae survivorship T↓ N↓#		Humanes et al*
					Larval settlement	Minor effects of	Humanes et al*
					Recruit survival T↑		Humanes et al*
		Foraminifera	T↓, DIN↓= **additive**	T↓ (also chlorophyll)	Survivorship:T↓, DIN↓ = **additive**	Symbiodinium bearing (*M. vertebralis*)	(Uthicke et al. 2012) (MTSRF)
		Foraminifera	In 2 species: T↓, DIN-	T↓ (also chlorophyll)		3 Diatom bearing species, no effect of DIN addition	(Schmidt et al. 2011) (MTSRF)
		Biofilms		Under high light: additive neg. effect of T and DIN on production		Both T and DIN also alter microbial community	(Witt et al. 2012) (MTSRF)
	(decreased) Light	Biofilms			No direct interaction, but some light x Nutrient effects dependent on light levels		(Witt et al. 2012) (MTSRF)
		Seagrasses		Depending on species: T and L effects, for Zm high light can ameliorate neg. effects of T		*Zostera muelleri*, *Halodule uninervis*	(Collier et al. 2012) (MTSRF)
	Pollution	Corals		T, Diuron and Atrazine: ↓**additive** for Photosynth. Efficiency, **synergistic** for MQY		*Acropora millepora*	(Negri et al. 2011) (MTSRF)

		CCA		T↓, no Diuron or interactive effect			(Negri et al. 2011)
		Foraminifera		T↓ Diuron↓, cause bleaching	Most effects were **additive**, few **sub-additive**	Several species with different symbionts	(van Dam et al. 2012) (MTSRF)
CO_2 X	Nutrients	Corals	TBA	TBA			Vogel, in preparation.
		Halimeda	TBA	TBA			Vogel, in preparation.
		Seagrass	TBA	TBA			Ow et al., in prep (LI studies)
		Foraminifera	pCO_2 no effect, DIN↓	Chlorophyll: pCO_2 no effect, DIN↑			Uthicke et al. in prep (LI Experiments)
	(decreased) Light	Coral	pCO_2↓ Light↓	Light↓	**Additive** effects of light and OA on growth		Vogel et al in press
	(increased) Turbidity	Halimeda	Light↓ pCO_2 dark calcification	Light↓			Vogel et al in prep
		Seagrass	TBA	TBA			Xiang-Ow in prep
	(hypo) Salinity	Corals	TBA	TBA			Teng et al. in prep
CO_2 X Temp		Corals		T↓, CO_2 ↑	Mild OA (750 µatm pCO_2) did not increase bleaching susceptibility in common coral taxa in the field nor in the	Field: coral families Acroporidae, Faviidae, Pocilloporidae or	Noonan and Fabricius (in review)
		Foraminifera	- CO_2 ↓	T↓ T↓	CO_2 also reduced chlorophyll T and CO_2 had negative	*M. vertebralis* *H. depressa*	(Schmidt et al. 2014)
		Echinoids (adult)				Several metabolic parameters +gonad development	(Uthicke et al. 2014)

Project 5.3 was established in response to extensive seagrass loss that occurred from 2009 to 2011 in the Great Barrier Reef when there was above average run-off for multiple wet seasons, which culminated in the passage of cyclone Yasi through the northern GBR in 2011. Seagrass meadows in coastal and estuarine regions of the GBR were exposed to plumes of variable water quality during the wet season months (Nov-April). Ocean colour information derived from remote sensing was used to develop water quality thresholds that occur when seagrasses have experienced greater than 50% loss in abundance. Different permutations of ocean colour conditions have been extracted for the four main seagrass habitats. The derived water quality thresholds all relate to the constituents (TSS, chl-a, CDOM) that influence the light attenuation. Therefore, in situ data and aquarium-based experiments were used to test seagrass responses to salinity, light and nutrients to identify which aspect of flood plumes have the greatest effect on meadow health.

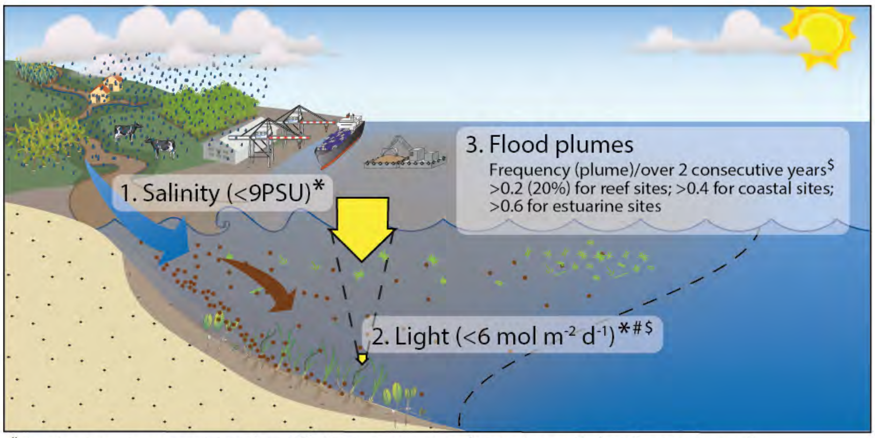
The response of seagrasses to hypo-salinity was tested from 3 PSU (almost freshwater) to 36 PSU (seawater). GBR seagrasses had broad hypo-salinity tolerance with thresholds (associated with mortality) occurring at <3 PSU for Zostera muelleri and <9 PSU for Halophila ovalis and Halodule uninervis after 10 weeks (0). There was a stress-induced morphometric response at low-moderate salinities (9 – 15 PSU) whereby shoot density proliferated in response to hypo-salinity. Given the broad salinity tolerance it is highly unlikely that low salinity was the primary cause of seagrass losses associated with flooding. Thus hypo-salinity is not seen as a future issue for seagrasses and would not be a component of any further interactive experimental testing.

Seagrass abundance at Magnetic Island and Dunk Island was correlated to in situ light levels using data from the Reef Rescue MMP. High and significant ($p<0.05$) correlations between seagrass loss and low light, suggests that low light contributed to seagrass loss from 2009 to 2011. Therefore, effects of low light were prioritized for further experimental work, including the interactive effects of elevated nutrients and seasonal variations in water temperature. Four seagrass species were grown at two temperatures, warm (~27°C) and cool water (~22°C), and were exposed to light levels ranging from 0 to 70% of full sunlight (0-23mol m^{-2} d^{-1}) in aquaria experiments for 3 months. All species suffered faster mortality (declines in seagrass) in warm compared to cooler water, and H. ovalis and Z. muelleri were more sensitive to low light levels than C. serrulata and H. uninervis.

From this study, light thresholds for any chosen level of seagrass decline (e.g. 10, 20, 50% decline) could be calculated. 50% loss occurred at 3 to 6 mol m^{-2} d^{-1} after 14 weeks exposure depending on species and water temperature (0), and 20% loss occurred at 7.4 to 10.4 mol m^{-2} d^{-1}. This experimental approach revealed a very similar light threshold for H. uninervis from Magnetic Island derived using in situ decline and in situ daily light (both approximately 4 mol m^{-2} d^{-1} for 50% loss after 3 months in warm water). The similarity has increased confidence in thresholds derived from experimental work for other species and verified the conclusion that low light was a large contributor to recent in situ seagrass loss in the GBR (thresholds summarised in Figure 2-6, Table 2-2).

Indicators of light reduction, tested using experimental approaches were quantitatively reviewed from 58 published studies. Meadow-scale responses were the most consistent to respond, such as above-ground biomass and shoot density, followed by morphological responses. Physiological indicators, which are frequently tested as early-warning indicators of light reduction were the least consistent in their response, however a few indicators offer promise as reliable indicators of light reduction in monitoring programs (e.g. the tissue nutrient ratio C:N is currently used in the Reef Rescue MMP).

The Indo-Pacific seagrasses tested in this project differed in their sensitivity to flood plumes, light, nutrients and salinity. For example, Halophila ovalis was the most sensitive to both hypo-salinity (b) and light stress (g). Therefore, it is expected that this species will be the first to disappear following an impact involving these environmental stressors. This species is a disturbance specialist: it produces large seed banks and regrows quickly from seed after a mortality event (Collier and Waycott, 2009). In contrast, the slightly less sensitive species (e.g. H. uninervis), may initially resist stress, but then recover more slowly than other species. Diverse seagrass meadows that include these climax species will not be sustained in a scenario with chronic water quality decline, as well as event-based impacts.



*for short-term exposure, varies with time of exposure (up to 3 months) and among species
#affected by temperature $threshold is established for seagrass loss of greater than 50%

Figure 2-6. Summary of salinity, light and flood plume thresholds reported on in Project 5.3

2.4.3 Management outcomes

Outcomes of Project 5.2 will feed ecosystem models assisting managers in decision-making. Results were included in the Scientific Consensus Statement, which was used in support of the revision of ReefPlan 2013.The consensus statement was used to inform various chapters of the GBR Strategic Assessment. Project 5.2 also linked to many research-users (GBRMPA, regional and tourism management agencies) through a workshop (August, 2015) that reported on the type, scale and impacts of cumulative pressures on GBR ecosystems.

Project 5.3 has succesfully shown that water quality risks to seagrasses vary spatially, and for seagrasses, the highest risks occur in the Burdekin and Fitzroy NRM regions primarily due to high loads of catchment sourced suspended sediments (Brodie et al., 2013a). This risk assessment has provided a means by which management for improved water quality can be targeted for the greatest benefits. High turbidity and low light are not the only risks to seagrasses from declining water quality. Nutrients, and herbicides in particular affect seagrasses either directly or indirectly (Brodie et al., 2013a; Flores et al., 2013). Interaction between these stressors, particularly where synergistic or cumulative impacts occur, is a further concern.

This study has and will continue to contribute to the following management outcomes:

- Identified seagrass meadows at high risk of exposure to flood waters when certain conditions, defined by the frequency of colour classes, are experienced over two consecutive years.
- Different permutations of ocean colour information can provide information that can be used to develop guidelines on habitat scale seagrass loss.
- Developed new environmental thresholds (light), which will be incorporated into seagrass guidelines for protection of GBR seagrasses (scheduled for 2015).
- Measured new salinity thresholds, which occur at low salinities.
- Confirmed metric selection (sub-lethal indicators) and scoring for Reef Rescue MMP reporting.

Table 2-2. Summary of findings in relation to the environmental variable, light for seagrass community measurements.

Approach	*Environmental parameter*	*Range tested*	*Finding*
Flood plume exposure	Primary and secondary water types. Contains: high turbidity, high chlorophyll *a* high CDOM all attenuating light	Primary and secondary water types	Meadows exposed to moderate frequency of both primary (Fp) and secondary (Fs) waters are the most sensitive and both water types have high light attenuating properties (0.4 – 0.7)
Event-based *in situ* seagrass loss/*in situ* light loggers	Daily light (mol m^{-2} d^{-1}) Frequency of low light days Hsat	2.3 – 14.2 mol m^{-2} d^{-1} % days <14 mol m^{-2} d^{-1} 3.6 – 10.56 hrs	• In-situ changes in seagrass abundance (*H. uninervis*-dominated communities) were correlated with *in-situ* light • This relationship enabled identification of light thresholds for >50% loss • Loss of Halodule-dominated meadows occurred at 4 mol m^{-2} d^{-1} over 3 months
Light experiment	Daily light (mol m^{-2} d^{-1}) Percent of surface light (%SI)	2.8 – 11.1 mol m^{-2} d^{-1} 10 – 40%	Sub-lethal (early warning) indicators tested (prior to shoot loss) C/N, $\delta^{13}C$ and rhizome carbohydrates were sensitive to light but: • C/N only sensitive at low-moderate nutrient concentrations • $\delta^{13}C$ and rhizome carbohydrates were less sensitive to nutrients, and sensitivity was species dependant
Light x nutrients	Daily light (mol m^{-2} d^{-1}) % of surface light (%SI)	2.2 – 8.7 mol m^{-2} d^{-1} 10 – 40%	
Light x temperature	Daily light (mol m^{-2} d^{-1}) Percent of surface light (%SI)	0 – 23 mol m^{-2} d^{-1} 0 – 70%	• Shoot loss and growth reductions at low light (0 – 10% SI) over 14 weeks • Time to complete seagrass measured: Ho<Zm<Cs<Hu • Light thresholds developed e.g. 3.8 mol m^{-2} d^{-1} for 14 weeks leads to 50% loss of seagrass • Experimental light thresholds were comparable to in-situ thresholds (*H. uninervis, Z. muelleri*)

2.5 Priority areas for management

2.5.1 Issues

Ecosystems in the Barrier Reef lagoon are at risk from upstream pollutants sources from the adjacent catchments. In order to manage these risks, managers need a reliable way to assess the risk posed by different land uses, catchment characteristics and toxicants to different inshore ecosystems of the GBR. A flexible, ecological risk assessment (ERA) methodology was recommended, based on well recognized international approaches, for assessing the relative risk of contaminants and associated land uses in the GBR region. The strategy was finalised during the scoping study of the project based on the (i) a review of risk assessment approaches currently being conducted by CSIRO (ii) the data availability as determined during the information gathering and synthesis component and (iii) the suitability to achieve the objectives of this project.

Increasing coastal development of the Great Barrier Reef coastal zone is inevitable in the coming decades. Development will increase shipping, intensive agriculture, urban development, and tourism. To inform management, planning, and policy, it is therefore necessary to assess potential scenarios of coastal development and their cumulative impacts on marine species and ecosystems.

2.5.2 Research outcomes

Project 4.3 finalised a scoping study to determine the most effective approach for assessing risks to biodiversity in the inshore Great Barrier Reef (GBR) from declining water quality. It involved an extensive review of the methodology required for a comprehensive GBR risk assessment and gave final recommendations as to the most suitable method to drive the assessment. Outputs included a 'meta database' of the existing data and listed all the information needed to run a risk analysis. As an outcome of this project, the proposed methodology recommends a combination of qualitative and semi-quantitative assessments for the relative risk of water quality pollutants from major agricultural land-uses in the GBR catchments and sub-catchments. These methodologies outline an approach which focused on the relative risk of different reef contaminants e.g. sediments (different size fractions), nutrients (nitrogen, phosphorus) and pesticides (different types) to different ecosystems and their keynote species.

The outcomes considered that any risk assessment should consider land-uses, catchment characteristics and pollutant runoff in identifying the impacts on estuarine wetlands, seagrass, coral reefs and the pelagic zone ecosystems) of the GBR lagoon. This information will be required to address the relative risk of different water quality contaminants in the GBR catchments to the different ecosystems and their keystone species. This will enable the pollutants that are most damaging to different ecosystems to be identified and managed.

The preliminary findings from this project have helped guide the process of completing a GBR wide risk assessment, This risk assessment method was developed and applied to the GBR to provide robust and scientifically defensible information for policy makers and catchment managers on the key land-based pollutants of greatest risk to the health of the two main GBR ecosystems (coral reefs and seagrass beds). This information was used to inform management prioritisation for Reef Rescue 2 and Reef Plan 3. The risk assessment method needed to take account of the fact that catchment-associated risk will vary with distance from the river mouth, with coastal habitats nearest to river mouths most impacted by poor marine water quality (see Brodie et al. 2014; Waterhouse et al., 2014). The outcomes from this revised risk assessment are summarised in Figure 2-7.

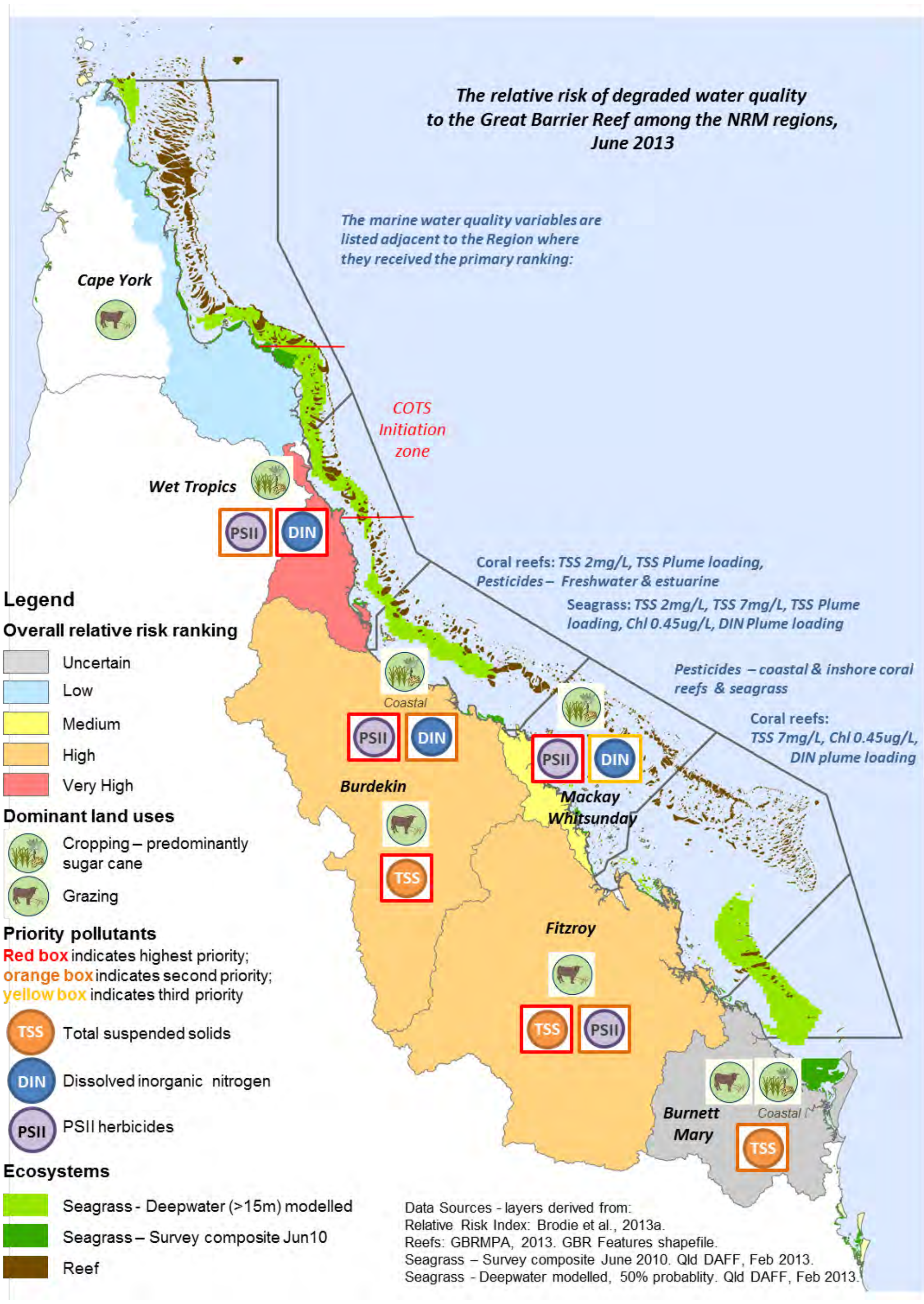


Figure 2-7. Illustration of the overall outcomes of the assessment of the relative risk of degraded water quality to Great Barrier Reef coral reefs and seagrass. The map shows the dominant land uses and priority pollutants and results of the overall relative risk ranking in each NRM region.

Project 9.4 compiled spatial data on biodiversity pattern in Great Barrier Reef coastal ecosystems. Results to date have informed management on changing baselines by the assessment of potential scenarios of coastal development and their cumulative impacts on marine species and ecosystems. Along the Great Barrier Reef coastal zone, the project produced eight spatially-explicit scenarios of coastal development for 2035, covering land uses and related marine activities using Geographic Information Systems. The range of 2035 scenarios incorporated uncertainty around demand for food, mineral and coal, tourism, and environmental services, and took into account technical advances, preference for coastal living, and governance.

For Project 9.4 Bayesian networks (BNs) have now been developed for three selected marine assets (seagrass, dugongs, coral reef fish) to produce general models for cumulative impact assessments of the land-use change scenarios previously produced (see Figure 2-8 for an example of the process for relating land use change scenarios to seagrass coverage). The BNs are applied spatially using the spatial marine layers depicting areas and intensities of marine activities and runoff resulting from the coastal development scenarios. The results are a visualisation of cumulative impacts on the selected case studies as maps that help managers understand the consequences of particular spatial allocations of development along the coast. This will be used for spatial planning for coastal development to mitigate impacts on marine values of the GBRMP.

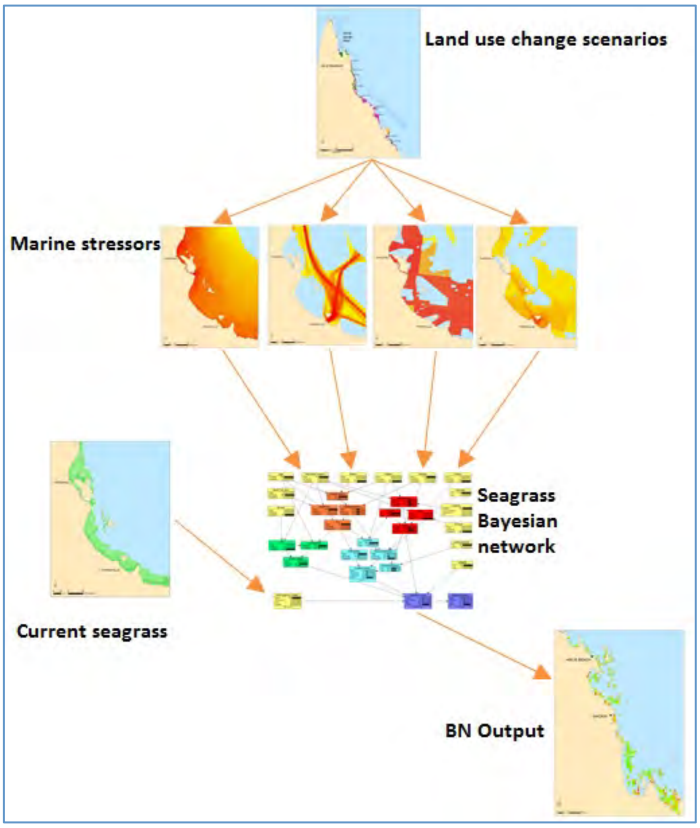


Figure 2-8. Outline of process utilizing a Bayesian network approach to develop future coastal scenarios and estimate their impacts on seagrass.

2.5.3 Management outcomes

Project 9.4 has advanced world's best-practice in systematic conservation planning, both scientifically and in terms of collaboration with managers and other stakeholders. The project's science and application are specifically designed to allow managers to make more informed decisions about the conservation of Queensland's tropical coastal zone and the GBRWHA.

Along the Great Barrier Reef coastal zone, eight spatially-explicit scenarios of coastal development were produced for 2035, covering land uses and related marine activities using Geographic Information Systems.

The framework developed in this project includes:

1. Governance analysis for the GBR coastal zone,
2. Coastal development scenarios and spatially-explicit representations,
3. Spatially-explicit marine consequences of these scenarios,
4. Conservation objectives, and
5. Cumulative impact assessment.

The range of 2035 scenarios incorporated uncertainty around demand for food, mineral resources, tourism, and environmental services, and took into account technical advances, preference for coastal living, and governance. The process used Bayesian belief networks with elicitation to capture both data and expert opinion on the related factors linking land-use changes in the coastal zone to impacts on specific marine species and ecosystems, taking account of related changes to water quality and activities in the Reef's lagoon. This approach provides a quantitative understanding of cause-and-effect relationships under a range of future scenarios and greatly improves understanding of cumulative impacts. It provides a large-scale planning and decision-support tool for managers and policy-makers to explore and minimise the impacts of coastal development. This approach can be adapted easily to investigate small parts of the coastal zone, including sites of individual developments, and to estimate the cumulative impacts of government policies.

There is a high level of interest from the GBRMPA in using the methodology developed in Project 9.4 for decision support regarding coastal management. The agency will continue to liaise with the project team to develop a working prototype. GBRMPA has also expressed interest in integrating the published governance risk assessment technique into future outlook reports, and including this monitoring approach into the unfolding Sustainability Planning process. This framework and the methodology for each step in the project constitute the description of a decision-support process for coastal-zone managers towards spatial planning for the entire GBR coastal zone.

The data from Project 9.4's cumulative impact assessment will be combined with herbicide persistence data, water quality and climate data to contribute to cumulative risk models and thus to policy development to provide information on how the GBR will respond to the cumulative effects of pollution and climate change, and to attempts to mitigate adverse impacts.

This data will be combined with herbicide persistence data, water quality and climate data to contribute to cumulative risk models and thus to policy development to provide information on how the GBR will respond to the cumulative effects of pollution and climate change to protect the coastal area of the GBR.

Key outcomes from preliminary risk assessment in project 4.3 included the selection of a systematic, objective and transparent approach to assess the relative ecological risks posed by nutrients, pesticides and suspended sediments to GBR ecosystems. The final report identifies an approach which will give more usable and much more robust results than the previous MCA approaches. This project has had direct engagement with strategic stakeholders, including industry groups, Australian Government, Queensland Government and regional NRM bodies.

This project outlined a process for the final GBR risk assessment that included:

- Hindcast hydrodynamics and connectivity to establish relationships between flood conditions and COTS abundance / distribution
- Nutrient (N:P) ratios in river and marine environment
- TSS analysis
- Pesticide analysis
- Surface exposure modelling - GBR wide
- Status of ecosystems – seagrass and coral
- Risk assessment and coordination

Using this information in a GBR wide risk assessment, the overarching conclusion drawn from this follow up project is that the greatest water quality risks to the GBR are from nitrogen discharge, associated with crown of thorns starfish outbreaks and their destructive effects on coral reefs, and fine sediment discharge which drives light reduction for seagrass ecosystems and inshore coral reefs. Pesticide inputs pose a risk to freshwater and some inshore and coastal habitats. These statements have been included in the Reef Plan Scientific Consensus Chapter (Chapter 3) Relative risks to the GBR from degraded water quality (Brodie et al. 2013b).

2.6 Monitoring and evaluation of key ecosystems

2.6.1 Issues

Much of our knowledge on the Great Barrier Reef (GBR) comes from spatially and temporally limited studies which can hinder our ability to appropriately assess the current state of the reef. The objective of this large scale project was to provide a deep-time, baseline understanding of changes in ecological and environmental condition across the entire length of the inshore GBR (Figure 2-10). Using palaeo-ecological and –environmental approaches combined with precise geochemical techniques, we provide millennial scale histories of reef development from Cape Grenville in the north to Hervey Bay in the south, with evidence for recent changes in coral community composition in the central region of the GBR attributable to dramatic land use changes since European settlement (c. 1850 AD). Using highly precise U-Th dating methods we have been able to constrain the timing of changes in coral community composition with precisions of up to ± 1 yr, allowing us to pinpoint the likely cause for mortality (e.g. Clark et al. 2014). The many outcomes from this research will prove invaluable to reef managers by extending their knowledge of reef dynamics beyond marine monitoring programs, assisting with identifying the timing and drivers of change, as well as the reasons behind the lack of recovery at many inshore reefs.

High-precision U-series dating (to precisions of ±1-10 years) has been used to establish a reliable chronological framework for processes and events to be reconstructed and correlated for the ecological reconstruction of coral reef communities. This will include high-precision boron isotope analysis for ocean acidification studies, reconstruction of past cyclone activity through dating a combination of cyclone proxies such as transported reef blocks, super-cyclone ridges and lagoon sediment profiles, reconstruction of high-resolution sea-level based on microatolls, high-resolution geochemical proxy analysis for reconstruction of ambient environmental conditions (e.g. SST, SSS, turbidity, etc).

The geochemical, geochronological and palaeoecological methods used in this project are highly innovative, and have allowed for the investigation of a range of GBRMPA priority-listed key stressors: rising sea-level; rising sea-surface temperature; seawater acidification; increased sediment/nutrient discharge; increased pollution from urban development; and other climatic drivers such as ENSO and cyclones.

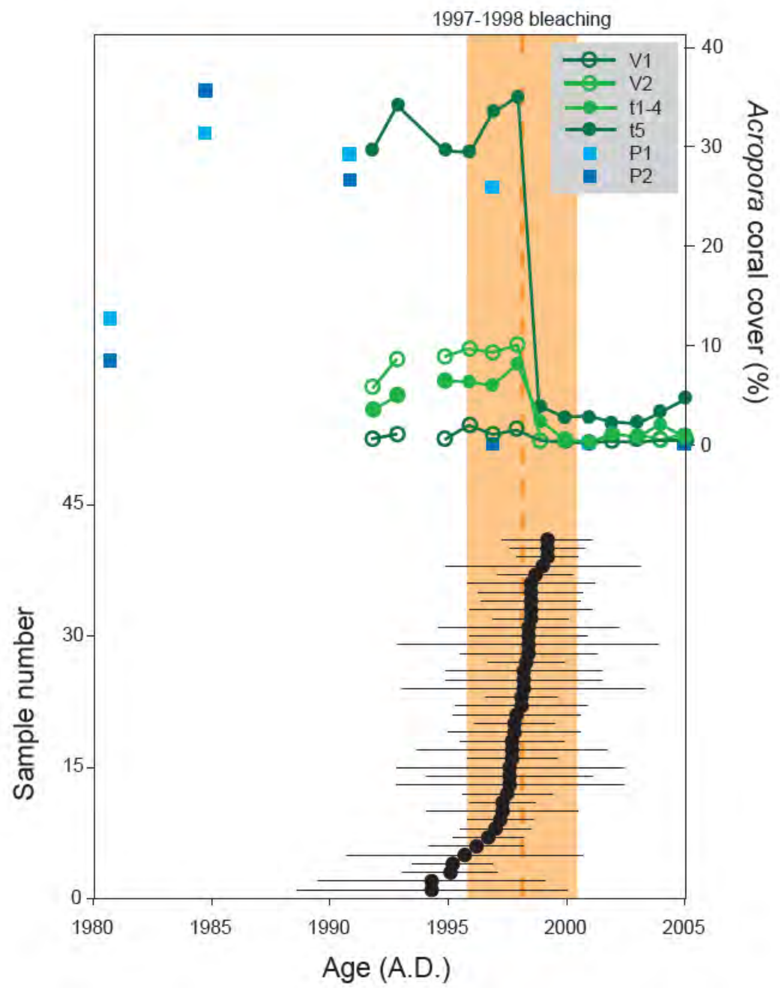


Figure 2-9. Example of high-precision U-Th dating of young corals and the ability to link mortality with specific drivers. U-Th age data obtained from 41 dead Acropora corals collected from Pandora Reef (bottom) overlaps precisely with the timing of Acropora coral collapse reported by the AIMS long-term monitoring program and Done et al. (2007) in 1997-1998 as a result of anomalously high sea-surface temeratures (vertical orange bar) (modified from Clark et al. 2014).

2.6.2 Research outcomes

The aim of Project 1.3 was to improve our understanding of ecological and environmental changes on the inshore region of the Great Barrier Reef (GBR) over broad temporal and spatial scales using a range of cross-disciplinary methods. This work characterised the impacts of global, regional and local stressors on the present and past biodiversity of the GBR (Table 2-3). Key findings were across several sub-projects, with strong input from post graduate work.

The overarching goal of project 1.3 was to correlate the historical changes in the ecology of GBR inshore reefs with major anthropogenic stressors and with natural and anthropogenically-driven climatic events over the past several millennia, through European settlement and up until present day (Figure 2-10). By the end of the project in 2014, a total of 269 reef matrix cores were taken, with the majority exceeding 3m in length and providing a record of reef devlopement spanning ~6 000 years in some cases.. More than 750 death assemblage samples, 15 massive Porites cores, 191 micoratoll samples, and over 41 samples from storm transported corals were also collected. Some of the key research findings are detailed below with further information on methods and outcomes listed in Table 2-3.

Environmental change on inshore reefs of the GBR

To improve our understanding of ocean acidification and the impact it will have under future climate change scenarios, this project investigated the use of high-resolution boron isotope data obtained from massive Porites coral skeletons to reconstruct past seawater pH. Much of this work is still in its infancy; however, D'Olivo et al. (2014) showed a clear seasonal pattern in boron isotopes, with low values observed in summer and high valuesin winter. The variation in seawater pH reconstructed from the boron isotope data was found to be larger than values observed from the limited in situ instrumental seawater pH records. The offset between the coral data and in situ measurements suggests that the coral amplifies the environmental signal. The implications for the interpretation of the boron isotopes are yet to be established.

A thorough understanding of past storm/cyclone history is also important, not only to be able to make future predictions, but also to understand how these events influenced coral commnuties in the past. In the Frankland Islands, central GBR, U-series ages obtained from large transported coral colonies were found to match well with known historical storm/cyclone events in the last century. In addition, storm/cyclone activity was found to correlate with positive phases (generally warm/dry climate conditions) of the Pacific Decadal Oscillation (PDO) over the last millennium (Liu et al. 2014). In the Hervey Bay region, U-series dating of a distinct coral fossil ridge which has been preserved in the adjacent coastline 2.3 to 4.6 m above sea level has revealed that a possible tsunami/storm event occurred around 1636 AD. Interestingly, coral growth forms that dominate the fossil ridge (mainly branching corals) are completely different to modern corals currently found off Hervey Bay (massive growth forms such as Favia and Turbinaria spp. typical of inshore turbid reefs). However, it is not known whether the coral remains were sourced from the Hervey Bay region, or were transported from further offshore (Butler PhD Thesis).

Ecological changes on inshore reefs of the GBR

Changes in coral communities measured by different palaeoecological techniques showed a marked difference in response to acute disturbance events and changes in environmental condition over broad spatial scales (the entire inner GBR) and at more local, regional scales. In the Palm Islands region, loss of large branching Acropora corals was highly variable between sites, and was driven by a combinationof global, regional and local stressors, including thermal bleaching and flooding (Roff et al. 2013; Clark et al. 2014). Their lack of recovery is argued to be a result of a chronic decline in water quality caused by increased sediment delivery (and other pollutants) to the region as a result of land-use changes since European settlement (c. 1850). Preliminary data from reef-matrix cores collected in the Frankland Islands region has also revealed evidence of Acropora decline. This is in contrast to the Keppel Islands in the southern GBR, where branching Acropora corals have remained the dominant reef builder for the past 6000 years.

Towards the end of the project, fieldwork was also conducted in the remote far northern sector of the GBR. The information contained in the 45 reef matrix cores that were collected (such as changes in community composition and community response to disturbances) will be highly valued as a 'control' for comparison with reefs from the central and southern regions of the Great Barrier Reef that are regularly influenced by human activities.

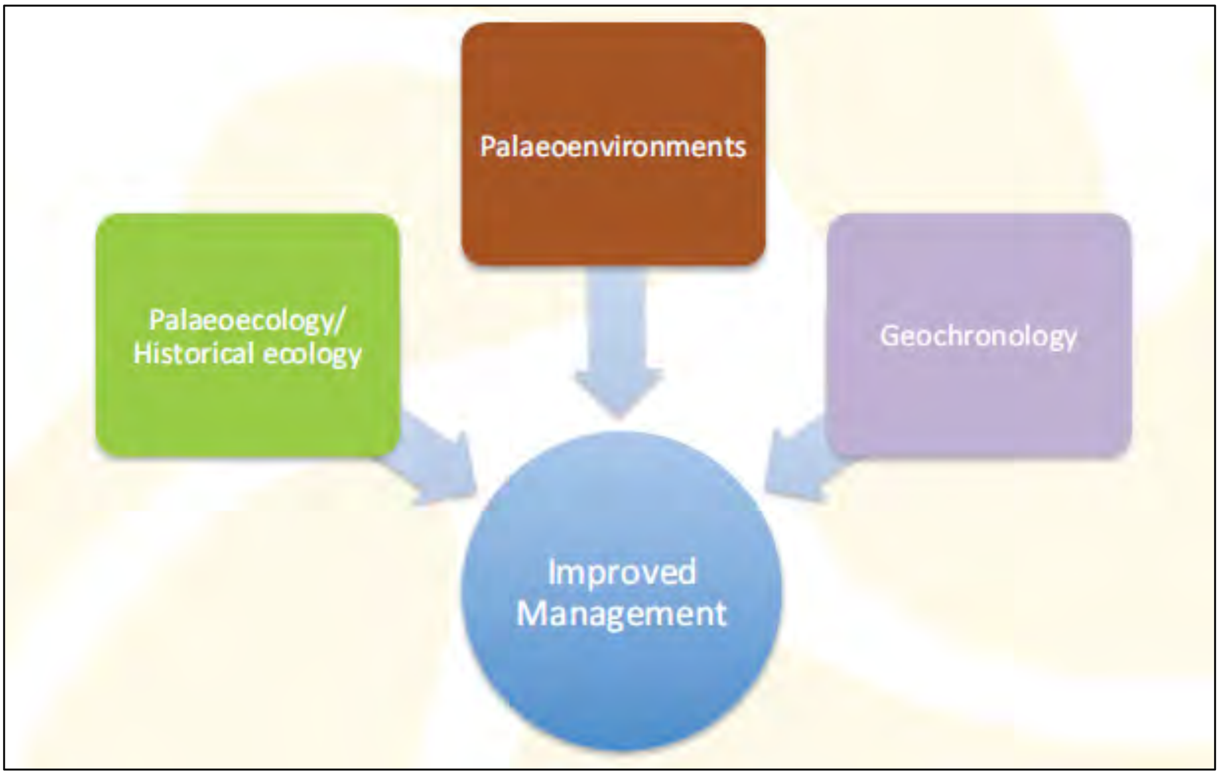


Figure 2-10. The utilization of palaeoecological data for improved and informed management decisions.

The main outcomes from this multi layered research program demonstrate just how important palaeoecological studies can be in the provision of a quick assay to determine timing of ecological change at sites on individual GBR reefs. Results show that identifying drivers for the lack of recovery is just as important as identifying timing and drivers of change.Variability at multiple spatial scales adds complexity to the underlying effects of a shifted baseline in Great Barrier Reef coral communities. Land use changes since European colonization have depleted abundances of Acropora on inshore reefs of the GBR. Many of the drivers kill corals, including bleaching, COTS, cyclones) but lack of recovery on inshore reefs appears to be related to water quality. At impacted sites, historical composition differs markedly from that derived from present day and decadal-scale monitoring surveys.

Table 2-3: Overarching goals of NERP Project 1.3 and a description of the various methods used to achieve the goals

Goals	Objectives	Sampling Methods & Geoarchives	Age range	Methodology
What are the environmental changes on inshore GBR reefs over broad temporal scales?	SST, SSS, ENSO variability and cyclicity	Coral cores/long-lived coral specimens	Prior to/after European settlement	Multi-proxy records of environmental parameters/geochemical proxy analysis of U-series dated coral cores/long-lived coral specimens
	Past sea level variability	Well-preserved coral microatolls	Millennial to yearly scale	U-series dating/elevation survey
	Cyclone history/freq	Transported reef blocks/cyclone ridges/lagoonal sediment cores	Past 1-3 millennia	U-series dating/grain size analysis
	Water quality (WQ) change	Coral cores/reef sediment cores	Since European settlement	Geochemical proxy analysis and palaeoecological data
	Seawater alkalinity variation/recent acidification		1000-1500 yrs (annual – 5 yrs for key periods of ecological change)	Boron isotope analysis
What are the ecological changes in inshore GBR coral reef communities over broad temporal scales?	Ecological history of coral reef communities: coral reef community structure/coral death rates	Existing systematic field surveys/new live surveys/historical photos/sea floor death assemblage/ reef sediment cores for fossil assemblages	Last 150 yrs/centennial to millennial time-scales	Nested sampling over time and space/palaeoecological analysis/U-series dating

	Patterns of coral calcification through time	Corals from reef sediment cores/long-lived coral specimens	Past 1-3 millennia	X-radiography/CT scanning/Gamma densitometry (linear extension and density measurements)
	Colony partial mortality rates	Massive coral cores	Past several centuries	X-radiography
	Reef accretion rates	Reef sediment cores	Past 1-3 millennia	U-series dating/core stratigraphy
How do inshore GBR communities respond to environmental change?	What was natural for inshore GBR reefs? Cumulative effects of multiple environmental stressors on reefs Attribution of palaeoecological change with natural and anthropogenic events (European colonisation and climate change)	Sea floor death assemblages, back-reef and lagoonal sediment cores, historical photographs, fossil assemblages, massive coral cores, cyclone transported reef/coral blocks, storm ridges	Past 1-3 millennia/all time-scales (decadal to millennial)	Time correlation – ecological changes and physical environmental drivers (SST, acidity, salinity, cyclones, floods, runoff, WQ, boron isotopes)/multiple methodologies/global warming scenarios

2.6.3 Management outcomes

The large multi-disciplinary project 1.3 adddressed key questions in our understanding of ecological and environmental changes on the inshore region of the Great Barrier Reef (GBR) over broad temporal and spatial scales. This long term data provides the baseline of information required for managers to make informed decisions on the causes and consequences of change in GBR coral reef ecosystems. This project developed a dated chronological framework to correlate historical stressors and assess their interactions and relative contributions toward reef degradation. Our sampling strategy covered high- and low- impact regions along a latitudinal gradient to isolate different stressors (e.g. water quality, climate change) and assess their relative roles in different regions. This long-term high-resolution environmental baseline will be useful to managers to quantify natural variability and cyclicity, and against which the impact of European settlement and anthropogenic global warming can be isolated and properly assessed.

This project has convened two workshops, with the first workshop presenting a broad introduction to the project and several presentations of outcomes to reef and catchment managers.

Work presented examined the broader scope of the program to ascertainin the link between terrestrial discharge, water quality, global warming, ocean acidification on the GBR over decades – centuries – millennia. This work is done through combining coral reef ecology, paleoecology, high-precision U-series dating, geochemical analysis (environmental reconstructions). The main deliverables presented included:

- Palaeoecological reconstruction of coral mortality events, coral reef community structure changes, reef accretion, and coral calcification prior to and since European settlement
- Reconstruction of past climate variability prior to and since European settlement (natural stressors)
- Reconstruction of past seawater characteristics prior to and since European settlement (anthropogenic stressors)

The second workshop was to bring together a small sub-section of researchers to write a definitive paper on historical pressures on the GBR.

3. Summary – WQ projects.

Several key issues have been addressed in the outcomes of these water quality projects. A summary of the issues and a brief description of the main research and management outcome is presented in Table 3-1.

Table 3-1. Summary of research issues, outcomes and management uptake associated with water quality projects.

Issue	Research outcomes	Management Uptake
Water clarity is a key parameter affecting the health of coastal marine systems and their tourism values.	*Project 4.1 investigated the variation in coastal turbidity for the whole inshore GBR over 10 years, using daily Modis Aqua remote sensing data at 1 km resolution.* GBR water clarity is strongly related to river discharges in many but not all parts of the GBR. Effects extend to lagoon in southern region, to midshelf in Burdekin Region, and to outer shelf in Wet Tropics; patterns are weaker in Cape York In the northern and central GBR, the river influence is NOT restricted to inshore waters River effects are strongest and reach all the way to the offshore reefs between Cairns and Lizard Island, the COTS primary outbreak region. The river effects last on average 6 - 8 months per year. There is intra- and inter-annual capacity for water clarity to recover.	Improved paramaterisation into the Receiving Waters Model / eReefs project Data has led to the development and application of a whole of GBR wave and sediment transport model. Inshore water quality is affected by terrestrial runoff, and hence amenable to improvement through improved land management Reducing terrestrial runoff of nutrients and sediments should improve water clarity in the GBR, ***leading to significant ecosystem benefits.***
Herbicides detected in the GBR are higly persistent in seawater and can impact seagrass through cumulative pressures	Project 4.2 Herbicides that have been detected in the GBR take more than a year to break down, explaining their presence in the lagoon year round. The sensitivity of seagrass to herbicide exposures increased	***New phytotoxicity data will be available to contribute to the development of new water quality guidelines and to assess the protection afforded to seagrass by the current***

	at both high and low temperatures and high and low light levels, indicating that the cumulative effects of multiple pressures may increase risks posed by herbicide exposure under certain flood-plume conditions. This project developed and applied new methods to accurately measure acute and chronic seagrass toxicity.	***guidelines.*** ***The herbicide persistence and toxicy data are also available for current and future spatial risk assessments.***
The need to develop a systematic, objective and transparent risk-based approach to quantify the relative risk of pesticides, nutrients and sediment to the ecosystems of the GBR	Project 4.3 finalised a scoping study to determine the most effective approach for assessing risks to biodiversity in the inshore Great Barrier Reef (GBR) from declining water quality. It developed the methodology required for a comprehensive GBR risk assessment and gave final recommendations as to the most suitable method to drive the assessment. Outputs included a 'meta database' of the existing data and listed all the information needed to run a risk analysis	The preliminary findings from this project have helped guide the process of completing a GBR wide risk assessment. This risk assessment method was developed and applied to the GBR to provide robust and scientifically defensible information for policy makers and catchment managers on the key land-based pollutants of greatest risk to the health of the two main GBR ecosystems (coral reefs and seagrass beds). The results were used in the setting of regional ecologically relevant targets for fine sediment in the Burnett-Mary and Wet Tropics WQIPs, and will likely be used for other WQIPs ***This information was used to inform management prioritisation for Reef Rescue 2 and Reef Plan 3.***
Local Stressors - Water quality affected by terrestrial runoff has significantly altered Great Barrier Reef ecosystems,	*Project 5.2 conducted over 15 experiments to assess individual and cumulative impacts of water quality, ocean warming and ocean acidification.*	Outcomes of 5.2 will feed into ecosystem models assisting managers in decision-making. Results were included in the Scientific Consensus Statement, which was used

especially on inshore reefs. **Global stressors such as increasing temperatures and ocean acidification (OA) will increase pressure on reefs over the coming decades. Cumulative effects of these global and local stressors are poorly understood**	Organisms investigated included key species of corals, algae, seagrasses, foraminifera and echinoderms Combination of stressors showed additive effects, thus clearly suggesting that land-management can ameliorate impacts of climate change.	in support of the revision of ReefPlan 2013.The consensus statement was used to inform various chapters of the GBR Strategic Assessment.
The level of exposure of seagrass meadows to broad scale and long-term changes in water quality associated with wet season conditions **The influence of light, nutrients and salinity on seagrass condition** **Refined thresholds of concern for light, nutrients and salinity**	Project 5.3 Identified seagrass meadows at high risk of exposure to flood waters when certain conditions, defined by the frequency of colour classes, are experienced over two consecutive years. Different permutations of ocean colour information can provide information that can be used to develop guidelines on habitat scale seagrass loss. Developed new environmental thresholds (light), which will be incorporated into seagrass guidelines for protection of GBR seagrasses (scheduled for 2015). Measured new salinity thresholds, which occur at low salinities	This project confirmed metric selection (sub-lethal indicators) and scoring for Reef Rescue MMP reporting.
Increasing development of the Great Barrier Reef coastal zone is inevitable in the coming decades. Development will increase shipping, intensive agriculture, urban development, and tourism.	Project 9.4 produced eight spatially-explicit scenarios of coastal development for 2035, covering land uses and related marine activities using Geographic Information Systems. Our range of 2035 scenarios incorporated uncertainty around demand for food, mineral resources, tourism, and environmental services, and took into account	To inform management, planning, and policy, it is therefore necessary to assess potential scenarios of coastal development and their cumulative impacts on marine species and ecosystems. This approach provides a quantitative understanding of cause-and-effect relationships under a range of future scenarios and

	technical advances, preference for coastal living, and governance. We use Bayesian belief networks with elicitation to capture both data and expert opinion on the related factors linking land-use changes in the coastal zone to impacts on specific marine species and ecosystems, taking account of related changes to water quality and activities in the Reef's lagoon.	greatly improves understanding of cumulative impacts. It provides a large-scale planning and decision-support tool for managers and policy-makers to explore and minimise the impacts of coastal development. Our approach can be adapted easily to investigate small parts of the coastal zone, including sites of individual developments, and to estimate the cumulative impacts of government policies.
Much of our knowledge on the Great Barrier Reef (GBR) comes from spatially and temporally limited studies which hinders our ability to appropriately assess the current state of the reef.	*Project 1.3 provided a deep-time, baseline understanding of changes in ecological and environmental condition across the entire length of the inshore GBR.* Using palaeo-ecological and –environmental approaches combined with precise geochemical techniques, we provide millennial scale histories of reef development from Cape Grenville in the north to Hervey Bay in the south, with evidence for recent changes in coral community composition in the central region of the GBR attributable to dramatic land use changes since European settlement (c. 1850 AD). Using highly precise U-Th dating methods we have been able to constrain the timing of changes in coral community composition with precisions of up to ± 1 yr, allowing us to pinpoint the likely cause for mortality.	The many outcomes from this research will prove invaluable to reef managers by ***extending their knowledge of reef dynamics beyond marine monitoring programs, assisting with identifying the timing and drivers of change, as well as the reasons behind the lack of recovery at many inshore reefs.***

4. Research informing policy and management

For the NERP water quality theme, there has been a strong link to previous research (and monitoring) efforts (e.g. CRCs, MTSRF, Paddock to Reef (P2R), Scientific Consensus Statement (SCS)), links to other research programs (e.g. Reef Rescue R&D, P2R) and pathways into current management and institutional arrangements. Integration across all these programs and processes are essential to develop solutions for science, policy and management of water quality in the GBR. The research-user interface has been through several different processes and program, including the 6 monthly water quality integration meetings, Canberra visits focusing on water quality issues, fact sheets, summary reports, and several technical reports. Project 4.2 has also been instrumentatl in developing and driving a Pesticide Workgin Group which has successfully brought researchers, research-users, government and industry together to discuss research outcomes and issues associated with the use of pesticides on the GBR catchment. These workshops bring together researchers, managers and industry representatives working specifically on pesticide research, monitoring and management in the GBR. The water quality projects have also all fed into the various government initiatives for monitoring and assessment of risk and the prioritization of management actions for water quality remediation. These processes include the recent GBR risk assessment (Brodie et al., 2013) and the Wet Tropics Risk assessment (Waterhouse et al., 2014), the Outlook Report (GBRMPA, 2014), and results have been included in the Scientific Consensus Statement, which was used in support of the revision of ReefPlan 2013. A summary of all these communication initiatives are outlined in Table 4.2.

NERP projects have always worked in conjunction with several other key research programs to ensure that the information is accessed from the upstream catchment to the marine environment. There are linkages between researcher and managers involved in a cross section of catchment to marine water quality projects which has been utilised and improved through the inputs into the risk assessment, the Scientific Consensus Statement and the Outlook Report (see Figure 4-1).

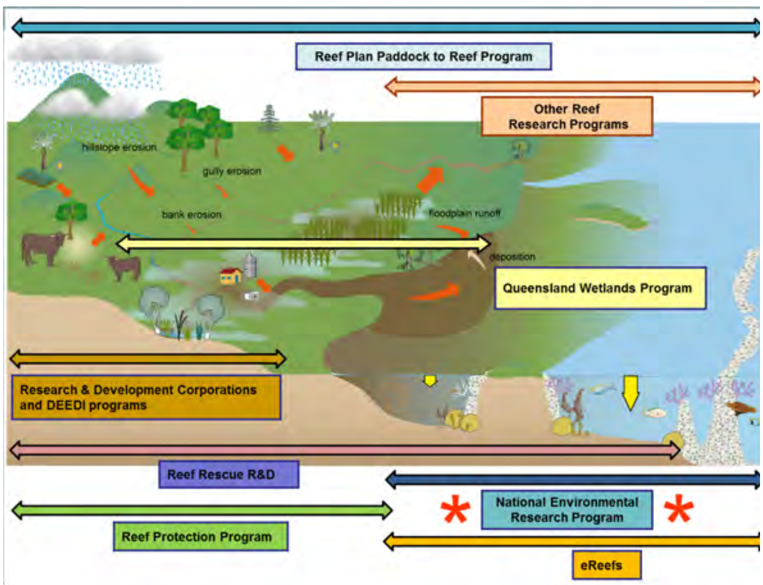


Figure 4-1. Linkages between the NERP Water Quality programs and other completed and existing water quality programs.

Table 4-1. Summary of research-user focused outputs for the NERP Water Quality Projects.

Initiative/Process	Description	Outcomes	References/Information
NERP: Informing Policy	The NERP team hosted two separate workshops associated with water quality, pesticides and seagrass ecosystem issues for the Great Barrier Reef in Canberra on 21 and 22 May. The initiative is one of several supported by the NERP Contestable Funds allocation, intended to facilitate uptake of the NERP research findings.	The workshop involved presentations from researchers involved in NERP Tropical Ecosystems Hub and the Reef Rescue R&D program (James Cook University, the Australian Institute of Marine Science and the University of Adelaide), with attendance by representatives from many sections within SEWPaC (including the GBR Taskforce, Reef Rescue, Water Quality Policy, Chemical Assessment Unit, Wetlands section), GBRMPA and DAFF. The main purpose of the workshops was to provide an overview of recent findings of the research projects, encourage dialogue between managers and researchers regarding the implications of the findings, and identify opportunities for application of the research into policy processes. *The interactions at the workshop identified opportunities for the research outputs to influence broader guidelines, standards and State of Environment processes, and highlighted the importance of efforts to synthesise findings across research projects and initiatives. Several avenues for further collaboration with industry partners were also identified, in addition to the need to engage a range of targeted communication approaches for transferring and applying new*	
Pesticide Working Group	These workshops showcase the latest pesticide information from projects funded by *NERP*, *Reef Rescue R&D*, the *Paddock to Reef Program* and the *Reef Protection Package Science Program*. The workshops have precipitated regular communication between the groups, facilitating a more coherent discussion on the role of pesticides in GBR status and	The PWG has have enabled direct exchange of knowledge and information for improved understanding of industry needs and management requirements. The latest science information can benefit the decisions being made on the usage of pesticides in the GBR catchment. There have been four workshops to date, each which has focused on a different aspect of pesticide management. PWG now a key forum for both researchers and research	http://www.nerptropical.edu.au/publication/herbicides-gbr-research-overview-andrew-negri Lewis, Negri, Devlin et al., in press. Pesticide Synthesis Report:A summary of issues (2010-2014): A report to

	management.	users involved in the development of the Pesticide Synthesis Report 2010-2014	Queensland Department
Cumulative Impact working Group	Communication on cumulative impacts has been achieved through the NERP IG meetings and a well-attended stakeholder workshop on cumulative impacts on the GBR. The main objectives of this workshop were to inform stakeholders about NERP water quality outcomes. In addition and in collaboration with stakeholders, the workshop began a process of developing a clear definition of cumulative impacts and identifies information needs of the research-users. Finally, the workshop identified future research focus areas for experimental ecology/modelling in engaged discussions between researchers and research-users.	Project 5.3 and Project 4.2 provided input into management agencies on how various pressures can combine into cumulative impacts. The workshop focused on the measurement of the accumulation of impacts on reef organisms from simultaneous and sequential pressures which are diminishing the ability of the reef to recover to previous states (i.e. impaired resilience). Discussion focused on the need to develop an cumulative impact assessment policy, accounting for the multiple use of the GBR and the multiple pressures that it faces. The tools available are monitoring, models and scenarios built from the outcomes of the driver-response data collected in the NERP water quality projects. Stakeholders included GBRMPA, DOE, AMPTO, Reef Catchments and NQ Dry Tropics	http://www.nerptropical.edu.au/project/experimental-and-field-investigations-combined-water-quality-and-climate-effects
Strategic /coastal assessment workshops	Conservation goal workshop in Townsville. This was a one-day workshop with the aim to define criteria to articulate goals and select assets to be looked at in project 9.4. Further workshops were held to define the scenarios and develop the Bayesian models.	The workshop gathered experts in GBR ecosystems to determine the best process to draw out information on assets and goals. An initial participatory discussion was conducted where NRM plan goals were identified as the best basis. The development goals are included in the different scenario storylines because three of the drivers are development-related (for instance doubling tourism).Attendance included representation from GBRMPA and DSEWPAC	Augé, 2014
Risk Assessment	A risk assessment method was developed and applied to the Great Barrier Reef (GBR) to provide robust and scientifically defensible information for policy makers and catchment managers on the key land-based pollutants of greatest risk to the health of the two main GBR	This information was used to inform management prioritisation for Reef Rescue 2 and Reef Plan 3. The risk assessment method needed to take account of the fact that catchment-associated risk will vary with distance from the river mouth, with coastal habitats nearest to river mouths most impacted by poor marine water quality. The main water quality pollutants of concern for the GBR	Brodie, Waterhouse et al.,2013. Assessment of the relative risk of water quality to ecosystems of the Great Barrier Reef. A report to the Department of the Environment and Heritage

	ecosystems (coral reefs and seagrass beds).	are enhanced levels of suspended sediments, excess nutrients and pesticides added to the GBR lagoon from the adjacent catchments. This information about the relative exposure to and effects of these pollutants to guide effective prioritisation of the management of their sources. Many of the projects funded under NERP were direct contributors to this process, particularly Project 4.1, 4.2, 4.3, 5.2 and 5.3	Protection, Queensland Government, Brisbane. TropWATER Report 13/28, Townsville, Australia.
Scientific Consensus Statment	To support the development of the Reef Water Quality Protection Plan 2013 (Reef Plan) a multidisciplinary group of scientists, with oversight from the Reef Plan Independent Science Panel, was established to review and synthesise the significant advances in scientific knowledge of water quality issues in the Great Barrier Reef and to reach consensus on the current understanding of the system.	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 All NERP water quality projects were part of the SCSU, particularly in Chapter 3 - Relative risks to the Great Barrier Reef from degraded water quality	http://www.reefplan.qld.gov.au/about/scientific-consensus-statement.aspx http://www.reefplan.qld.gov.au/about/scientific-consensus-statement/water-quality-risks.aspx
Outlook Report	Every five years, GBRMPA publish an Outlook Report that examines the Great Barrier Reef's health, pressures, and likely future. The report is required under Great Barrier Reef Marine Park Act 1975 (section 54) and aims to provide a regular and reliable means of assessing reef health and management in an accountable and transparent way. This assessment is also a response to the revised requirements of our Act and the World Heritage Committee requesting an explicit assessment of the area's outstanding universal value.	The report acknowledges there's been a range of positive actions since 2009, including government and landholders focusing on improving the quality of water that runs off the land. The report finds the greatest risks to the Reef are still climate change, land-based run-off, coastal development, some remaining impacts of fishing and illegal fishing and poaching. The extensive assessment and stakeholder engagement work undertaken for the Great Barrier Reef Region Strategic Assessment was very strongly drawn on in the process of developing this Outlook Report.	http://www.gbrmpa.gov.au/managing-the-reef/great-barrier-reef-outlook-report

5. Conclusions and future research direction

5.1 Conclusions

The NERP Tropical Ecosystems Hub generated significant outcomes for informing the design and implementation of water quality monitoring, evaluation and conservation programs. In particular, has advanced understanding of the extent and influence of two priority pollutants, and investigated the cumulative pressures that are driving changes in GBR ecosystems. Two projects have provided key management information on areas most at risk from terrestrial run-off (nutrients, sediments and pesticides) and coastal development. Research outcomes have also provided information on historical changes for coral reefs allowing more realistic baselines to be developed. These have been applied to the Outlook report (http://www.gbrmpa.gov.au/managing-the-reef/great-barrier-reef-outlook-report), a GBR risk assessment (Brodie et al., 2013a), and form key points of evidence in the Scientific Consensus Statement (Brodie et al., 2013b) for Chapter 3 *Relative risks to the GBR from degraded water quality* (Brodie et al. 2013c).

These pressures are not static therefore predicting and preparing for change is a significant challenge for environmental decision makers charged with stewardship of Queensland's natural environment. Changing climates, extreme natural events, changes in natural resource use and population growth are some of the pressures facing these ecosystems. Projects such as these NERP water quality projects provide the detailed information required to build an understanding of the evolving pressures the reef faces and the ability of the GBR to continue to be a functioning, healthy ecosystem in face of a changing landscape and climate. Projects linking catchment changes to the water quality condition of the GBR allows assessment of the main pressures driving change, and also provides information on the resilience of the GBR to withstand change, and our ability to manage and reduce those pressures to provide a pathway to recovery.

5.2 Future research direction

Water quality is a management priority for the long-term health of GBR seagrasses and for the animals (e.g. dugong) and ecological processes (e.g. nutrient uptake) that are dependant on healthy, diverse and productive meadows. Pulsed run-off from flood plumes, localized water quality impacts (e.g. dredge plumes) as well as chronic inshore water quality declines are all priority management concerns.

The NERP TEH water quality research synthesised in this report has also revealed knowledge gaps and new areas of research that should be progressed to inform continuous improvement of water quality in the Great Barrier Reef The future research directions are summarised below for each system component that has been studied through the program.

5.2.1 Fine Sediment delivery

- Assess the effects of additional drivers of turbidity (for example, dredging), as a cumulative pressure in the delivery of fine sediment.
- Understanding the extent of additional system stress due to greater light variability (ie not only chronic shading) in response to terrestrial runoff, and its implications for the GBR ecosystems

5.2.2 Pesticides

Reducing pesticide loads transported to the GBR is a detailed issue due to the complexity of defining pesticide movement pathways through the environment from agricultural land to the Great Barrier Reef. At present there are varying levels of research attention given to pesticide use rates, application methods, off-site transport, the impact on aquatic ecosystems and water quality guidelines describing tolerable pesticide levels within environments. The outcomes of this project have fed directly into a GBR wide synthesis on pesticide research and will contain recommendations for Government and industry in relation to future policy direction and potential investment in identified priority research and extension areas. A short description of some knowledge gaps are listed below, with a detailed summary of these research gaps in Appendix 1.

- What are the toxicity, transport, exposure and fate characteristics of the alternate pesticides and current formulations and which pesticides are known to be used in farming but are not routinely monitored (e.g. glyphosate, 2,4-Dparaquat)?
- Which freshwater, estuarine and coastal ecosystems, with important connectivity to the Reef, are at the highest risk from pesticides?
- Linking the catchment monitoring with the marine monitoring: determining what risk the pesticides measured in the catchments equates to in the receiving marine ecosystems.
- What is the extent of pesticide exposure in the marine areas most at risk from pesticides?
- What are the impacts of multiple pesticides and of pesticides in combination with other stressors relevant to flood plumes?

5.2.3 Cumulative Impacts

Water quality affected by terrestrial runoff has significantly altered Great Barrier Reef ecosystems, especially on inshore reefs. Global stressors such as increasing temperatures and ocean acidification (OA) will increase pressure on reefs over the coming decades. Cumulative effects of these global and local stressors are poorly understood. ***Future work on cumulative impacts should contribute to the development of measurable climate- and regionally adjusted water quality targets and cumulative impact guidelines. In addition, multi-generational experiments are needed to investigate the potential of acclimation and adaptation to cumulative impacts.***

Flood plume impacts have led to recent unprecedented levels of seagrass loss. There is, however, signs of recovery in a number of the impacted seagrass meadows with colonizing species increasing in abundance (McKenzie et al., In Prep). It will take a number of years (up to 10 years) before the foundational species return to their former abundances. Disturbances (such as cyclones) resulting in loss and recovery of seagrass have been a part of the GBR seagrass ecosystems (Birch and Birch, 1984); however, as the types and frequency of disturbances increase, recovery processes (such as recruitment and germination) may be affected. The effect of pollutants on seagrass meadows is an especially important topic due to their close proximity of the coast. As agriculture and coastal development have increased and are expected to further increase over the coming years, it is particularly important to develop methods to interpret ecological change where environmental and WQ in-situ data are not available or limited. ***The link between remote sensing and seagrass condition shows the strong potential of satellite images for understanding ecological change. Future work should focus on the development of this technique as well as the integration of in-situ, site-specific logger data, and experimental approaches (aquaria) to investigate effects of water quality on seagrasses.***

Recovery times, which depend on reproduction and connectivity, will be critical to the capacity for seagrasses to recover from future and ongoing water quality impacts. Declining water quality is not the only effect on seagrasses, physical disturbance (e.g. cyclones Birch and Birch, 1984; McKenzie et al., 2012) and climate change, in particular increasing temperature, both chronic (Collier et al., 2011) as well as event-based extremes (Campbell et al., 2006; Collier and Waycott, 2014; Rasheed and Unsworth, 2011) threaten the resilience of seagrasses for coping with changing water quality. ***Future work should include research that measures the resilience of seagrasses in the face of these cumulative pressures***. Knowledge gaps include the effect of interactive stressors on light thresholds, light thresholds and how to report them in intertidal habitats, minimum light requirements, spectral light shifts, turbidity/chlorophyll a thresholds (sensu. De'ath and Fabricius, 2010), secondary effects of light limitation (e.g. changes in sediment biogeochemistry).

5.2.4 Priority areas for management

Incorporate more areas and more scenarios for improved setting of trajectories.

5.2.5 Monitoring and evaluation

- Look for evidence of historical macro-algal dominance in reef sediments through the use of ancient DNA from collected sediment cores.
- Understanding the cumulative effects of stressors on calcification over a broad range of tax using CT scans from corals that occur in our reef matrix cores
- Understandnig fishing intensity over tme using historical archives.
- Develop predictive tools (models) for predicting winners and losers from reduced water quality over time using a traits-based approach

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7 Annex One

7.1 A1: List and details of research gaps for pesticide research in the GBR catchment and marine systems.

1. **What are the toxicity, transport, exposure and fate characteristics of the alternate pesticides and current formulations and which pesticides are known to be used in farming but are not routinely monitored (e.g. glyphosate, 2,4-D, paraquat)?**

   Farmers are encouraged to replace the priority PSII herbicides with the knockdown herbicides, glyphosate, paraquat and 2,4-D, as part of best management practices. These three pesticides now have the highest application rates in GBR catchments, however, we have very little understanding of their transport, exposure and fate (and therefore ecological risk) as they are not included in the Paddock to Reef routine pesticide monitoring program. Furthermore, preliminary monitoring has demonstrated that other herbicides are being detected frequently in catchments, which is expected to increase as farmers move away from using the priority PSII herbicides. In addition, a wide range of new and emerging herbicides are being used in cropping systems; much less is known about their behaviour and fate than for PSII herbicides. We need to increase efforts to monitor and study the fate of non-PSII pesticides and their breakdown products in rivers, estuaries and coastal ecosystems to ensure that as they are increasingly used to supplement the priority PSII herbicides on the paddock, the total risk of pesticides to the GBR is reduced. Additives in the commercial formulations and activators which are simultaneously applied on farm to increase efficacy (and may enhance toxicity) have not been monitored to date and should be considered in future monitoring and fate studies.
2. **Which freshwater, estuarine and coastal ecosystems, with important connectivity to the Reef, are at the highest risk from pesticides?**

   Ecosystems which have important connectivity with coral reefs are vital to maintain in order to sustain resilience of the coral reefs (Nystrom et al 2008). From the 2013 Scientific Consensus Statement it was evident that the freshwater, estuarine and coastal ecosystems adjacent to the GBR are most likely exposed to the highest concentrations of pesticides. The risk of pesticides to the functioning of those adjacent ecosystems with important connectivity roles for the coral reefs must be assessed to ensure resilience of the GBR. To do this we need to examine, on a longitudinal scale, which ecosystems have the highest exposure to pesticides and what factors determine this, e.g. catchment size, discharge volume, land use proportions. Once a relationship between pesticide risk and the deterministic variables are established, we could predict where the highest risk occurs for all catchments.

3. **In-stream pesticide fate.** Further study of pesticide breakdown and sorption/desorption during in-stream transport is needed to determine the potential for prioritising management spatially. Little or no information is available on pesticide behaviour in-stream and in estuaries. Waters (unpublished) data on dissipation in the

Condamine-Balonne River (weir pools) indicated slow dissipation (half-lives = > 1 yr). If in-stream dissipation is slow, increased management of pesticides is needed in all source areas. If dissipation is rapid, more distant sources are of less importance for management. These questions are, initially at least, amenable to laboratory studies.

4. **Pesticide exposure in sediment communities:** determining the concentrations, extent of exposure and desorption potential (i.e. re-release back into the water column under various conditions) of insecticides and herbicides in freshwater, estuarine and coastal sediment communities. We know that pesticides are partitioned between the dissolved and bound phase, however we only monitor for the fraction in the dissolved phase. Most pesticides will have a fraction in the bound phase as they range from being slightly non-polar (i.e. mostly herbicides) to highly non-polar (i.e. mostly insecticides). Loads of sediment bound pesticides in GBR catchments are only slightly understood and only for the more soluble herbicides (Packett et al. 2013). Some emerging products were found to be transport in sediment as well as in the dissolved phase at the small plot scale (e.g. pendimethalin, imazapic as well as diuron). This means that we are underestimating the amount and number/types of pesticides being transported to the Reef. Furthermore, desorption rates from bed and water column sediments are unknown and may be affected by other components in the commercial formulations and/or activators which are simultaneously applied on farm to increase efficacy. Sediment bound loads may also affect the sediment as in environment in its own right. To date we have excluded sediment communities in our assessment of pesticide exposure and risk even though they play an important role in the aquatic food chain, particularly for fisheries.

5. **Linking the catchment monitoring with the marine monitoring: determining what risk the pesticides measured in the catchments equates to in the receiving marine ecosystems.** The current methods for measuring the success towards achieving the Reef Plan goal for pesticides, is to measure the reduction in pesticides in the catchments. Therefore, we need to understand how the measured pesticide concentrations in the catchments translates to risk to the marine environment. This cannot be done with the current marine monitoring sites as they are not situated in the receiving waters of the catchments that are being monitored. Establishing this dataset will help model the risk of pesticides to the marine environment based on the measurements of pesticides in the catchments.

6. **What is the extent of pesticide exposure in the marine areas most at risk from pesticides?** The current marine monitoring sites are not situated in the marine areas where exposure to pesticides would be greatest. Our understanding of concentration and exposure of pesticides in the marine environment, based on the current monitoring results, is likely to be underestimated for those areas which directly receive pesticides from the catchments. The pesticide monitoring results to date has led some industry stakeholders to conclude that pesticides are not a threat to any of the marine ecosystems of the GBR. While efforts to date have focussed on measuring dissolved herbicides, further efforts need to be made to quantify emerging herbicides; less soluble insecticides and sediment or particle bound pesticides in marine waters.

7. What are the impacts of multiple pesticides and of pesticides in combination with other stressors relevant to flood plumes?

Pesticides are ususally detected in combinations and in the presence of othe confounding stressors in flood plumes such as low salinity and high suspended solids. While research so far has shown that the toxicity of PSII herbicides is additive, there has been little work to show how the toxicity of pesticides with different modes of action may affect seagrasses and corals. In the present program (4.2) the effects of herbicides in combination with high and low temperatures and light was explored but this needs to be expanded to include other plume related pressures such as low salinity which can also affect these species.

8 Annex 2

8.1 Full description on water quality related projects

NERP WQ and Biodiversity

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Related projects

Theme 2 : Understanding Ecosystem Function and Cumulative Pressures

Program 4 - Water quality of the Great Barrier Reef and Torres Strait

Program 4 will have three projects assessing risks to biodiversity from current water quality in the inshore Great Barrier Reef and a desktop hazard study for water quality outlook in the Torres Strait.

- Project 4.1: will map flood plumes from the Fly River which regularly reach the eastern margins of the Torres Strait, and map the hazard assessment of Norther GBR and declines in localised water quality issues
- Project 4.2: will measure the transport and settlement of fine sediments carried by river plumes and subsequently resuspended by winds. The new knowledge sought is the impact of these processes on light availability to benthic communities.
- Project 4.3:- will establish the half-lives of common agricultural chemicals in the marine environment and study the impacts on biodiversity of chronic low-level exposure to these pollutants. This information will contribute to the Reef Water Quality Protection Plan (Reef Plan) and was designed in consultation with the Reef Rescue Program.
- Project 4.4 will develop a methodological pilot study recommending how to conduct a formal risk analysis of the threats from multiple stressors in water quality that would be used to prioritise future investment decisions in the catchments (i.e. what is the relative risk from sediments, excess nutrients, and contaminants?).

Program 5 - Cumulative impacts on benthic biodiversity

Program 5 will have three projects designed to assess the impacts of cumulative pressures on coastal biodiversity in the GBR.

- Project 5.1 :Synthesis and analysis of spatial and temporal patterns of inshore biodiversity seeking to partition the influence of different environmental drivers (water quality, crown of thorns starfish, cyclones, and connectivity) and identify synergistic interactions between stressors.
- The other two will be multi-factorial experiments exposing corals and seagrasses to different combinations of stressors in order to incorporate cumulative hazards into quantitative risk models.

Theme 1 : Assessing Ecosystem Condition and Trend

Program 1- Historical and current condition of the Great Barrier Reef

Program 1.3: Characterising the cumulative impacts of global, regional and local stressors on the present and past biodiversity of the GBR
The status of coral reef communities of the GBR including damage assessments from three major cyclones (Larry, Hamish, Yasi) as a basis for estimating rates of recovery and resilience of reefs in different regions. Situational awareness for industry and managers on phenomena such as *Acanthaster* densities and coral disease.

Theme 3 : Managing for Resilient Tropical Systems

Program 9- : Decision support systems for GBR managers

Program9.3: Prioritising management actions for Great Barrier Reef islands An assessment of a range of stakeholder views on the relative value of different market and non-market goods and services provided by the GBR using innovative techniques..

Program 10- Socio-economic value of GBR goods and services

Program 10.1; Social and Economic Long Term Monitoring Programme (SELTMP)
A long-term social and economic monitoring programme covering all major social groupings and industries within the GBR region, and development of a management system for program implementation.

Program 9- : Decision support systems for GBR managers

Program 9.4: Long term monitoring of visitor patterns in the GBR will be connected with attributes of reef health to determine their importance to different classes of marine tourist. .

Program 10- Socio-economic value of GBR goods and services

Program 10.2; Socio-economic systems and reef resilience A long-term social and economic monitoring programme covering all major social groupings and industries within the GBR region, and development of a management system for program implementation.