

# **Synthesis of knowledge and concepts - Bioavailable Nutrients: Sources, delivery and impacts in the Great Barrier Reef**

**Supporting Concept Paper for the Bioavailable Nutrients Workshop 15 March 2018**

Jane Waterhouse, Dr Joanne Burton, Dr Alexandra Garzon-Garcia, Dr Stephen Lewis,  
Dr Jon Brodie, Dr Zoe Bainbridge, Dr Barbara Robson, Professor Michele Burford,  
Dr Renee Gruber and Cameron Dougall



Queensland Government

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Supported by the Queensland Reef Water Quality Program through the Office of the Great Barrier Reef within the Department of Environment and Science, and the Australian Government's National Environmental Science Program Tropical Water Quality Hub.

*This paper was coordinated by Jane Waterhouse<sup>1</sup> with contributions from Dr Joanne Burton<sup>2</sup>, Dr Alexandra Garzon-Garcia<sup>2</sup>, Dr Stephen Lewis<sup>3</sup>, Dr Jon Brodie<sup>1</sup>, Dr Zoe Bainbridge<sup>3</sup>, Dr Barbara Robson<sup>4</sup>, Professor Michele Burford<sup>5</sup>, Dr Renee Gruber<sup>4</sup> and Cameron Dougall<sup>6</sup>.*

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National Environmental Science Programme

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National Library of Australia Cataloguing-in-Publication entry:

978-1-925514-25-4

This report should be cited as:

Waterhouse, J., Burton, J., Garzon-Garcia, A., Lewis, S., Brodie, J., Bainbridge, Z., Robson, B., Burford, M., Gruber, R., Dougall, C. (2018). *Synthesis of knowledge and concepts - Bioavailable Nutrients: Sources, delivery and impacts in the Great Barrier Reef, July 2018. Supporting Concept Paper for the Bioavailable Nutrients Workshop, 15 March 2018.* Supported by the Office of the Great Barrier Reef's Queensland Reef Water Quality Program, and the Australian Government National Environmental Science Program Tropical Water Quality Hub (84pp.).

Published by the Reef and Rainforest Research Centre on behalf of the Australian Government's National Environmental Science Program (NESP) Tropical Water Quality (TWQ) Hub and the State of Queensland.

The Tropical Water Quality Hub is part of the Australian Government's National Environmental Science Program and is administered by the Reef and Rainforest Research Centre Limited (RRRC). The NESP TWQ Hub addresses water quality and coastal management in the World Heritage listed Great Barrier Reef, its catchments and other tropical waters, through the generation and transfer of world-class research and shared knowledge.

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## ACKNOWLEDGEMENTS

We would like to thank all of the workshop participants for their input to the workshop which informed the contents of this paper (see attendees in Attachment 2), and in particular, the authors of this paper.

Funding for the workshop and the supporting documents including this paper was provided by the Office of the Great Barrier Reef (OGBR) within the Department of Environment and Science (DES), and the Australian Government's National Environmental Science Program (NESP) Tropical Water Quality (TWQ) Hub. The organisations of the contributing authors also provided considerable in-kind contributions.

The support from staff in the Department of Environment and Science is greatly appreciated, including Lex Cogle, Leigh Smith and Jean Erbacher. C<sub>2</sub>O Consulting *coasts climate oceans* led the project; Jane Waterhouse coordinated the workshop, concept paper and key messages briefing paper, and Johanna Johnson facilitated the workshop.

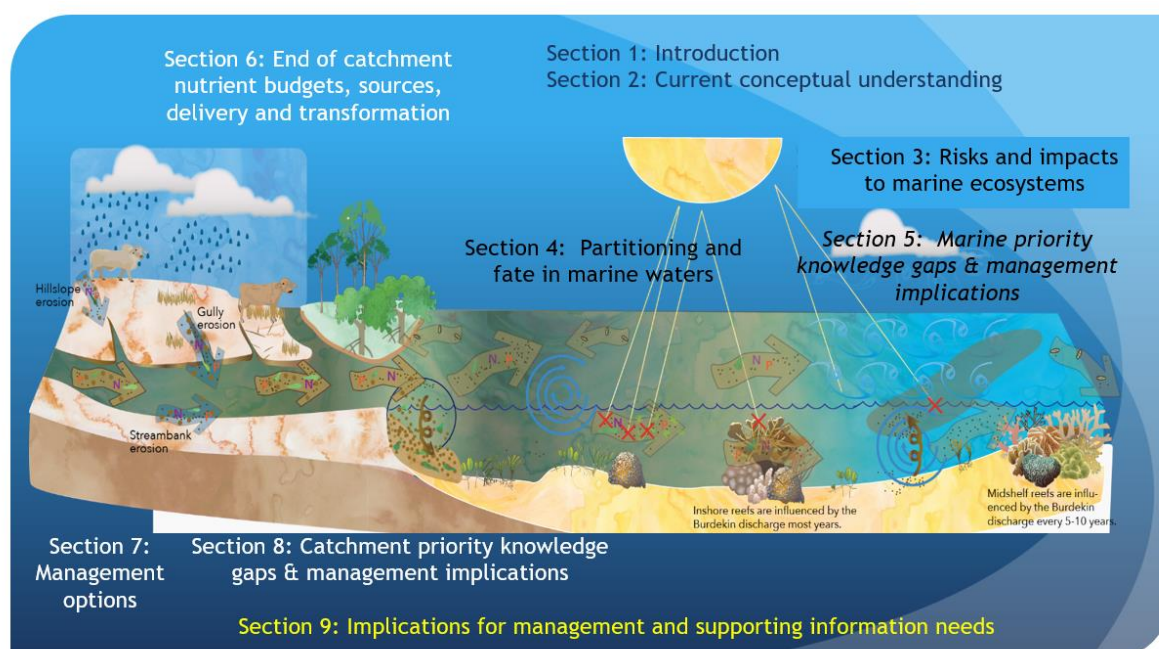
## GLOSSARY

|                 |   |
|-----------------|---|
| BAN             | Bioavailable nutrients. Nutrients (especially nitrogen and phosphorus) that are in forms that directly support biological processes such as growth of phytoplankton.  |
| Bioavailable PN | Bioavailable Particulate Nitrogen. BAN that is specifically derived from the mineralisation, desorption and dissolution of PN associated with eroded soils.   |
| Bioavailable PP | Bioavailable Particulate Phosphorus. BAN that is specifically derived from the mineralisation, desorption and dissolution of PP associated with eroded soils.   |
| DIN             | dissolved inorganic nitrogen = nitrate, nitrite and ammonium. Nitrogen in these forms is highly bioavailable and can be taken up directly by plants including phytoplankton and other algae.  |
| DON             | dissolved organic nitrogen. DON includes any dissolved nitrogen in a chemical form that is compounded with carbon. This includes a wide range of substances, from very bioreactive urea (applied as fertiliser on crops), RNA and DNA, through to very refractory (i.e. unreactive) dissolved substances. As measured in practice, DON also includes colloidal nitrogen. DON is typically assumed to be less bioavailable than DIN. |
| DOP             | dissolved organic phosphorus. Analogous to DON and usually part of the same chemical compounds, DOP is dissolved phosphorus in organic forms, from DNA and RNA to anisotol phosphorus. The ratio between nitrogen, phosphorus and carbon in dissolved and particulate organic material is often an important indicator of its bioavailability and nutritional quality.  |
| DRPDRP          | dissolved reactive phosphorus (i.e. dissolved inorganic phosphorus plus highly reactive dissolved organic phosphorus)   |
| PIN             | particulate inorganic nitrogen. This includes the soluble nitrate and ammonium in the interstitial pore water, and adsorbed ammonium.   |
| PIP             | particulate inorganic phosphorus. Particulate inorganic phosphorus can be an important constituent of PP. PIP includes both inorganic phosphorus adsorbed to sediment particle surfaces, which exists in equilibrium with DRP in the surrounding water and is readily bioavailable, and chemically immobilised phosphorus, which is very unreactive and not likely to contribute to biological processes on relevant time-scales.   |
| PN              | particulate nitrogen. PN includes nitrogen in any form that does not pass through a filter, from nitrogen associated with suspended soils and leaf litter, to living and dead phytoplankton and organic aggregates of carbohydrates and detrital animal material.   |
| PON             | particulate organic nitrogen. PON is PN in organic forms, i.e. carbon compounds. The majority of particulate nitrogen in the water column is usually PON.   |
| POP             | particulate organic phosphorus. Analogous to PON and usually part of the same chemical compounds and biological materials.  |
| PP              | particulate phosphorus. PP is the sum of PIP and POP.   |

# EXECUTIVE SUMMARY

On behalf of the Office of the Great Barrier Reef (OGBR), C<sub>2</sub>O Consulting *coasts climate oceans* coordinated a workshop on 15 March 2018 aiming to provide clearer direction for future efforts to support improved understanding and management of bioavailable nutrient sources, pathways and impacts in the Great Barrier Reef (GBR). The outcomes will guide investment in management responses associated with bioavailable nutrients for achieving outcomes for the health of the GBR.

In support of the workshop outcomes, this concept paper captures the current understanding of the bioavailability of nutrients in the GBR, highlighting any new or emerging knowledge since similar material was synthesised in Brodie et al. (2015). As shown in Figure i, the report is structured by marine and catchment interactions, and in recognition of the importance of the interactions between these landscapes, discusses key concepts across the catchment to reef interface. It summarises the established evidence, highlights new evidence and identifies priority knowledge gaps and management implications for a number of key research areas.



**Figure i: Structure of this concept paper, framed within the overarching conceptual framework of the current understanding of the bioavailability of nutrients in the Great Barrier Reef.**

The report is intended to provide a summary of current knowledge and is not intended to be a comprehensive review or synthesis of knowledge related to the bioavailability of nutrients in the GBR. Readers should refer to the reports and papers referenced in this report for further detail.

A separate paper highlighting the key messages included in this report has also been prepared, targeting a policy audience. The priority knowledge needs have been incorporated into the recently completed *Reef 2050 Water Quality Improvement Plan Research Development and Innovation Strategy, 2017-2022*.

The new evidence highlights that:

- The relative importance of specific management of particulate nutrients in the catchment is increased due to enhanced knowledge that demonstrates more rapid timeframes for the bioavailability of particulate nutrients than previously assumed. The extent of influence is inshore and midshelf areas.
- There is a shift in the conceptual understanding of nutrient cycling and how it is represented; this has implications for the framework of how bioavailable nutrients are measured and modelled and adjusts assumptions in the modelling.
- Carbon has an important influence on nutrient processing in the marine environment; further investigation is required to fully understand these influences.
- In grazing and dryland cropping catchments, eroded sediments can now be viewed as a significant source of bioavailable particulate nutrients (DIN in the marine environment).
- Different management practices will target different erosion processes and should be considered in the context of generation of fine sediment and particulate bioavailable nutrient yields per unit area. There is a need to develop and promote land management practices that reduce loss of nutrient-rich fine sediments.
- Further targeting of effort to manage DIN from erosion requires additional information for refinement (identified in the priority knowledge gaps). Specific studies will be required to understand the generation of bioavailable particulate nutrients under different land management conditions, specifically for hillslope erosion. Focus catchments could include continuation of the current efforts in the Johnstone and Bowen/Burdekin catchments, plus addition of the Olive Pascoe basin for end of system and native paddock scale sites.
- Adding the bioavailability of particulate nutrients to the prioritisation of erosion management will accelerate the benefit to water quality of these investments. However, assessment of the time lags of managing DIN from fertiliser versus soil erosion is important, especially if the relative importance of DIN and PN is assessed.
- The 2017 GBR end of catchment load targets for PN and PP mirror the fine sediment reductions for each basin. There is a need to specifically address bioavailable particulate nutrients when the targets are revised for the WQIP update in 2022). This would require further quantification of DIN from erosion and quantification of the bioavailability of particulate nutrients in more catchments (both during transport to end-of-catchment and in the estuarine/marine receiving water columns). *This requires an integrated catchment to reef approach.*
- Setting ecologically relevant end of catchment load targets for P is important and should be progressed for definition by 2022. *This requires an integrated catchment to reef approach.*
- Explicit addition of particulate nutrient loads and assessment of their bioavailability (e.g. by catchment, sediment type in plume) is required for future marine nutrient risk assessments – both in the marine modelling and in linking to end of catchment loads.
- Nutrient markets/offsets and trading for nitrogen forms should take into account the bioavailability of the different pools of particulate nutrients.
- It is important to communicate that our understanding of nutrient budgets has changed and that this improved knowledge may influence (within) catchment prioritisation.



# 1. INTRODUCTION

On behalf of the Office of the Great Barrier Reef (OGBR), C<sub>2</sub>O Consulting *coasts climate oceans* coordinated a workshop on 15 March 2018 aiming to provide clearer direction for future efforts to support improved understanding and management of bioavailable nutrient sources, pathways and impacts in the Great Barrier Reef (GBR). The outcomes will guide investment in management responses associated with bioavailable nutrients for achieving outcomes for the health of the GBR.

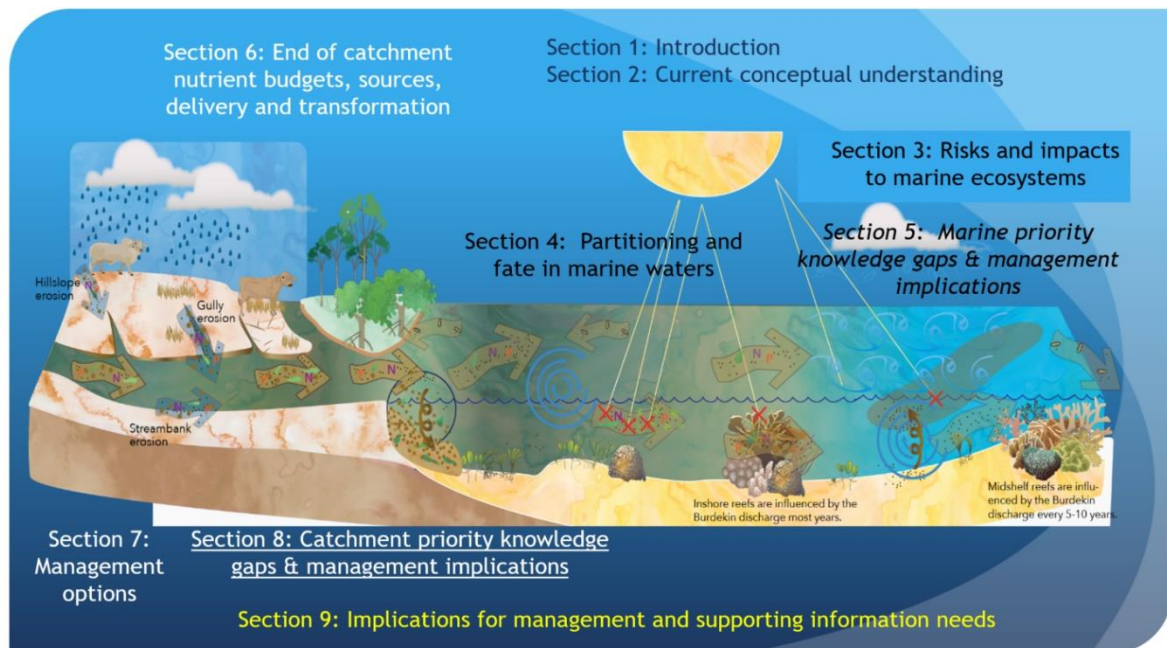
The workshop aimed to provide:

1. An agreed conceptual model of the delivery, transformation and fate of bioavailable nutrients from their source to the GBR. This will help communicate this complex issue for management, policy and modelling and support understanding of where future research investments need to focus.
2. A clear picture of current knowledge and additional research required to determine: what happens to particulate nutrients in the marine environment; what are the risks of particulate nutrients on varying timescales in the GBR lagoon; what is the contribution of particulate nutrients to bioavailable nutrients in the GBR lagoon relative to the bioavailable nutrients (primarily dissolved inorganic nitrogen) discharged directly from agriculture; and what are the options for managing bioavailable nutrients. Ultimately, identify the key research required, how much funding that research requires, and who can undertake the research.
3. An indication of the effort required and the benefits of including new information into Source Catchment and eReefs modelling.
4. Consensus of the potential management implications of new evidence related to bioavailable nutrient delivery, transport and fate.

In support of the workshop outcomes, this concept paper captures the current understanding of the bioavailability of nutrients in the GBR, highlighting any new or emerging knowledge since similar material was synthesised in Brodie et al. (2015) (the technical summary of this report is provided as Attachment 1). The paper is framed within the overarching conceptual framework of the current understanding of the bioavailability of nutrients in the GBR, illustrated in Figure 1.1.

A separate paper highlighting the key messages has also been prepared, targeting a policy audience. The outcomes of the workshop (the workshop notes are provided as Attachment 2) and additional technical reports are also referenced.

Funding for the workshop and the supporting documents including this paper was provided by the OGBR within the Queensland Department of Environment and Science, and the Australian Government National Environmental Science Program (NESP) Tropical Water Quality Hub. The organisations of the contributing authors also provided considerable in-kind contributions.



**Figure 1.1. Structure of this concept paper framed within the overarching conceptual framework of the current understanding of the bioavailability of nutrients in the Great Barrier Reef.**

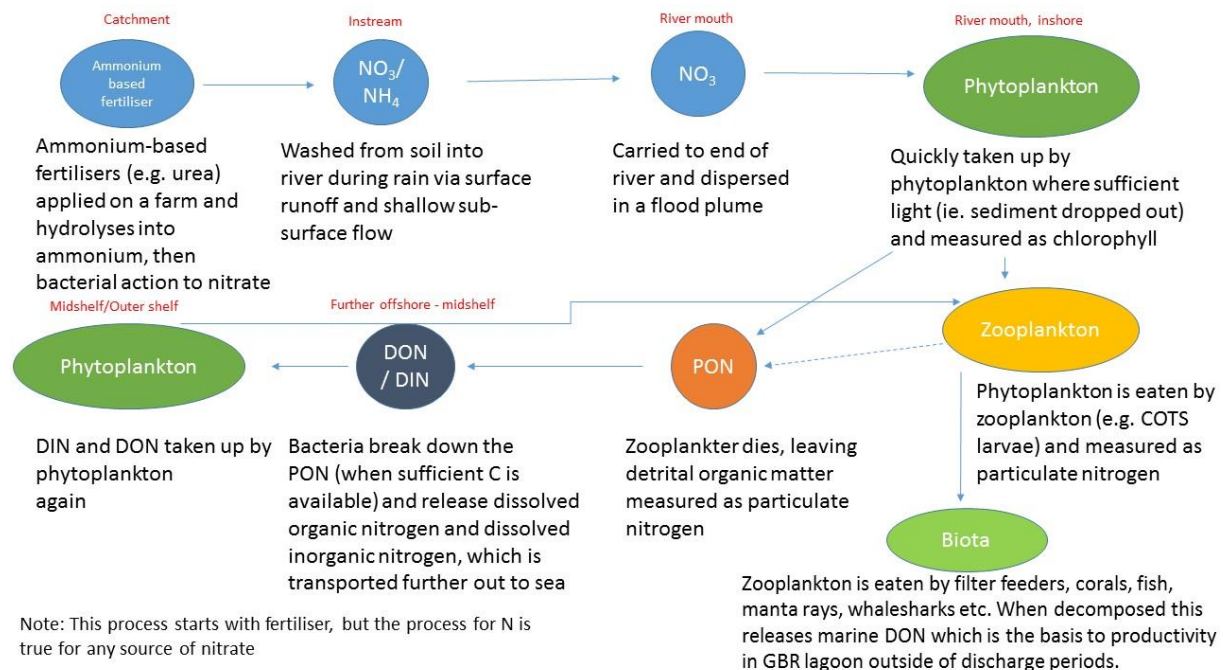
## **2. CURRENT CONCEPTUAL UNDERSTANDING OF THE BIOAVAILABILITY OF NUTRIENTS IN THE GBR**

This paper is underpinned by the current conceptual understanding of the following processes:

- The cycling of nitrogen from ammonium-based fertilisers (Figure 2.1);
- The cycling of nitrogen from soil organic matter (Figure 2.2);
- Cycling of nitrogen from dissolved organic sources (Figure 2.3); and
- Cycling of particulate organic and inorganic phosphorus (Figure 2.4).

These are represented in the diagrams below.

## Cycling of nitrogen from ammonium-based fertilisers

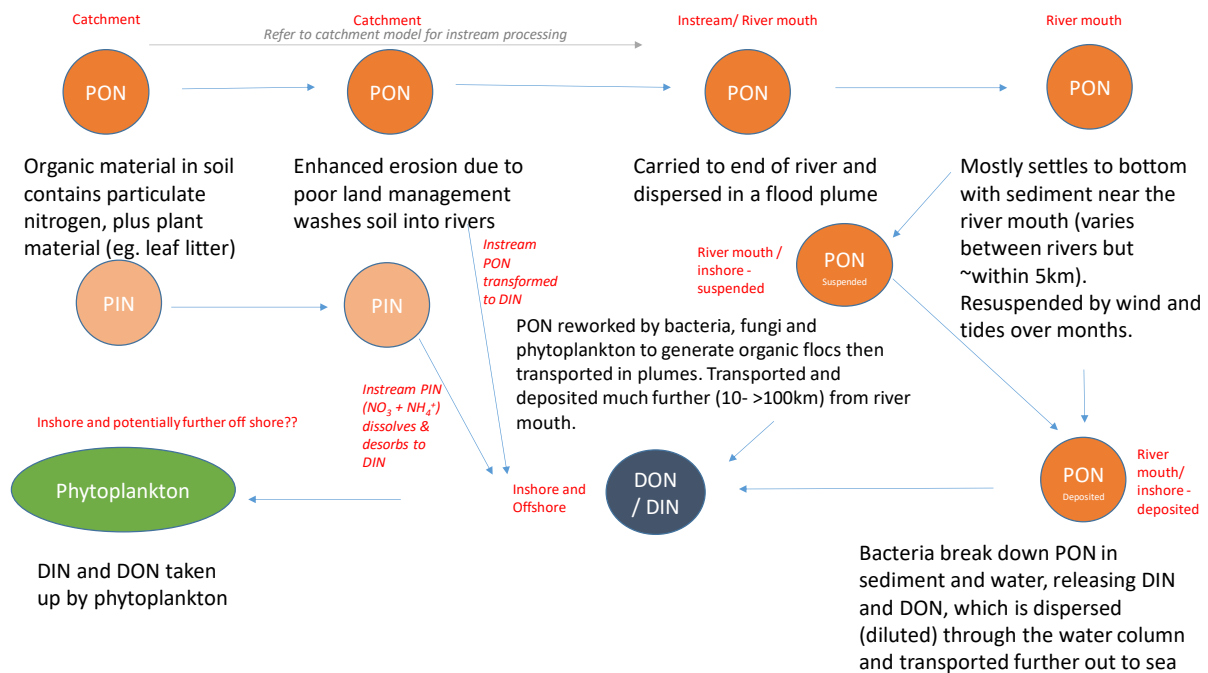


**Figure 2.1. Cycling of nitrogen from ammonium-based fertilisers.**

### Explanatory text and notes:

1. This model ignores lateral movement of nitrate-N in perched water-tables/groundwater which is often the major source of base-flow DIN.
2. This model also ignores exchangeable ammonium-N which is the major form of mineral N in runoff/sediments from enhanced efficiency fertilisers incorporating nitrification inhibitors.
3. The form of nutrients that is measured in the marine environment is not necessarily the same as the form of nutrients that was generated in the catchment and delivered to the end of system. Constant nutrient cycling occurs, so it is complex to determine whether different forms are directly important for catchment management.
4. There are three periods that are considered to be the most important in terms of potential ecological impact on GBR ecosystems:
  - river discharge periods (greatest influence);
  - wet season (periodic river discharge, higher temperature); and
  - non-wet (dry) season with no river discharge (usually cooler temps – but resuspension events and potential mineralisation).

## Cycling of nitrogen from soil organic matter



**Figure 2.2. Cycling of nitrogen from soil organic matter. Note: Nitrate associated with the soil will immediately dissolve becoming DIN in stream. This is not currently represented.**

### Explanatory text and notes:

1. A significant proportion of the PON in runoff falls to the bottom (sediments) in close proximity to the river mouth along with inorganic terrestrial sediment.
2. Some of the remaining PN is incorporated into organic aggregates within runoff plumes and can be dispersed more widely in the GBR lagoon.
3. DON in river discharge may also be converted to PON in estuarine processing and may thus enter the PON pool.
4. A portion of this terrestrial PN is ultimately mineralised to DIN by water column and benthic bacteria, provided sufficient carbon is available, and then may enter the GBR inorganic N cycle. Much of the PN may be quickly converted to  $\text{N}_2$  via mineralization, nitrification and denitrification processes and hence removed from the N cycle in the lagoon.
5. Current understanding of the influence of PON on nutrient availability, and whether it persists for a longer period after delivery (months) indicates that:
  - Input may continue in the longer term from mineralisation but unlikely to have important impact - not at concentrations that are of concern to ecosystems.
  - However, if direct uptake of DON occurs, it can reduce light penetration for longer periods of time leading to secondary processes in mid-shelf areas which can have implications. Importantly though, bleaching response is eliminated in this time, and COTS recruitment – so assume limited impact from this source.

## Cycling of nitrogen from dissolved organic sources

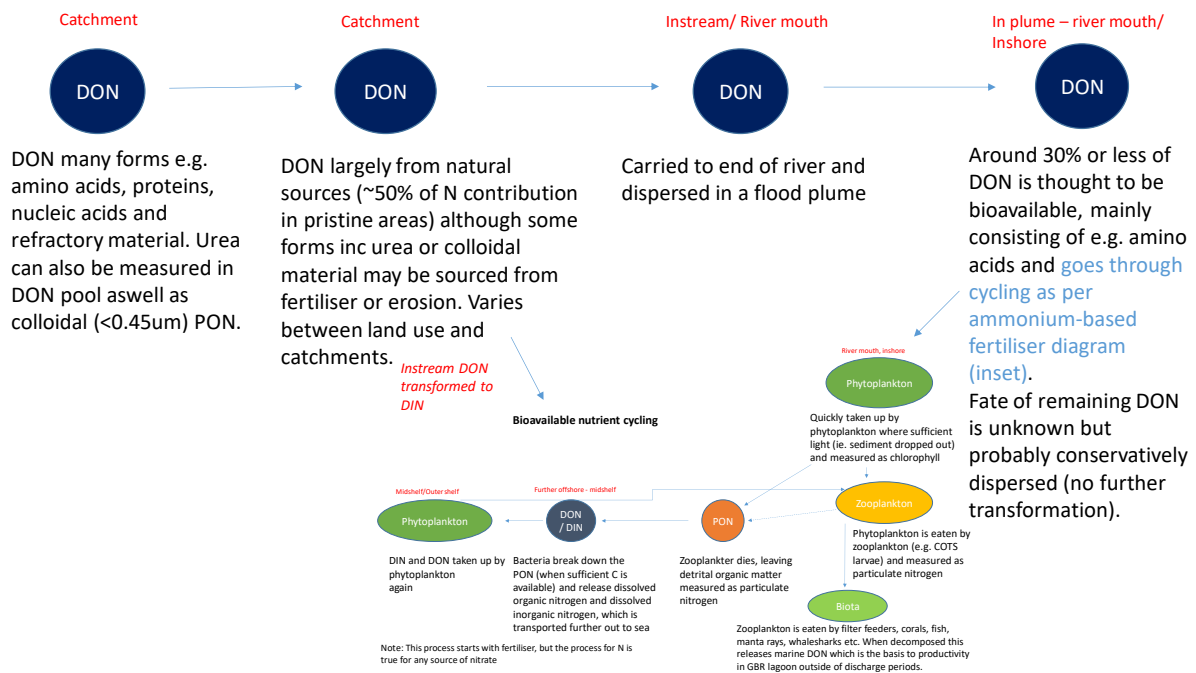
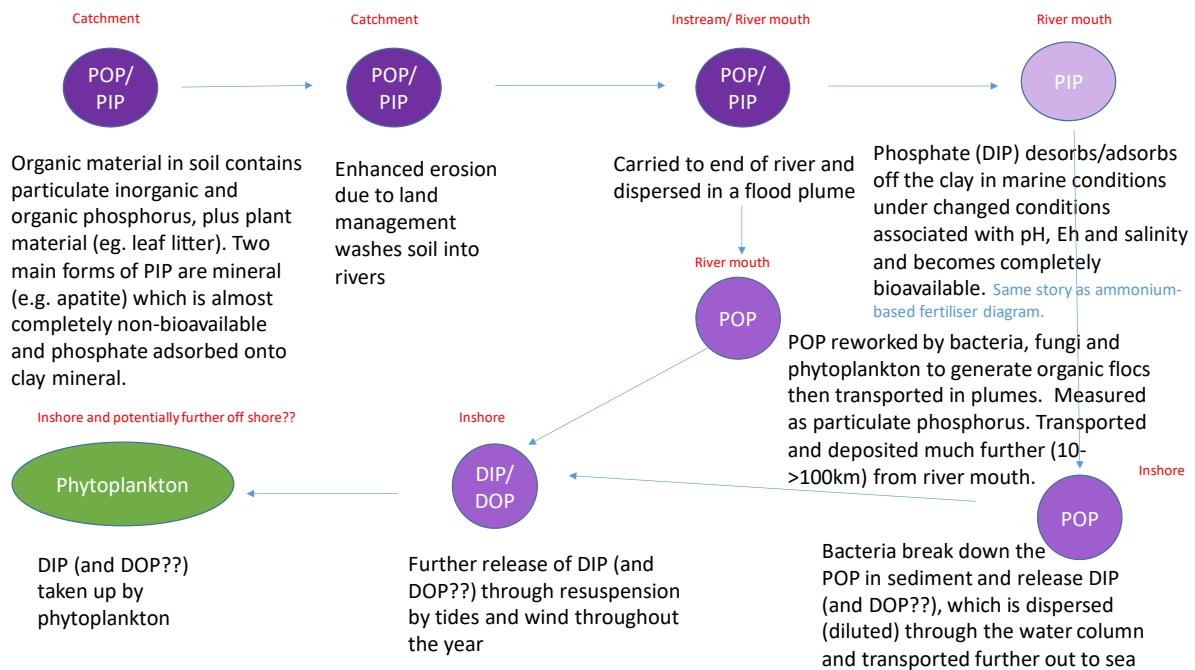


Figure 2.3. Cycling of nitrogen from dissolved organic sources.

### Explanatory text and notes:

1. The DON in terrestrial runoff is derived from degraded plant material and soil and differs in character from marine DON. A significant, but still uncharacterised fraction of the terrestrial DON in runoff is mineralised to DIN in the GBR lagoon and then enters GBR food webs.
2. Sources of increased DON (excluding urea fertiliser) in catchments are associated with improved drainage and other hydrological modifications, fertilised soils and potentially changed rainfall intensities.

## Cycling of particulate organic and inorganic phosphorus



**Figure 2.4. Cycling of particulate organic and inorganic phosphorus.**

### Explanatory text and notes:

1. The POP in terrestrial runoff is derived from degraded plant material and soil and differs in character from marine POP.
2. PIP is P attached to soil particles. In the case of PIP, it can be released when particulates reach marine waters to produce phosphate (DIP).
3. POP may be processed by bacteria, provided sufficient carbon is available, with DOP and DIP being products.
4. Bacteria can also utilise these sources and produce smaller DOP molecules, e.g. phosph-esters, phosphonates, which can be used by phytoplankton. Phytoplankton also use DIP for growth.

## **PART I: MARINE INTERACTIONS**

### 3. THE RISK OF PARTICULATE NUTRIENTS IN THE MARINE ENVIRONMENT

#### 3.1 Impacts of land-derived particulate nutrients on GBR ecosystems

##### *Summary of established evidence*

In this section, it is assumed that a reasonable proportion of land-derived particulate nutrients become bioavailable on timescales of days/weeks that are relevant to the impact of DIN on marine ecosystems. The particulate component that settles out is not considered in this section specifically. This justification is explained in Section 4 of this paper. Suspended particulate matter, i.e. particulate organic matter and mineral sediment, is also important when considering the potential influences of particulate nutrients on GBR ecosystems.

- Excess nutrient pollutant export from the rivers in the GBR has been associated with several ecosystem impacts (Brodie et al., 2011; Fabricius, 2011; Schaffelke et al., 2017). These include:
  - Reef degradation and overall reduced coral biodiversity between Townsville and Cooktown, with a reduction in species richness of 40 species compared with the expected value in this region (DeVantier et al., 2006).
  - Increased presence of macroalgae (D'Angelo and Wiedenmann, 2014), which can reduce coral diversity and/or larval coral settlement (Birrell et al., 2008) and recruitment (De'ath and Fabricius, 2010) through space competition (McCook et al., 2001); altering the corals' microbial environment which affects coral metabolism (Hauri et al., 2010; Vega Thurber et al., 2016) and larval survival (Morrow et al., 2017). Macroalgae can also increase the susceptibility to coral disease (Morrow et al., 2012; Vega Thurber et al., 2014).
  - Reef damage from coral-eating crown-of-thorns starfish (CoTS) (*Acanthaster planci*) outbreaks (Fabricius et al., 2010). CoTS are one of the major causes of coral mortality in the GBR (De'ath et al., 2012; Osborn et al., 2011). River nutrients can influence CoTS outbreak dynamics (Schaffelke et al., 2017) when wet season discharges from the Wet Tropics and the Burdekin rivers occur in the region between Ayr and Cooktown, in the period when phytoplankton-feeding CoTS larvae are present in the water column (November to March) (Brodie et al., 2005; Brodie et al., 2017a; Fabricius et al., 2010).
- For nutrient effects listed above, nitrogen must be bioavailable. For example, while nitrate is immediately bioavailable, bacterial action can transform organic nitrogen to ammonium (known as mineralisation), making it bioavailable to phytoplankton. Dissolved inorganic nitrogen (DIN - nitrate plus ammonium) derived from agricultural fertiliser losses is immediately bioavailable. The particulate nitrogen (PN) derived from soil erosion is likely to become bioavailable for phytoplankton through mineralisation within the lagoon waters or in the sediment (Brodie et al., 2015).

- Most detrimental effects on the GBR are attributed to excessive nitrogen loads, but phosphorus and carbon are also linked to remineralisation rates and should not be overlooked. At present, the lability of particulate and dissolved organic carbon and phosphorus remains poorly understood in the GBR lagoon (Furnas et al., 2005; Furnas et al., 2011).
- Terrestrially-derived particulate nutrients can contribute to the formation of 'marine snow' organic rich flocs (muddy *marine snow*) which reduces water quality and can smother coral reefs (Fabricius and Wolanski, 2000).

### *Summary of new evidence*

- Algal blooms associated with flood plumes due to inputs of river-derived nutrients reduce water clarity. These phytoplankton blooms, as well as non-algal suspended particulate matter (detritus, clay particles) in the plume reduces light availability for benthic plant communities including seagrass and coral (Bainbridge et al., in press; Collier et al., 2016a; Petus et al., 2014; Storlazzi et al., 2015). In inner-shelf waters, the reduction of in situ light penetration due to resuspended sediment is usually a more dominant effect, but in deeper waters (>15 m) where resuspension does not normally occur (except in cyclonic conditions), the light reduction due to phytoplankton (and zooplankton) may be an important factor for communities such as deepwater seagrasses (Collier et al., 2016a; Collier et al., 2016b) and mid-shelf coral reefs. Recent studies show that some of the suspended particulate matter (which particulate nutrients can contribute to) can be transported over long distances, transformed into large and easily resuspendible organic-rich sediment flocs, which then may lead to prolonged reductions in water clarity and impact upon coral reef, seagrass and fish communities (Bainbridge et al., 2012; Bainbridge et al., in press; Storlazzi et al., 2015).
- Enhanced vulnerability of reef corals to thermal bleaching stress (e.g. Wooldridge, 2016). Elevated DIN concentrations can cause changes that disrupt the ability of the coral host to maintain an optimal population of algal symbionts (Wooldridge, 2016; Wooldridge et al., 2017). Together with increased temperature, elevated DIN concentrations and changes in N:P ratios can increase the susceptibility of corals to bleaching (D'Angelo and Wiedenmann, 2014; Fabricius et al., 2013b; Humanes et al., 2016; Rosset et al., 2017; Vega Thurber et al., 2014; Wiedenmann et al., 2013; Wooldridge, 2016; Wooldridge et al., 2017).
- Bioerosion of living and dead corals occurs via a range of mechanisms involving many different organisms and can be enhanced by the growth of borers (Chazottes et al., 2017; Glynn and Manzello, 2016; Hutchings et al., 2005). Eutrophication of reefal waters by land-based sources of nutrient pollution can also magnify the effects of ocean acidification through nutrient-driven bioerosion (Prouty et al., 2017). Thus, increased bioerosion by these organisms can interact with reduced calcification due to ocean acidification to additively reduce reef net calcification (DeCarlo et al., 2015; Glynn and Manzello, 2016).
- Coral disease manifests as a general response to multiple stressors of corals, it has been positively correlated to sedimentation, elevated concentrations of nutrients and organic matter and increased plastic pollution (Haapkylä et al., 2011; Harvell et al., 2007; D'Angelo and Wiedenmann, 2014; Lamb et al., 2016; Lamb et al., 2018; Pollock et al., 2014; Thompson et al., 2014; Vega Thurber et al., 2014; Zaneveld et al., 2016).

## 3.2 Importance and risk of land-derived nutrients in the marine environment

### *Summary of established evidence*

The relative risk to GBR ecosystems from the various forms of nitrogen depends on the size of the input, the dispersal 'footprint' of the material and the degree of bioavailability of the different nitrogen forms over time (Brodie et al., 2015). In summary:

- DIN is immediately bioavailable for algal growth, and is therefore preferentially used. The potential impacts of increased DIN concentrations are well known, as described above.
- A large portion of both marine and terrestrial-sourced PN is potentially bioavailable for phytoplankton (timeframe of days to months) after bacterial mineralisation to DIN or ingestion by filter feeders. However, a significant fraction may be removed through denitrification in sediments (see next section).
- The bioavailability of DON for phytoplankton is variability and not well-understood. A significant proportion of DON may be unavailable over time frames longer than water residence times in the GBR system.
- To our current knowledge, land-derived dissolved organic nutrients are relatively less important than DIN and PON. Currently not easily manageable (see Wallace et al., 2010). However, primary producers, such as phytoplankton, are capable of directly using simple forms of DON. This includes urea and dissolved free amino acids. PN and larger molecular weight DON can also indirectly provide N for primary producers once particles are remineralised. There are also phytoplankton which are mixotrophic, i.e. using organic carbon to grow whilst utilising nitrogen. Dissolved organic matter from terrestrial vegetation has also been shown to inhibit algal growth, with exposure to light making it more inhibitory. However, this has not been examined in marine waters in the GBR.
- Abiotic processes are an important consideration in conversion between N pools. The definitions of PON and DON are based on particle size and are purely operational. These compounds exist on a size spectrum and conversion between the two occurs due to many abiotic forcing factors including turbulence and intermolecular forces (He et al., 2016). Additionally, conversion of DOC to DIC via photochemical degradation can be an important abiotic pathway, at least for DOC derived from coastal sources (Miller and Moran, 1997). It is not presently clear if this pathway liberates substantial amounts of N, which may depend on the origin of DOM.
- Dissolved organic matter from terrestrial vegetation has also been shown to inhibit algal growth, with exposure to light making it more inhibitory. However, this has not been examined in marine waters in the GBR.

Further discussion of nutrient forms, transformation and fate is covered in Section 4; this section covers the combined effects of elevated nutrients in the GBR as it is difficult to trace the fate of all end of catchment nutrient loads.

## *New evidence*

### **3.2.1 Timing of inputs**

The timing of nutrient inputs is important in influencing ecological risk in the marine environment. The following information is summarised from Waterhouse et al. (2017).

Nutrient inputs are most important during river discharge events and for a period of time afterwards (Waterhouse et al., 2017). In the Wet Tropics, river discharge is an important process at an annual scale, whereas for the Burdekin discharge is important at scales of every 1 to 2 years, and Fitzroy every 3 to 5 years or longer. This is when the availability of bioavailable nutrients can influence adverse ecosystem effects e.g. COTS larval survivorship (Nov to Feb), bleaching susceptibility (coupled with temperature – January to March), coral disease (coupled with temperature – January to March). Effects of nutrients on seagrass in areas of resuspension (leading to reduced light) may be important throughout the year. During discharge periods, nutrient inputs may be important in deeper areas (>15m) – associated with phytoplankton growth and reduced light (knowledge is less certain).

Outside of those times, terrestrial influences are small and nutrient requirements for productivity are dominated by recycling in the GBR lagoon or from water column PON/DON (Furnas et al., 2011; Furnas et al., 2013). Resuspension of material outside of discharge periods is thought to be less important for nutrient bioavailability, but this is yet to be quantified. Upwelling is a large DIN input to the lagoon, though is generally restricted to outer shelf areas (e.g. Swains, Palm Passage, far northern GBR). PON may be more available than DON.

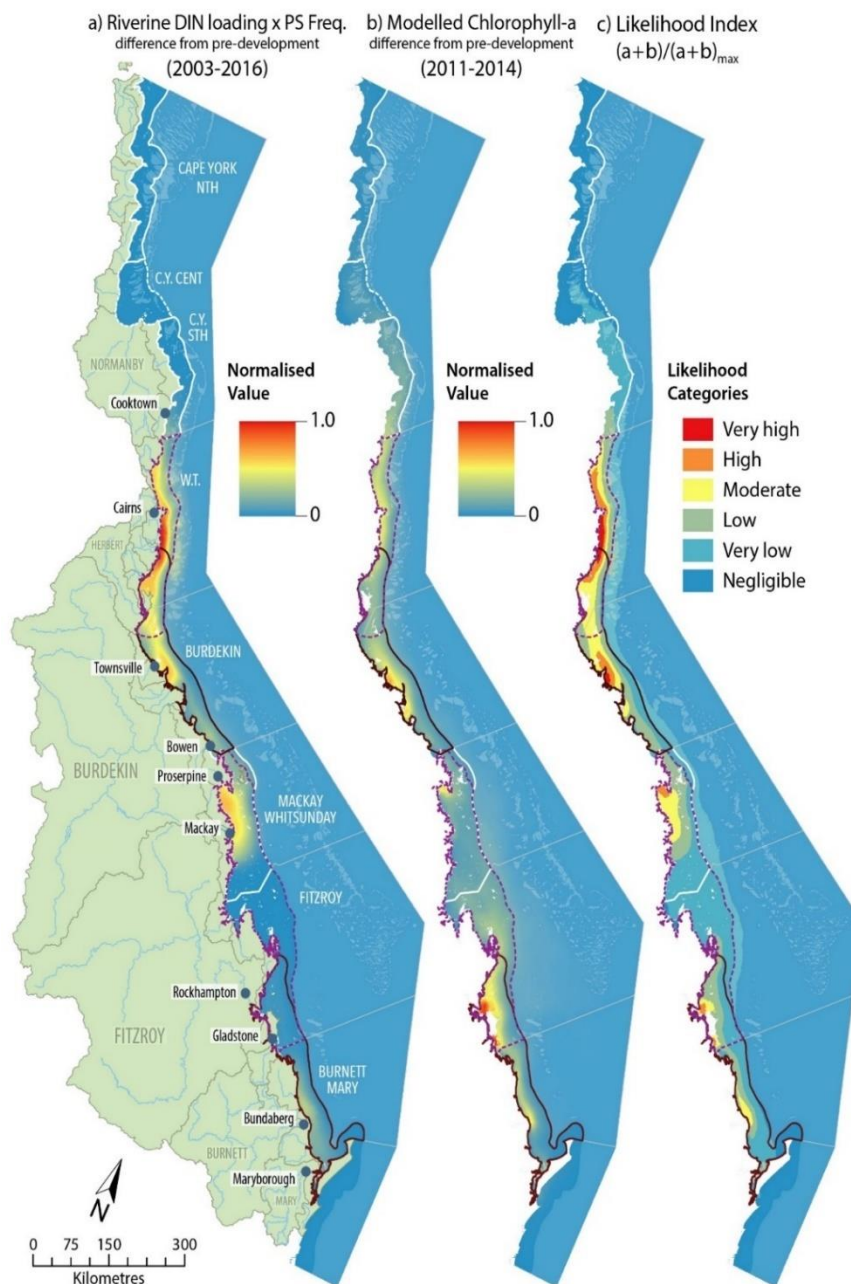
### **3.2.2 Ecological risk assessment**

The most recent risk assessment of river-derived pollutants on the GBR was conducted as part of the 2017 Scientific Consensus Statement, Chapter 3 (Waterhouse et al., 2017). This work assessed the likelihood of exposure of coral reef and seagrass to sediments and nutrients. Importantly, in this and previous risk assessments, marine risk for nutrients was only assessed as DIN, so it did not fully capture the bioavailable component of particulate nutrients or dissolved organic nutrients (except perhaps indirectly in the Chlorophyll and light attenuation input data). Consideration of turbidity and reduced light availability may account for this to some extent, but not explicitly. For management prioritisation, the nutrient results are currently only linked back to end of catchment DIN loads for basin scale prioritisation. Nevertheless, this new work is important and is relevant to the current understanding of the risk of bioavailable nutrients to GBR ecosystems. The main findings are summarised below and found in full in Waterhouse et al. (2017).

Spatial layers were selected to represent annual and wet season conditions that influence nutrient availability, including the predicted dispersion of end-of-basin DIN loads in the wet season, analysis of the frequency of exposure to wet season water types that may represent enriched nutrient conditions, and the difference between modelled estimates of current Chl-a concentrations and pre-development Chl-a concentrations scenarios to assess 'anthropogenic influences'. The results showed that:

- Exposure to DIN is significant to all inner shelf areas and the midshelf area between Lizard Island and Townsville adjacent to basins with high anthropogenic DIN loads.

- The relative importance of DIN to seagrass ecosystems is still uncertain, but it may influence light availability for deepwater seagrass in areas deeper than 10 to 15 m due to increased phytoplankton growth.
- The greatest coral reef and seagrass exposure to DIN is from the Herbert, Haughton, Johnstone, Russell-Mulgrave, Tully, Plane and Murray Basins.
- Anthropogenic PN is also likely to be of some importance in the same areas, as well as the Fitzroy Basin – but knowledge on the bioavailability of particulate nitrogen to marine ecosystems relative to that of DIN is still limited.



**Figure 3.1. The results of the assessment of the likelihood of exposure of anthropogenic DIN in the GBR showing a) riverine anthropogenic DIN-loading and the frequency of primary and secondary water types (2003-2016), b) modelled anthropogenic Chl-a (2011-2014), and c) the likelihood of exposure of DIN in the GBR, based on a combined output of a) and b). Source: Waterhouse et al. (2017).**

### 3.2.3 The relative importance of N and P

Furnas et al. (2013) described the current understanding of the relative importance of N and P in the GBR. Ratios between concentrations of readily bio-available forms of the major algal nutrients (N, P, Si) in GBR waters indicate that GBR waters are more likely to be N than P or Si-limited. DIN:DIP ratios (typically < 4) are persistently lower than the canonical composition ratios of the dominant micro-organisms for physiologically balanced growth (phytoplankton N:P = 16:1, bacterial N:P ~ 9:1). These low ratios may not affect instantaneous growth of phytoplankton and bacteria due to concurrent remineralisation, but increases in plankton biomass are constrained by the absolute availability of N. Inorganic P (DIP) is almost always measurable and there is always sufficient Si available to support production of additional diatom biomass.

Stoichiometry of carbon, nitrogen, and phosphorus in seston of the inshore GBR has historically been close to the Redfield ratio (106:16:1), with long-term averages of ~121:12:1 (Schaffelke et al., 2012). However, N:P ratios in seston can vary substantially with region and between inshore and offshore waters (Furnas et al., 2011).

In recent decades, studies have shown that N:P elemental ratios in phytoplankton can be highly variable and are not necessarily indicative of nutrient limitation. Ratios of N:P may vary substantially around Redfield, and the transition from N- to P-limitation is variable and in the range of 20-50 N:P (Geider and La Roche, 2002). However coastal studies using algal bioassays in the subtropics and tropics consistently show stimulation of growth with N, not P, addition, e.g. a study in Moreton Bay demonstrated a threshold of 2  $\mu\text{mol L}^{-1}$  DIN which gives the maximum photosynthetic response by phytoplankton while P did not increase photosynthesis (Saeck et al., 2016).

The eReefs biogeochemical model indicates that: (1) though nitrogen is more often limiting, phosphorus does sometimes limit phytoplankton and coral symbiont growth in the GBR, and (2) nitrogen fixation by *Trichodesmium* makes an important contribution to the nitrogen supply. Nitrogen fixation is in turn limited by the phosphorus supply. Recent process studies in marine waters also show that nitrogen and phosphorus often co-limit production, contrary to previous assumptions.

## 4. PARTITIONING AND FATE OF PARTICULATE NUTRIENTS IN THE MARINE ENVIRONMENT

*Summary of established evidence*

**Source: Brodie et al. (2015)**

- Most of the nitrogen (N) in GBR waters is in organic form. Overall, approximately 80% of water column N, regardless of location or season, is present as DON (nominal concentration range 5-10  $\mu\text{M}$ ). Particulate forms of nitrogen (nominal concentration range 1-2  $\mu\text{M}$ ), which are largely organic, comprise close to 20% of the fixed N pool. Concentrations of DIN are usually very low (nominal concentration range 0.01-0.2  $\mu\text{M}$ ), comprising only 1-2 percent of the total water column N pool.
- PN in the water column is comprised of a combination of living, e.g. primary producers, bacteria, and non-living, i.e. detritus material. Most of the non-living PN in GBR waters is of marine and biological origin. Although it is not strictly bio-available to primary producers (algae), almost all PN is susceptible to microbial degradation to N-forms bio-available to phytoplankton or can be consumed and digested by larger filter-feeders or detritus feeders in the water column and benthos.
- GBR primary production rates generally fall between 0.5 and 1  $\text{g C m}^{-2} \text{d}^{-1}$ . This level of productivity is primarily sustained by rapid recycling of organic N and P in the water column and sediments to bio-available DIN and DIP which can be readily assimilated by algae and bacteria. Directly measured and indirectly estimated turnover times for GBR water column DIN pools range from < 1 hr to several days. Frequently, the available DIN (primarily  $\text{NH}_4^+$ ) is recycled in < 1 day.
- Between 140 and 440  $\text{km}^3$  of rainwater falls onto the GBR annually (Furnas et al., 1997). The rainwater volume can vary significantly from year to year. Individual estimates of annual rainfall are poorly constrained by the available data which are largely based on coastal stations. Rainwater contains approximately 6  $\mu\text{M}$  of N, approximately half of which is organic N (DON and PN).
- Concentrations of DON and PN in GBR lagoon waters are higher than in the adjacent Coral Sea, and there is exchange between the two water masses along the shelf break. Inputs of DIN to the shelf through upwelling along the shelf-break are partially offset by exports of DON and PN in displaced shelf waters.
- Most of the DON in GBR waters is thought to be of marine origin and largely recalcitrant on time frames of algal and bacterial growth and turnover (ca. 1 day). Only a small portion of the marine DON pool, chiefly amino acids, urea and other N-excretory products, which are normally present at nanomolar concentrations ( $10^{-9}$  to  $10^{-7}$   $\mu\text{M}$ ) is readily bio-available. These small concentrations give a false impression that there is limited DON available. However, high turnover of DON can mean that produced low-molecular weight DON is being consumed at the same rate. The bulk of marine DON is assumed to occur as complex polymeric molecules with turnover times of months to millennia. This time range is long relative to water residence times on the GBR shelf.
- N-containing particulate organic matter is continually cycled between the water column and sediments by deposition and resuspension. Downward vertical fluxes measured with sediment traps suggest that water column POM is deposited on time scales of 1 to several

days. However, sediment trap methods do not measure resuspension and thus cannot estimate benthic fluxes of PN.

- GBR sediments contain considerable amounts of organic matter and nutrients compared to the overlying water column. The upper 1 cm of sediment (the layer most susceptible to resuspension) typically contains orders of magnitude greater N concentrations than the overlying water column. Fluxes of DIN (present in high concentrations in sediment porewater) to the water column during resuspension events may provide an episodic source of 'new' N for phytoplankton uptake. Major resuspension events during cyclones likely inject large amounts of N into the water column where DON/PN may be remineralised and taken up by phytoplankton, although this requires further study. Porewater also has high  $\text{NH}_4$  (and a little  $\text{NO}_x$ ), which contribute to water column DIN.
- Estimates of denitrification in GBR inner-shelf sediments indicate annual N removal of similar order to N inputs in terrestrial runoff (Furnas et al., 2011). However, estimates of regional-scale denitrification are still not well constrained due to the small number of denitrification measurements and the difficulty of weighting the measured rates to spatial distributions of sediment types.

### *Summary of new evidence*

Two research projects have been contributing to the evidence base associated with the partitioning and fate of particulate nutrients from the catchment source to the delivery and fate in the marine environment. These are:

[\*NESP TWQ Hub Project 2.1.5: What's really damaging the Reef? Tracing the origin and fate of the environmentally detrimental sediment\*](#) led by Dr Stephen Lewis, TropWATER James Cook University. The final project report with detailed results will be completed in the end of 2018. A summary of the key findings is presented here.

*RP125G Bioavailable Particulate Nutrients – Phase 2* led by Dr Joanne Burton and Dr Alexandra Garzon-Garcia from the Queensland Department of Environment and Science. The key findings from this work are published in Franklin et al. (2018) and Garzon-Garcia et al. (2018a), with a summary provided below.

## **4.1 What's really damaging the reef? The role of biogenic sediments**

The [\*NESP TWQ Hub Project 2.1.5: What's really damaging the Reef? Tracing the origin and fate of the environmentally detrimental sediment\*](#), has characterised the physical, biogeochemical and isotopic composition of suspended sediment samples from flood plumes and resuspension events in the GBR. This has enabled the within-catchment source of the sediments to be traced, providing insight into the various sediment and nutrient transformations that occur as fine clay-sized sediment moves from 'catchment to reef'.

The findings to date highlight that the composition of newly delivered fine sediment (predominately  $<20\ \mu\text{m}$ ) to the GBR lagoon changes during transport, deposition and resuspension, with increasing importance of the biological component.

Sampling was conducted in flood events in the Burdekin catchment and marine receiving waters in 2017 and 2018, and in the Tully and Johnstone catchment and Tully marine receiving waters in 2018.

The 2018 Burdekin sampling showed that patterns of suspended particulate matter (SPM; measured as TSS), particulate nitrogen (PN) and dissolved inorganic nitrogen (DIN) against salinity over the estuarine mixing zone were consistent with previous sampling years, with the bulk of the SPM and associated PN falling out by the ~5 salinity area. In contrast, DIN concentrations were more variable and conservatively mixed, at least in the early plume stages.

The 2018 Tully River to Dunk Island results showed that SPM concentrations in the Tully River were much lower than the Burdekin and, with the exception of the odd outlier likely related to sediment resuspension, levels gradually declined over the estuarine salinity mixing zone (but remained in the order of 10-20 mg/L), while flocs became larger in size.

Analysis of historical flood plume datasets was conducted to examine how SPM concentrations vary over the estuarine mixing zone for different rivers and over multiple flood years. As most sediment in the larger rivers is deposited in the 0 to 10 salinity zone and the deposited sediment in this zone is largely retained near the river mouth (see Lewis et al., 2014), it is the SPM in the 10 to 35 estuarine mixing zone that travels furthest and is likely the most ecologically important. Hence it is critical to examine the variability of TSS/SPM concentrations for this part of the salinity zone for the different rivers to appreciate their effect on the GBR. The analysis highlighted that it is critical to not only document the changes in TSS concentration across the salinity gradient of the different rivers but also to characterise the composition of SPM over this gradient. This is important for understanding the bioavailability of nutrient inputs.

Newly designed sediment traps allowed for collection of sediment over 2 years and included river discharge and resuspension events. The sediment was analysed for particle size, clay mineralogy, biogeochemical and isotopic characteristics. This data is being used to identify the 'most environmentally detrimental sediment' in terms of transportability and nutrient bioavailability (the full dataset is still being analysed as at July 2018). The organic component of the floc aggregates were also characterised to determine if they are of catchment or marine origin and how they change during successive resuspension events. Time series of logger data also show the influence of river discharge inputs versus resuspension events for turbidity data which is important for understanding the role of 'new sediment' and associated nutrients in influencing water clarity.

The particle size of the samples across the estuarine mixing zone become finer following the initial deposition of sediment at the river mouth. The organic content measured over the estuarine mixing zones in the 2018 flood plumes increased from ~ 10 to 25% at the end-of-river to 25 to 40% as salinities increased. However, this increase was not as pronounced as measured previously in 2017 and in Bainbridge et al. (2012) where up to 60% organics were measured in the higher salinity zones. Sediment colour only displayed minor changes in the sediment collected over the estuarine mixing.

## 4.2 Mineralisation and settlement

PON is mineralised in the water column to bioavailable form (e.g. DIN) and we have some idea of the rates. PON can be mineralised to ammonium in the sediment matrix and transformed to either nitrate (nitrification) or  $N_2$  (nitrification coupled with denitrification), or  $N_2O$ . The relative proportion of the rates of these two processes will vary depending on the redox conditions within the sediment matrix. Recent studies using  $^{15}N$  in the Brunswick River NSW with microphytobenthos (MPB) present showed that thirty-three days after the  $^{15}N$  was assimilated by MPB, 27% remained in the sediment, 16.5% had been effluxed as  $NO_3^-$ , 20.8% had been effluxed as  $NH_4^+$ , 20.7% had been effluxed as  $N_2$  and 15.1% was not accounted for (Eyre et al., 2016). It is predicted that most (12.6%) of the  $^{15}N$  label that was not accounted for was probably lost as dissolved organic N (DON) fluxes. However, this is for the specific conditions of the Brunswick River estuary.

The eReefs model handles mineralisation as a simple function of organic N concentrations and temperature, and denitrification as a function of nitrate concentrations, temperature and dissolved oxygen. It is still believed that between 10 and 30% of the DON from the river is bioavailable after discharge into the lagoon.

## 4.3 DIN generation in riverine sediment plumes – experimental results

Recent research has indicated that particulate nutrients associated with fine sediment are bioavailable to marine phytoplankton of the GBR (Franklin et al., 2018; Garzon-Garcia et al., 2018a). The magnitude of this bioavailability depends on the sediment load and sediment characteristics associated with its parent soil. These characteristics vary with soil type, land use and erosion process (surface versus subsurface erosion).

The bioavailability of particulate nutrients to phytoplankton is mediated by microorganisms (e.g., bacteria) which mineralise organic nutrients into inorganic forms that are directly available and preferentially used by phytoplankton, e.g. DIN. DIN is of particular importance because nitrogen is considered to be the limiting nutrient for phytoplankton growth in the GBR (Furnas et al., 2005).

The magnitude of the contribution to marine DIN from riverine sediment plumes has not been studied prior to this work. Understanding this contribution will enable an improved assessment of the risk caused by anthropogenic sediment and associated particulate nutrients to the Reef. It will also improve our understanding of the complex dynamics of large floc formation (muddy marine snow) in riverine sediment plumes (Bainbridge et al., 2012).

A number of key concepts require explanation to convey the results of these studies; these are summarised below. Further detail is presented in the documents cited in each section.

### 4.3.1 Indicators of particulate nutrient bioavailability for the GBR

*The following summary is derived from Garzon-Garcia et al. (2018a).*

To enable assessment of DIN generation in river plumes, it was first necessary to establish indicators of particulate nutrient bioavailability in fresh and marine waters. Historically,

measurement of nutrient bioavailability has been conducted by analysis of dissolved inorganic nutrients. Dissolved inorganic forms become available rapidly as they are disassociated from sediment particles, while organic forms may be processed more slowly. Therefore, measuring biological response is more meaningful.

Phytoplankton bioassays were used to assess freshwater and marine phytoplankton responses to sediments (Franklin et al. 2018). These assays take water from marine waters and add particulate matter in dialysis bags, incubate then measure photosynthetic responses. The best indicators were selected by regressing measurements of phytoplankton growth against nutrient bioavailability parameters measured on the sediments (Garzon-Garcia et al., 2018a). A key finding from this study was the importance of organic carbon in nutrient transformation, which appears to mediate bacterial conversion of particulate nutrients to more bioavailable forms. The equations also included various fractions of particulate nitrogen (N) concentrations (differentiating the adsorbed ammonium- N from the particulate organic N), and the ratios of C to N, which indicate the lability of the organic matter present in the sediment. Dissolved reactive phosphorus was also an important indicator in freshwater.

The bioavailability of particulate nutrients to phytoplankton also varied with sediment type, with differences found between sediments sourced from different land uses, soil types and erosion processes (surface and subsurface). The study developed an indicator equation and a new algal bioassay method, both of which can be used to prioritise erosion control to catchment areas which are most likely to contribute large amounts of bioavailable particulate nutrients to the GBR.

Monitoring the selected particulate nutrient bioavailability parameters would also give insight into the underlying biogeochemical processes driving particulate nutrient bioavailability which may in turn help to refine management strategies and prioritisation. These parameters include organic carbon, different particulate nutrient fractions (adsorbed ammonium, particulate organic N and dissolved reactive P) and ratios of C to N, which relate to the lability of sediment organic matter.

#### **4.3.2 DIN generation in Cyclone Debbie plume from the Burdekin River**

*The following summary is extracted from Garzon-Garcia et al. (in prep) incorporated into Lewis et al. (2018).*

A study conducted as part of NESP 2.1.5 (Garzon-Garcia et al. in prep) assessed the potential for DIN generation from PN in the Cyclone Debbie Burdekin River plume in 2017. To do this, plume sub-samples were incubated in the lab to quantify the mineralisation rates of PON to DIN, and a separate sub-sample was used to quantify the amount of ammonium that could be desorbed from the suspended sediment. The results indicate that the potential DIN generation associated with particulates in the marine environment during high flow events is significant.

The Cyclone Debbie Burdekin river plume was divided in three sectors according to estimated sediment travel times and total suspended solid concentrations (Figure 4.1):

1. a freshwater sector (Burdekin river at Inkerman to 0.1 PSU), with an estimated travel time of 1 hr;
2. a turbid sector (0.1 PSU to 11.7 PSU), with an estimated travel time of 2 hours and;
3. a clearer sector (11.7 PSU to 26 PSU), with an estimated travel time of 1 day.

A hypothetical longer travel time for the sediment plume was also assumed, considering this has been observed for larger events where the sediment plume has reached Palm Island, with an estimated additional 9 days of travel time (note: travel time derived from eReefs model simulation).

DIN generated loads for each plume sector were calculated using the mineralisation rates and the event sediment load remaining in suspension for each sector. Based on sediment concentrations in the plume and sediment settling rates calculated by end-of-river and flood plume data, it was assumed that 40% of the suspended sediment (and associated PN) would settle between Inkerman and 0.08 PSU, 55% would settle between 0.08 PSU and 11.7 PSU, and a further 5% in the last plume sector.

The total load of DIN estimated to be generated in the plume for the three identified plume sectors was 43 tonnes, which is equivalent to 25% of the whole of catchment 175 tonnes of DIN contributed at Inkerman for that event (Table 4.1, Figure 4.1). Particulate inorganic nitrogen (PIN) conversion to DIN (ammonium desorption) was an important process accounting for 70% of the generated DIN load in 1 day. All PIN was converted to DIN at salinities below 11.7 PSU. The other 30% was contributed by microbial mineralisation of the organic nitrogen (PON+DON). There is evidence to suggest that there is a large contribution of terrestrial sources to DON in plume water and of some production along the plume, though the trend is for DON concentrations to decline along the plume (Figure 4.2). The DIN load generated in each of the plume sectors can be observed in Table 4.1. When assuming a longer travel time for the sediment plume, it is estimated that a total DIN load of 147 tonnes would be generated from the sediment plume, which is equivalent to 84% of the whole of catchment DIN load contributed at Inkerman for that event.

**Table 4.1. Estimated DIN and cumulative DIN generation load associated with particulates from Cyclone Debbie Burdekin plume incubation experiments at the freshwater sector (Inkerman End of System – 0.1 PSU), turbid sector (0.1 PSU – 11.7 PSU), clearer sector (11.7 PSU -26 PSU) and hypothetical longer travel time of 9 days clearer sector. The total estimated event loads at Inkerman End of System are 1.9 million tonnes of TSS and 175 tonnes of DIN. Source: Garzon-Garcia et al. (in prep).**

| Sector     | Travel time | DIN load (tonnes) | Cumulative DIN load (tonnes) |
|------------|-------------|-------------------|------------------------------|
| Freshwater | 1 hour      | 0                 | 0                            |
| Turbid     | 2 hours     | 2                 | 2                            |
| PIN to DIN | Immediate   | 30                | 32                           |
| Clearer 1d | 1 day       | 10                | 43                           |
| Clearer 9d | 9 days      | 105               | 147                          |

Mineralisation rates had the tendency to increase along the plume with faster mineralisation rates at higher salinities (Figure 4.1). Importantly mineralisation was still increasing linearly at the end of the incubation experiment (Figure 4.2). This indicates that the sediment and associated particulate nitrogen have the potential to continue to generate DIN once deposited on the marine floor and/or resuspended. Previous research in the GBR has demonstrated that 74 to 92 % of deposited PN is mineralised to DIN and an average of 50% of deposited PN is lost through denitrification (Alongi et al., 2007). Mineralisation rates are those measured in laboratory conditions so may not necessarily be the same as *in situ*, however the incubation experiments enable the removal of the effect of algae, allowing the quantification of gross DIN

generation. This type of experiment gives information on the cycling rates of N in the plume which can't be obtained from direct DIN measurements on the plume water (Figure 4.3).

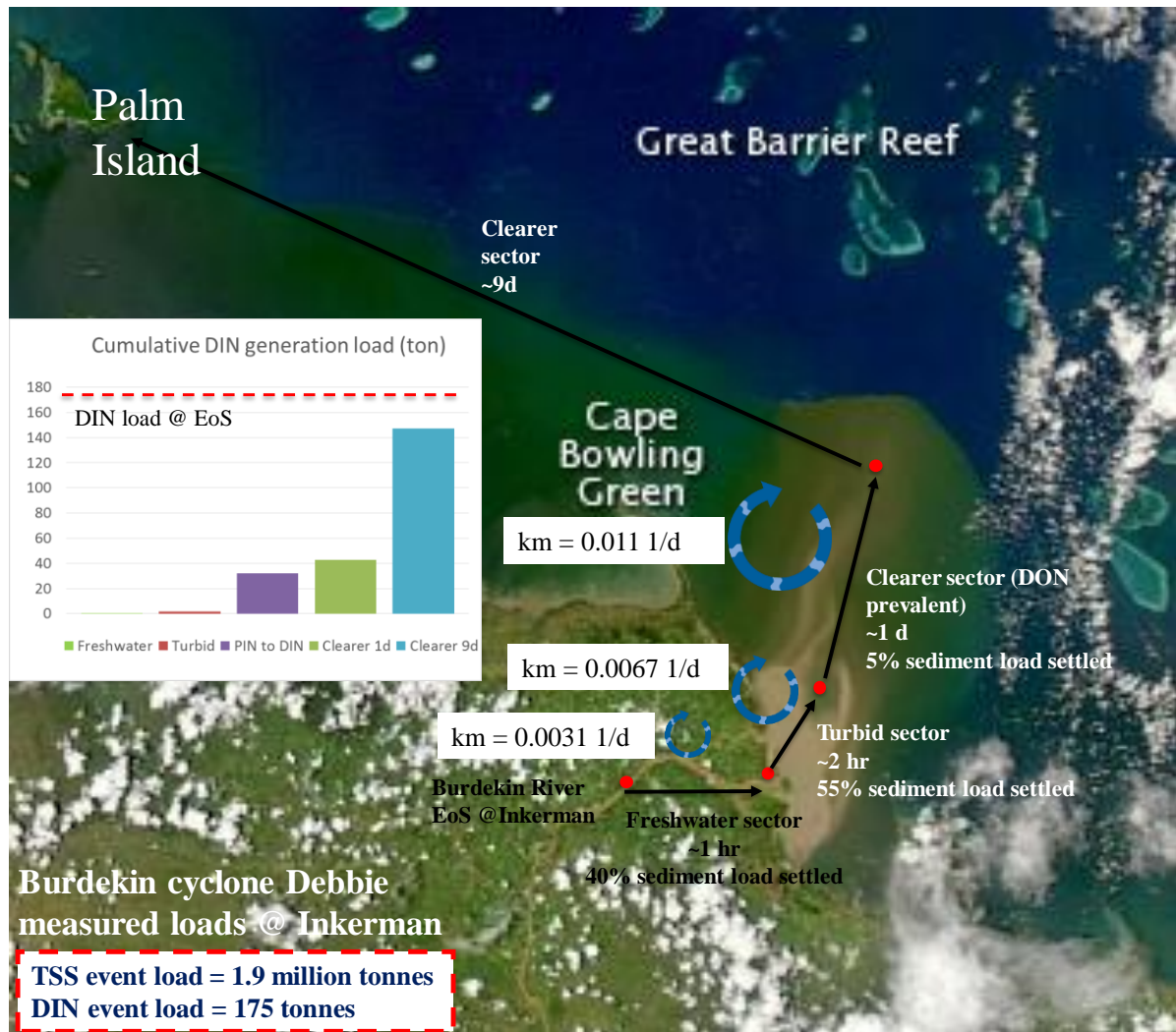
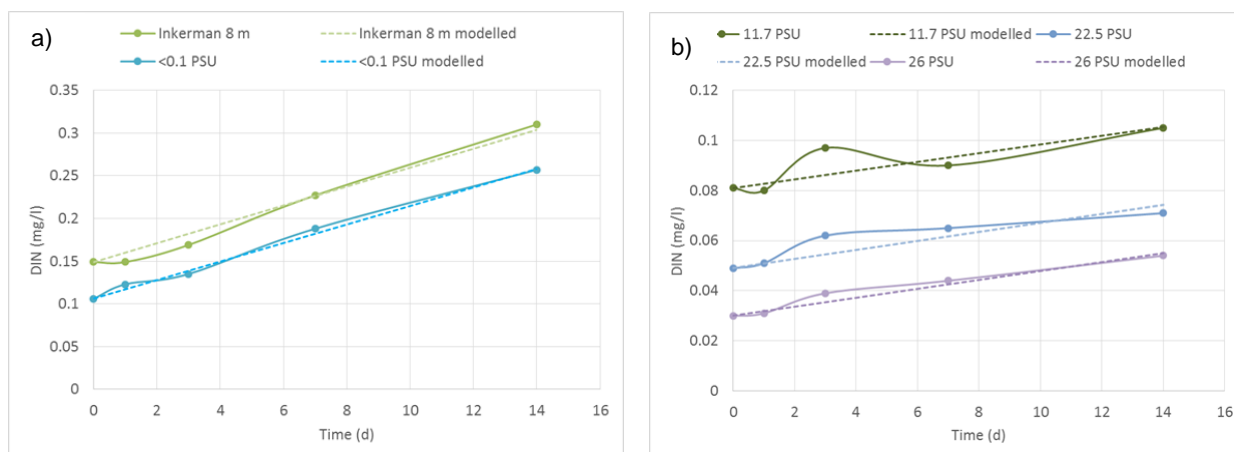
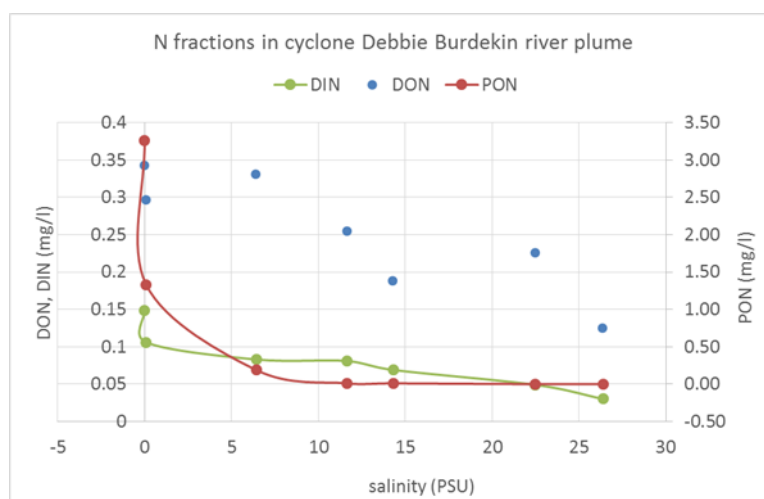


Figure 4.1. Estimated cumulative DIN generation loads associated with particulates and corresponding organic N mineralisation rates from Cyclone Debbie Burdekin plume incubation experiments at the freshwater sector (Inkerman End of System – 0.1 PSU), turbid sector (0.1 PSU – 11.7 PSU), clearer sector (11.7 PSU -26 PSU) and hypothetical longer travel time of 9 days clearer sector. The total estimated event loads at Inkerman EoS are 1.9 million tonnes of TSS and 175 tonnes of DIN. Garzon-Garcia et al. (in prep).



**Figure 4.2. DIN concentration during incubation experiments of Cyclone Debbie Burdekin plume samples at (a) Inkerman (hydrograph at 8 m) and 0.08 ppt and (b) at 11.7 PSU 22.5 PSU and 26 PSU. Continuous lines join sampled data and intermittent lines represent linear net mineralisation fitted models (net mineralisation rates can be seen in Figure 4.1) (Garzon-Garcia et al., in prep).**



**Figure 4.3. DON, DIN and PON in Cyclone Debbie Burdekin plume water along a salinity gradient going from 0 PSU at Inkerman End of System to 26 PSU. (Source: Lewis et al., 2018.)**

This is a preliminary analysis of data collected as part of NESP 2.1.5 and refers to results from one plume only, with work continuing in the 2018 wet season in both wet tropics and dry tropics catchments if possible. Mineralisation rates are those measured in laboratory conditions so may not necessarily be the same as in-situ, however the incubation experiments enable the removal of the effect of algae, allowing the quantification of gross DIN generation.

#### 4.4 Sources, transformations and fate of dissolved and particulate organic carbon in marine ecosystems

Dissolved and particulate organic carbon in marine ecosystems can come from marine and catchment sources. As with dissolved organic and particulate nitrogen, there are many forms with varying bioavailability to bacteria and other microbes. Organic carbon is critical to bacterial growth and mediates the processing and conversion of nutrients into more forms more

available to phytoplankton. As mentioned above, studies of the bioavailability of sediments from catchments in the GBR showed that organic carbon concentrations were linked to phytoplankton responses to catchment sediments (Garzon-Garcia et al., 2018a; Franklin et al., 2018). This likely demonstrates the mediating role that bacteria can play. The rates of transformations of organic carbon vary widely depending on the chemical complexity and the microbes present. Some phytoplankton, known as mixotrophs, can also utilise organic carbon, in either dissolved or particulate form, for growth. Organic carbon is ultimately respired, exported or buried.

A recent report for the Marine Monitoring Program identified a trend for increasing dissolved organic carbon (DOC) and particulate organic carbon (POC) concentrations in inshore waters in a variety of monitoring locations spanning the length of the GBR (Lønborg et al., 2016). While the precise ecological impacts of elevated organic carbon concentrations in the GBR ecosystem is not well understood, increases in organic carbon concentrations have been shown to promote the activity of heterotrophic microbes and some coral diseases in other tropical coastal ecosystems. There is, therefore, concern that elevated organic carbon concentrations may have deleterious impacts on the structure and functioning of the GBR marine ecosystem.

Several, potentially interactive, mechanisms have been hypothesised to help explain elevated DOC and POC concentrations in inshore waters of the GBR (Lønborg et al., 2016). These hypothesised mechanisms include (1) an increase in coral and planktonic primary production and/or organic carbon release and (2) an increased export of terrestrial organic carbon (Lønborg et al., 2016). However, there are likely other mechanisms controlling variation in DOC and POC concentrations. Coastal waters of the GBR are ecologically and biogeochemically complex, and an understanding of how the source, transformations, and fate of organic carbon changes through space and time is required in order to contextualise the potential mechanisms that help explain elevated DOC and POC concentrations in inshore waters of the GBR.

## **4.5 Biogeochemical modelling of the bioavailability of nutrients**

The eReefs biogeochemical model became operational in 2016, after the last synthesis was finalised.

Marine biogeochemical models make many simplifying assumptions in their representation of nutrient cycles and nutrient bioavailability (Robson, 2014). The eReefs marine modelling suite (Baird et al. 2016a; Baird et al. 2016b; Jones et al., 2016; Mongin et al., 2016), developed to help guide management of the GBR, is no exception, though it is at the more complex end of the spectrum of models in current use. Simplifications used in this and other biogeochemical models in part reflect a need to limit model complexity and in part reflect knowledge gaps and a lack of data that would be required to parameterise a more complex model (Robson, 2014).

Figure 4.4 and Figure 4.5 illustrate the pelagic nitrogen and phosphorus cycles as represented in the eReefs biogeochemical models. In summary, the model tracks the production and remineralisation of labile and refractory detrital material (i.e. particulate organic matter) and

dissolved organic material; production of ammonium and dissolved inorganic phosphorus by remineralisation of organic material; nitrification and denitrification; desorption, adsorption and immobilisation of inorganic phosphorus; physical transport of dissolved and particulate nutrients; biological uptake of dissolved inorganic nutrients, and other biological processes affecting plants, phytoplankton and zooplankton.

Each box in Figure 4.4 and Figure 4.5 represents one or more stores of nitrogen or phosphorus that are tracked for each model grid-cell. The model also tracks carbon and oxygen cycles as well as dissolved and particulate nitrogen and phosphorus components in benthic sediments stores, where they are subject to a similar suite of processes.

Transfer rates (shown as arrows in these diagrams) determined as functions of concentrations in each store, parameter values that in most cases represent measurable physical or biogeochemical process rates or biological traits, the temperature of the water and in some cases, the concentration of dissolved oxygen. The full equations and list of parameters and parameter values are given by Baird et al. (2017). For application to the GBR, model parameter values were obtained through a combination of past modelling experience, calibration of the model against monitoring data for the GBR, and reference to published literature from observational studies in the GBR and elsewhere, including the parameter library described by Robson et al. (2018), who also provide a more detailed discussion of the relationship between observational evidence and model parameter values.

Processes and components not currently included in the model include:

- Formation and break-up of organic aggregates and the impact of aggregation on transport and remineralisation;
- Heterotrophic nitrogen fixation, including nitrogen fixation in seagrass beds;
- Bacteria (though of course, bacteria are implicitly involved in the processes of remineralisation, nitrification and denitrification);
- Direct uptake of dissolved organic nutrients by phytoplankton and heterotrophs;
- Anammox (anaerobic ammonium oxidation);

Other simplifications include fixed particle sizes and settling rates for each component; the combination of a large number of distinct chemical species into umbrella groups such as “dissolved organic nitrogen” and “labile detrital nitrogen”; not including potential impacts of environmental variables such as salinity, ultraviolet light, micronutrients and minerals; radical simplification of the food web to consider only a few planktonic groups plus benthic plants, and radical simplification of sediment biogeochemistry and diagenesis. The accuracy of simulated sediment nutrient accumulation and depletion over time has not yet been adequately tested.

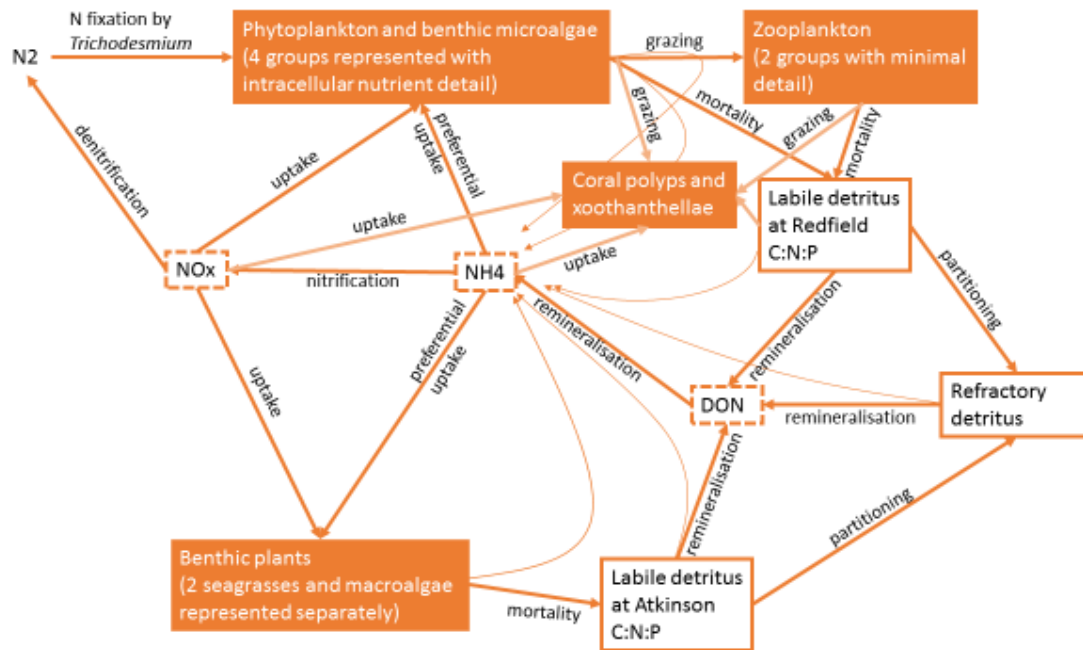


Figure 4.4. The pelagic nitrogen cycle as represented in the eReefs marine models (using CSIRO's EMS suite). Components with filled boxes are represented in more internal detail than shown here. Components in boxes with solid outlines are particulates, subject to settling and resuspension as well as advection and diffusion. Components in dashed boxes are dissolved, subject to advection and diffusion but not settling or resuspension. Dinitrogen (N<sub>2</sub>) is not explicitly tracked by the model. Note that several processes produce ammonium (NH<sub>4</sub>) as a by-product to maintain conservation of mass of nitrogen in the model. DON refers to dissolved organic nitrogen. NO<sub>x</sub> refers to nitrate and nitrite, which are combined in the model.



## 5. MARINE INTERACTIONS: PRIORITY KNOWLEDGE GAPS AND MANAGEMENT IMPLICATIONS

### *Priority knowledge gaps*

Further investigation of the rates and processes that influence nutrient **bioavailability in the marine environment**, including assessment of:

- Remineralisation rates of particulate organic material derived from terrestrial versus marine sources.
- The role of resuspension in injecting DIN and PON from sediment pools into the water column and implications for remineralisation. These factors should be considered in the assessment of the risk of particulate bioavailable nutrients to the GBR.
- The interaction of fine sediment, bioavailable nutrients and Chlorophyll in the central midshelf areas of the GBR. This will require frequent measurement of these parameters and analysis of the data correlations.
- The role of phosphorus in supporting phytoplankton growth, relative to nitrogen. This can be explored in more detail using the eReefs biogeochemical models, supported with marine process studies to confirm model results and improve parameterisation and representation of phosphorus and nitrogen fixation processes in the model.
- The effect of carbon on nutrient bioavailability (combined laboratory and field analysis).
- The differential and combined effects of bioavailable nutrients (N, P, C) on algal groups and linking to COTS initiation and survival.
- Phytoplankton dynamics in times of river discharge on the midshelf areas of the GBR, and measurement of nutrient enrichment across the GBR, especially in the midshelf and outer shelf between Townsville and Cairns where river discharge extends beyond inshore areas.
- Cumulative impacts of multiple nutrient stressors on GBR ecosystems.

Specific monitoring and modelling needs:

- Extension of routine measurement of nutrients (including PIN, DOC and POC) in the Marine Monitoring Program and include monitoring of midshelf areas in strategic locations where bioavailable nutrient sources may be important or where existing knowledge can be extended, e.g. link to crown-of-thorns starfish initiation in the Wet Tropics transects.
- Improve marine modelling (eReefs) capability to:
  - Simulate dissolved and particulate organic matter decay rates that vary as a function of stoichiometry and/or origin, incorporating knowledge of decay rates and POM composition gained from catchment and marine studies of particulate organic matter.
  - Adjust parameterisation of inorganic nutrient adsorption/desorption from suspended mineral sediments as information regarding these processes becomes available. Incorporate improved understanding of benthic sediment contributions in the eReefs model.
  - Provide better representation of the transport of flocs and N fixation, and test the sensitivity of ecosystem response to P inputs.

## *Management implications*

The new evidence:

- Reinforces that particulate nutrients can be a significant contributor of bioavailable nutrients in the marine environment which needs to be considered in risk assessment and spatial prioritisation.
- Identifies that there is a 'new' pool of bioavailable nutrients (derived from particulate nutrients) at the end of system that may not have been accounted for as a contribution to the marine environment before.
- Confirms that there is a shift in the conceptual understanding of nutrient cycling and how it is represented; this has implications for the framework of how bioavailable nutrients are measured and modelled and adjusts assumptions in the modelling.
- Highlights the need for further monitoring of bioavailable nutrients and sources in the salinity mixing zone.
- Highlights the influence of carbon on nutrient processing and the need for further investigation of these influences.
- Provides insights as to whether the DIN offshore in the plume is derived from the catchment particulate nutrients.
- Recognises that explicit addition of particulate nutrient loads and assessment of their bioavailability (e.g., by catchment, sediment type in plume) is required for future marine nutrient risk assessments – both in the marine modelling and in linking to end of catchment loads.
- Notes that the 2017 GBR end of catchment load targets for PN and PP mirror the fine sediment reductions for each basin. There is a need to specifically address bioavailable particulate nutrients when the targets are revised for the WQIP update in 2022 (need to be prepared to do that in 4 years time). This would require further quantification of DIN from erosion and quantification of the bioavailability of particulate nutrients in more catchments (both during transport to end-of-catchment and in the estuarine/marine receiving water columns). *This requires a combined catchment to reef approach.*
- Emphasises that setting ecologically relevant end of catchment load targets for P is important and should be progressed for definition by 2022. *This requires a combined catchment to reef approach.*

## **PART II: CATCHMENT INTERACTIONS**

## 6. END OF CATCHMENT NUTRIENT BUDGETS, SOURCES, DELIVERY AND TRANSFORMATION

*Summary of established evidence*

**Source: Brodie et al. (2015)**

- River runoff is the largest external source of “new” nitrogen to the GBR system. Under ‘pristine’ or pre-development conditions, DON is the dominant form of N exported from catchments. DON in runoff is primarily sourced from degraded plant material in the catchment, with a variable contribution from eroding catchment soils. Particulate forms of N are also important forms of N exported from undisturbed catchments. PN in runoff is primarily sourced from degraded plant material and detritus in eroding catchment soils. DIN is a less important N component in runoff from undisturbed catchments.
- Dissolved N forms are pre-dominantly exported into the GBR lagoon from wetter catchments. Particulate N is relatively more important in exports from the large dry catchments (Fitzroy, Burdekin) with significant erosion rates and higher suspended sediment loads.
- PN loads in rivers are strongly correlated with suspended sediment concentration which is generally correlated with discharge rate (rainfall, stream energy) and catchment erosion (vegetation cover, land use). However higher proportions of PN are found in fine sediments (especially the clay sized fraction) than in coarser sediments.
- At high summer discharge rates, organic N (DON + PON) forms contribute approximately 50 percent of N exports from well sampled Wet Tropics rivers (Tully, Johnstone) and approximately 80 percent of N exports from the two largest dry tropics rivers (Burdekin, Fitzroy). However, a large amount of DIN is also exported from the Burdekin Basin from sugarcane lands below the monitoring site for loads estimation and thus it is likely that organic N may only form about 50% of the N exports from the basin as a whole.
- Application of N-containing fertilisers increases the export of DIN from catchments in runoff. Increases in DIN exports are most pronounced in catchments supporting intensive sugarcane cultivation, which receives the greatest amounts of fertilizer inputs. Fertiliser N is lost through direct runoff of dissolved and soil-attached N, and through percolation of dissolved N through the water table to streams in groundwater.
- Urea-based fertilisers constitute a significant proportion of the fertilizer nitrogen applied within the GBR catchment. Under appropriate irrigation or rainfall conditions, appreciable amounts of urea can potentially run off into adjacent waterways. Urea-N concentrations in tropical coastal seawater is typically very low (nanomolar), but appreciable concentrations have been recorded in a small number of measurements in freshwater systems adjacent to heavily fertilized cropping lands. Although typically considered as part of the DON pool, urea-N is readily bio-available to phytoplankton and bacteria. Greater care needs to be given to the management of urea-based fertilizers in cropping systems adjoining the GBR.

## 6.1 End of catchment nutrient budgets

In addition to the information from Brodie et al. (2015), the information presented below on end of catchment nutrient budgets are established and have not yet been updated with the evidence of improved process understanding presented in the sections that follow (Section 6.2). This information is largely derived from the 2017 Scientific Consensus Statement Chapter 2 (Bartley et al., 2017) which is based on the 2015 data presented in the Great Barrier Reef Report Card 2016 (Australian and Queensland governments, 2017). McCloskey et al. (2017) provides the technical details of these results.

### 6.1.1 Current modelled estimates for DIN and particulate nutrient loads

The following points summarise the current knowledge of DIN and particulate nutrient load estimates for the GBR.

#### *Monitoring:*

- Based on the GBR Catchment Loads Program monitoring data, the Burdekin River had the highest average DIN, PN and PP delivery to the GBR at ~1,380 t/yr, 7,450 t/yr and 3,400 t/yr, respectively.
- In terms of specific nutrient yields, Cattle Creek (in the Pioneer Basin) had the highest specific yields for PN and PP, closely followed by the North Johnstone and South Johnstone catchments for each of these pollutants. The Tully Basin had the highest specific yields for DIN (~0.5 t/km<sup>2</sup>/yr).
- Based on the end-of-sub-catchment **monitored** specific loads (t/km<sup>2</sup>/yr), the results shows that the top quartile of sites (n = 8) contribute 79% of the DIN load, 70% of the PN load and 68% of the PP load **Error! Reference source not found..**

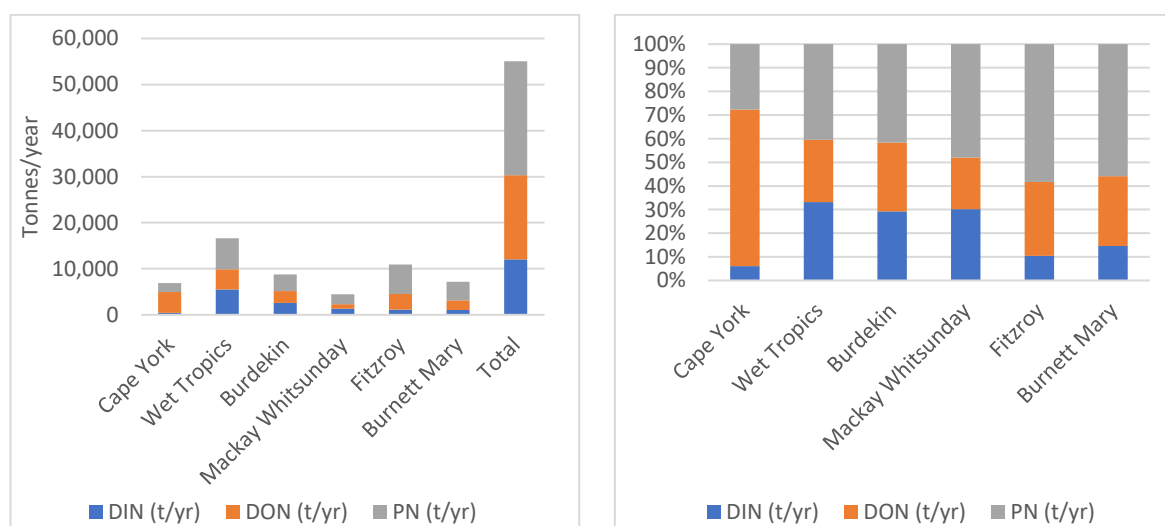
#### *Modelling:*

- Based on the most recent 2015 Source Catchments modelling, it is estimated that ~55 kt/yr of TN is delivered to the GBR (Table 6.1). The total amount of DIN delivered to the GBR lagoon is estimated to be ~12 kt/yr, which is a 1.2–6.0-fold increase from pre-development conditions. The amount of PN delivered is ~25 kt/yr which is a 2–5-fold increase above estimated average pre-development loads.
- On average, DIN contributes 22% of the TN load and PN contributes ~45% of the TN load (Table 6.1, Figure 6.1). On a regional basis the Wet Tropics has the highest loads of TN, DIN and PN (Table 6.1, Figure 6.1). The top five basins contributing to the DIN load are the Herbert, Burdekin, Johnstone, Haughton and Mulgrave-Russell (Figure 6.2). The top quartile of management units (i.e. 12 out of the 47 management units) contribute ~87% of the DIN based on the modelled area-specific nutrient yields (t/km<sup>2</sup>/y). The top five basins contributing to the PN load are the Fitzroy, Mary, Burdekin, Johnstone and Herbert.
- The modelling predicts that there is ~13 kt/yr of TP delivered to the GBR (Table 6.2.) and ~10 kt/yr of PP, which is a 3–5-fold increase. PP contributes 76% of TP. On a regional basis the Fitzroy region has the highest loads of TP, DIP and PP (Table 6.2, Figure 6.3). The top basins contributing to the TP and PP load are the Fitzroy, Burdekin, Mary and Johnstone basins (Figure 6.4). The top quartile of management

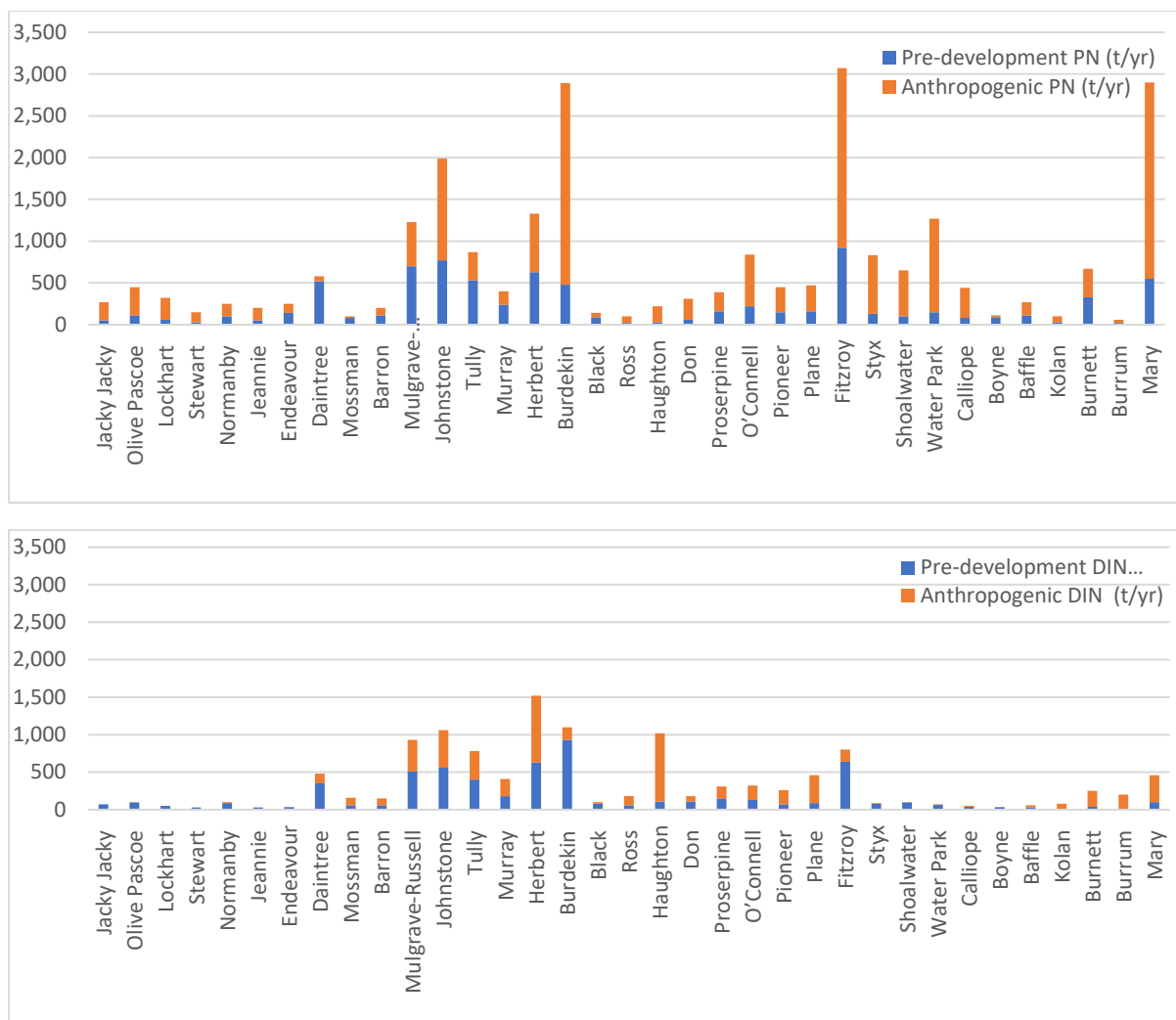
units (i.e. 12 out of the 47 management units) contribute 69% of the TP and 72% of PP based on the specific nutrient yields (t/km<sup>2</sup>/yr).

**Table 6.1. Contribution of nutrient forms to modelled regional nitrogen budget based on the 2015 modelling (total load) estimates. Source: Bartley et al. (2017).**

| Region            | DIN<br>(t/yr) | DON<br>(t/yr) | PN<br>(t/yr)  | TN<br>(t/yr)  |
|-------------------|---------------|---------------|---------------|---------------|
| Cape York         | 420           | 4,540         | 1,900         | 6,850         |
| Wet Tropics       | 5,500         | 4,390         | 6,700         | 16,580        |
| Burdekin          | 2,570         | 2,560         | 3,660         | 8,790         |
| Mackay Whitsunday | 1,350         | 980           | 2,150         | 4,810         |
| Fitzroy           | 1,140         | 3,410         | 6,360         | 10,910        |
| Burnett Mary      | 1,040         | 2,110         | 3,990         | 7,150         |
| <b>Total</b>      | <b>12,030</b> | <b>18,300</b> | <b>24,750</b> | <b>55,080</b> |



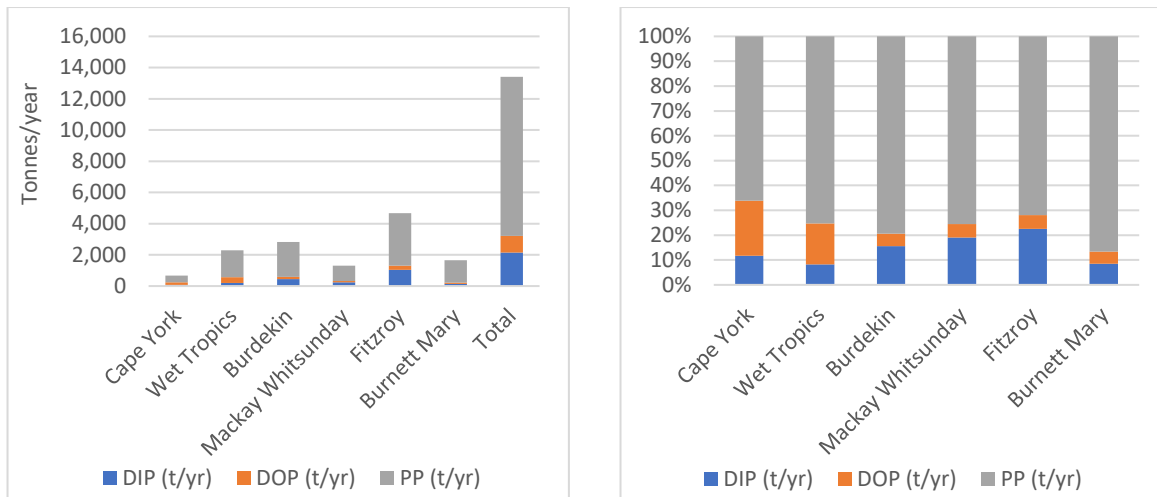
**Figure 6.1. Contribution of nutrient forms to modelled regional nitrogen budget based on the 2015 modelling (total load) estimates in (left) tonnes per year, and (right) proportion of the total nitrogen load.**



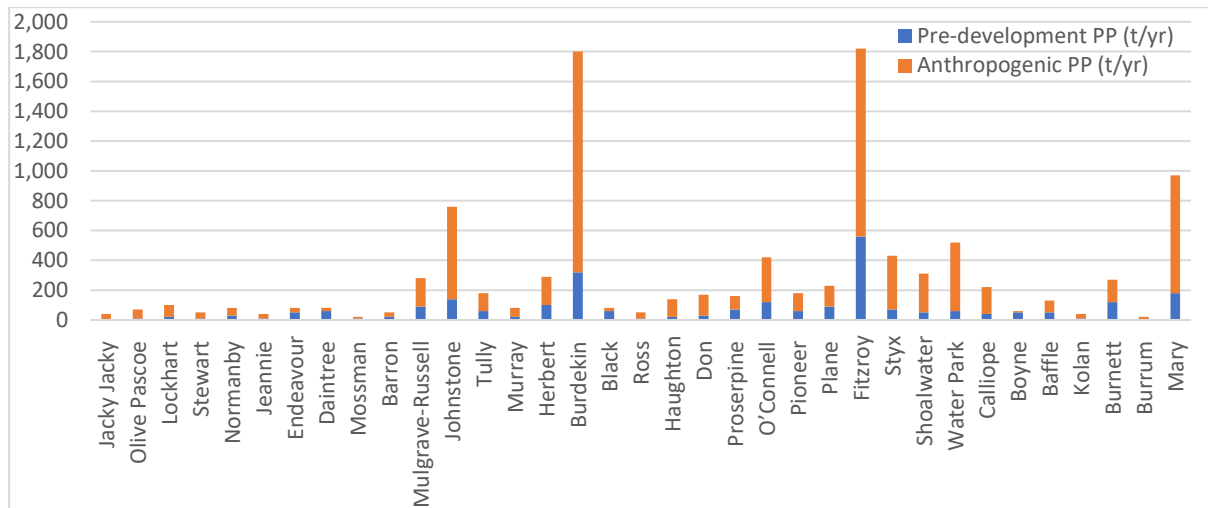
**Figure 6.2. Modelled end-of-catchment annual average particulate nitrogen (PN) (top) and dissolved inorganic nitrogen (DIN) (bottom) delivery (t/yr) for each of the 35 GBR basins. The modelling represents an annual average based on the 1986-2014 flow period.**

**Table 6.2. Contribution of nutrient forms to modelled regional phosphorus budget based on the 2015 modelling (total load) estimates.**

| Region            | DIP<br>(t/yr) | DOP<br>(t/yr) | PP<br>(t/yr)  | TP<br>(t/yr)  |
|-------------------|---------------|---------------|---------------|---------------|
| Cape York         | 80            | 150           | 450           | 680           |
| Wet Tropics       | 190           | 380           | 1,730         | 2,300         |
| Burdekin          | 440           | 140           | 2,240         | 2,820         |
| Mackay Whitsunday | 250           | 70            | 990           | 1,310         |
| Fitzroy           | 1,050         | 260           | 3,360         | 4,660         |
| Burnett Mary      | 140           | 80            | 1,430         | 1,640         |
| <b>Total</b>      | <b>2,140</b>  | <b>1,070</b>  | <b>10,200</b> | <b>13,420</b> |



**Figure 6.3. Contribution of nutrient forms to modelled regional phosphorus budget based on the 2015 modelling (total load) estimates in (left) tonnes per year, and (right) proportion of the total phosphorus load.**



**Figure 6.4. Modelled end-of-catchment annual average particulate phosphorus (PP) delivery (t/yr) for each of the 35 GBR basins. The modelling represents an annual average based on the 1986-2014 flow period.**

### 6.1.2 Land uses driving nutrient loss

Land use and land management change is seen as the primary factor responsible for changes in nutrient loss from the landscape and hence delivery to water bodies downstream (McCloskey et al. 2017). DIN is sourced from all land uses, whether in 'natural' (pre-development) condition or modified by human activity. Undisturbed landscapes can export large quantities of DIN but generally at low concentrations (Brodie and Mitchell, 2005).

The results of the most recent modelling estimates for DIN, PN and PP are presented in Table 6.3, 6.4 and 6.5, and Figure 6.3, 6.4 and 6.5 respectively. In summary:

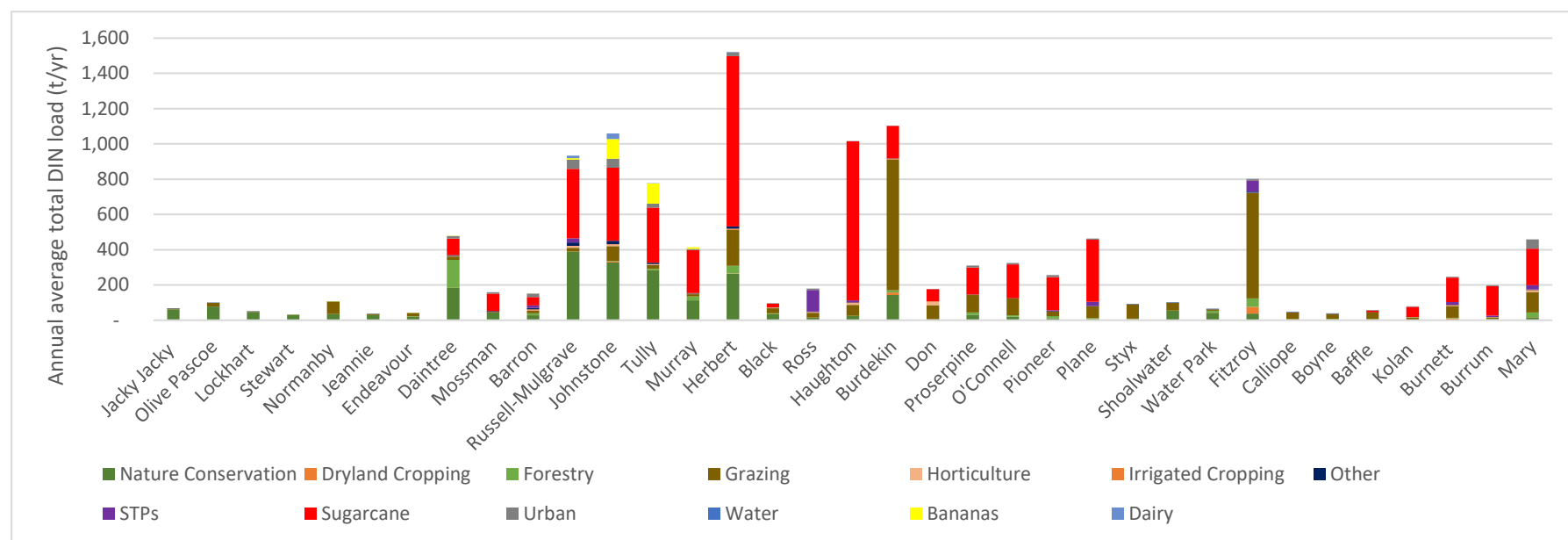
- Sugarcane delivers the most DIN to the GBR from the Wet Tropics, Burdekin, Mackay Whitsunday and Burnett Mary regions (Table 6.3). At a basin scale, sugarcane generates the largest loads in the Herbert and Haughton basin (Figure 6.5). In basins with large areas

of sugarcane, more than 40% of the total DIN load comes from sugarcane. Examples include Mulgrave-Russell (42%), Haughton (89%), Pioneer (73%) and Mary (45%). When considering anthropogenic sources, sugarcane contributes up to 80% of the total DIN load in some basins (Waters et al., 2014).

- Grazing is the highest contributor of total DIN in the Fitzroy region and also contributes >20% of the DIN load in all regions except the Wet Tropics (Table 6.3). At a basin scale, grazing generates the largest loads in the Burdekin and Fitzroy basin (Figure 6.5).
- In the Wet Tropics and Mackay Whitsunday regions, PN and PP delivery is dominated by sugarcane (Table 6.4, Table 6.5). At a basin scale, sugarcane generates the largest loads in the Johnstone, Russell Mulgrave and O'Connell basins (Figure 6.5). Grazing dominates PN and PP delivery in all other regions except Cape York. At a basin scale, grazing generates the largest loads from the Burdekin, Fitzroy and Mary basins (Figure 6.5).
- Urban areas contribute less than 7% of DIN, PN and PP.

**Table 6.3. Contribution of main land uses to the DIN load for each region (%). Derived from Source Catchment (2015 Report Card) end-of-basin annual average loads.**

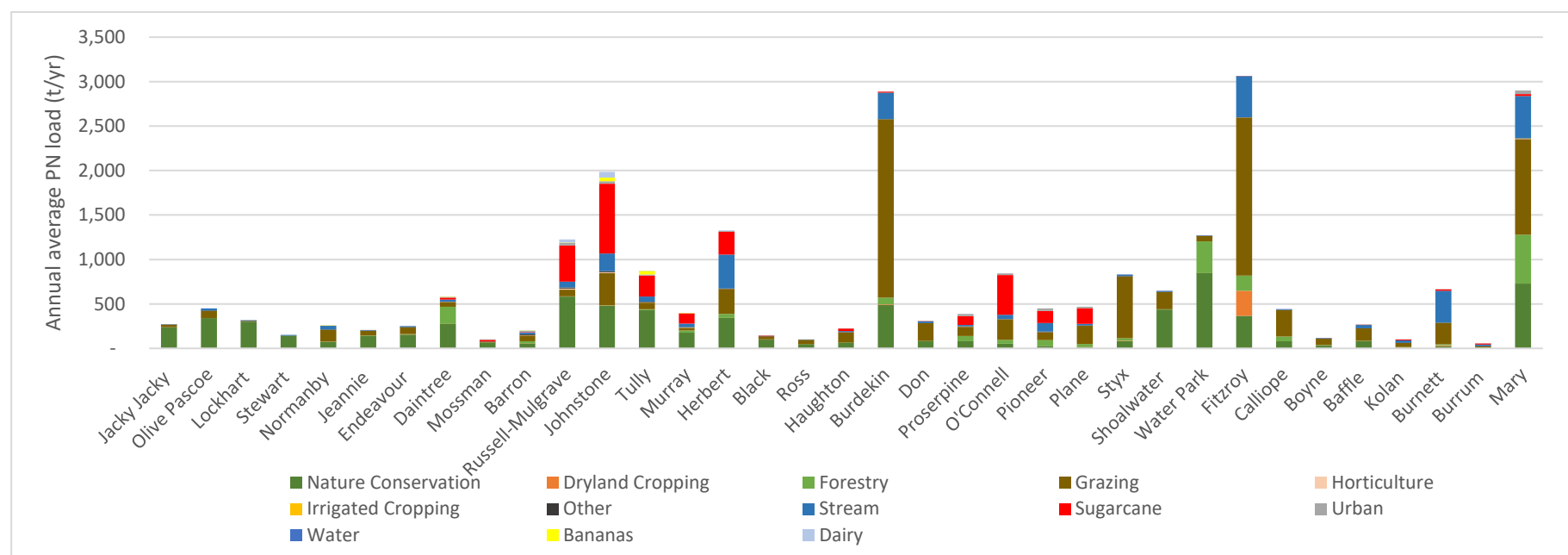
| DIN load (%)<br>Region | Nature conservation | Dryland cropping | Forestry | Grazing | Horticulture | Irrigated cropping | Sugarcane | Bananas | Dairy | Urban | Water | Other | Sewage Treatment Plants |
|------------------------|---------------------|------------------|----------|---------|--------------|--------------------|-----------|---------|-------|-------|-------|-------|-------------------------|
| Cape York              | 72                  | 0                | 0        | 28      | 0            | 0                  | 0         | 0       | 0     | 0     | 0     | 0     | 0                       |
| Wet Tropics            | 30                  | 0                | 5        | 7       | 1            | 0                  | 47        | 4       | 1     | 4     | 0     | 1     | 1                       |
| Burdekin               | 9                   | 1                | 1        | 36      | 1            | 0                  | 46        | 0       | 0     | 1     | 0     | 0     | 5                       |
| Mackay Whitsunday      | 5                   | 0                | 3        | 21      | 0            | 0                  | 65        | 0       | 0     | 3     | 0     | 1     | 2                       |
| Fitzroy                | 13                  | 3                | 6        | 70      | 0            | 0                  | 0         | 0       | 0     | 1     | 0     | 1     | 5                       |
| Burnett Mary           | 3                   | 1                | 4        | 24      | 1            | 1                  | 56        | 0       | 0     | 6     | 0     | 0     | 5                       |



**Figure 6.5. Contribution of main land uses to the DIN load for each basin. 'Other' includes intensive animal production, manufacturing and industrial, mining, rural and urban residential, transport and communication, waste treatment and disposal, ports/marine harbour, military areas and open water bodies.**

**Table 6.4. Contribution of main land uses to the PN load for each region (%). Derived from Source Catchment (2015 Report Card) end-of-basin annual average loads.**

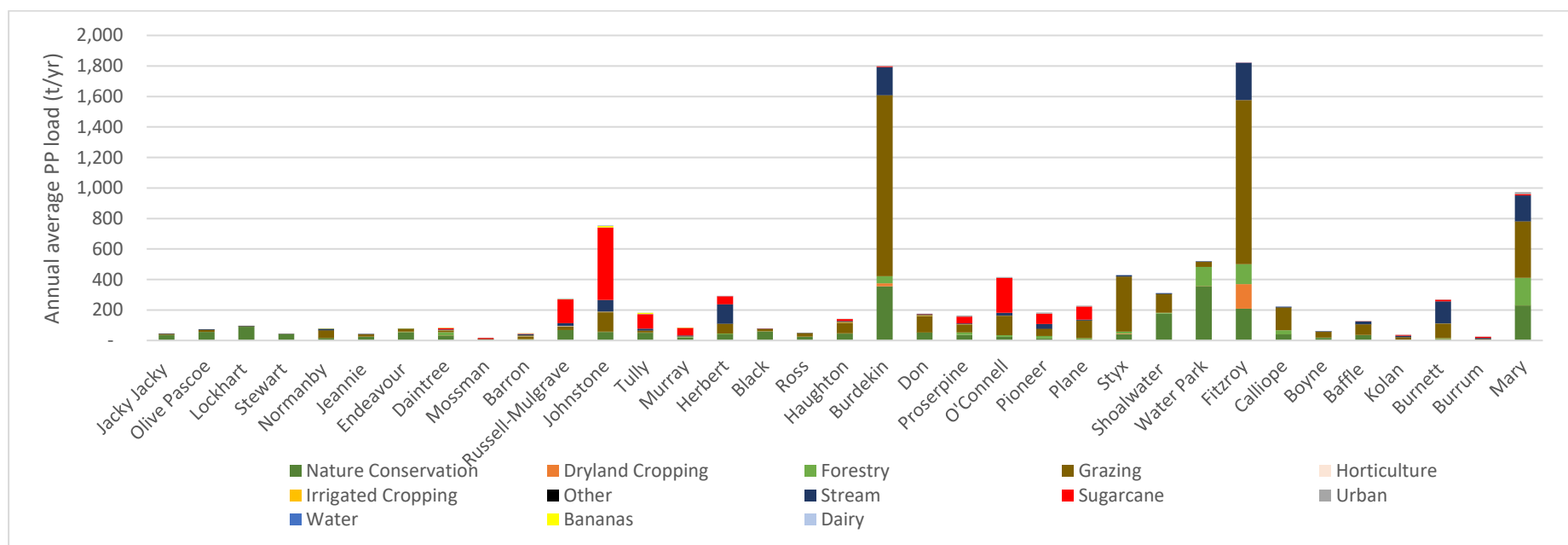
| PN load (%)<br>Region | Nature<br>conservation | Dryland<br>cropping | Forestry | Grazing | Horticulture | Irrigated<br>cropping | Sugarcane | Bananas | Dairy | Urban | Water | Other | Stream-<br>banks |
|-----------------------|------------------------|---------------------|----------|---------|--------------|-----------------------|-----------|---------|-------|-------|-------|-------|------------------|
| Cape York             | 73                     | 0                   | 1        | 21      | 0            | 0                     | 0         | 0       | 0     | 0     | 0     | 0     | 5                |
| Wet Tropics           | 36                     | 0                   | 5        | 14      | 1            | 0                     | 28        | 1       | 2     | 2     | 0     | 1     | 12               |
| Burdekin              | 22                     | 0                   | 2        | 65      | 0            | 0                     | 1         | 0       | 0     | 0     | 0     | 0     | 9                |
| Mackay<br>Whitsunday  | 8                      | 0                   | 10       | 29      | 0            | 0                     | 40        | 0       | 0     | 4     | 0     | 1     | 8                |
| Fitzroy               | 29                     | 5                   | 10       | 49      | 0            | 0                     | 0         | 0       | 0     | 0     | 0     | 0     | 8                |
| Burnett Mary          | 21                     | 1                   | 15       | 38      | 0            | 0                     | 2         | 0       | 0     | 1     | 0     | 0     | 23               |



**Figure 6.6. Contribution of main land uses to the PN load for each basin. 'Other' includes intensive animal production, manufacturing and industrial, mining, rural and urban residential, transport and communication, waste treatment and disposal, ports/marine harbour, military areas and open water bodies.**

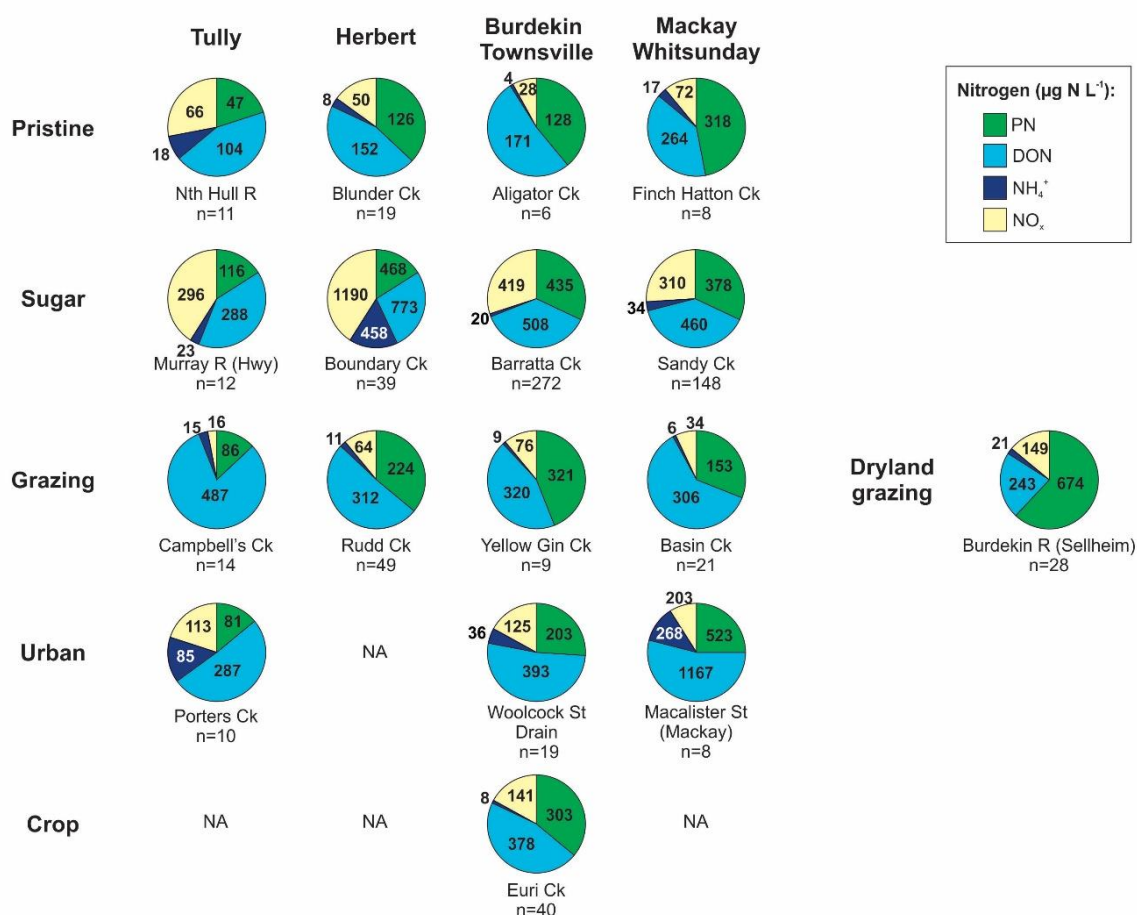
**Table 6.5. Contribution of main land uses to the PP load for each region (%). Derived from Source Catchment (2015 Report Card) end-of-basin annual average loads.**

| Region            | Nature conservation | Dryland cropping | Forestry | Grazing | Horticulture | Irrigated cropping | Sugarcane | Bananas | Dairy | Urban | Water | Other | Stream-banks |
|-------------------|---------------------|------------------|----------|---------|--------------|--------------------|-----------|---------|-------|-------|-------|-------|--------------|
| Cape York         | 71                  | 0                | 1        | 23      | 0            | 0                  | 0         | 0       | 0     | 0     | 0     | 0     | 5            |
| Wet Tropics       | 16                  | 0                | 2        | 15      | 0            | 1                  | 49        | 1       | 1     | 1     | 0     | 0     | 14           |
| Burdekin          | 24                  | 1                | 2        | 63      | 0            | 1                  | 1         | 0       | 0     | 0     | 0     | 0     | 9            |
| Mackay Whitsunday | 8                   | 0                | 5        | 34      | 0            | 0                  | 43        | 0       | 0     | 3     | 0     | 1     | 6            |
| Fitzroy           | 25                  | 5                | 9        | 53      | 0            | 0                  | 0         | 0       | 0     | 0     | 0     | 0     | 8            |
| Burnett Mary      | 20                  | 0                | 14       | 39      | 0            | 0                  | 2         | 0       | 0     | 1     | 0     | 0     | 24           |



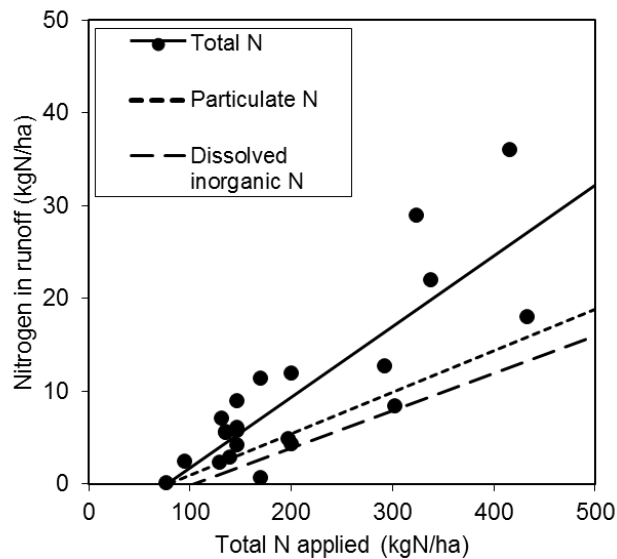
**Figure 6.7. Contribution of main land uses to the PP load for each basin. 'Other' includes intensive animal production, manufacturing and industrial, mining, rural and urban residential, transport and communication, waste treatment and disposal, ports/marine harbour, military areas and open water bodies.**

The proportion contribution of major N forms to TN for the different land use monitoring sites across the Tully, Herbert, Burdekin-Townsville and Mackay Whitsunday regions are shown in Figure 6.8. The graphs show mean and proportional contribution of DON, NO<sub>x</sub>, ammonium (NH<sub>4</sub><sup>+</sup>) and PN to total N (TN) concentrations across key land uses in the GBR catchment area; these uses include pristine, sugarcane, grazing, urban and cropping. All land uses are compared to the pristine sites as an examination of likely changes which have occurred as a consequence of land development. A description of these results is provided in Brodie et al. (2015).



**Figure 6.8.** The proportion contribution of major N forms to TN for the different land use monitoring sites across the Tully, Herbert, Burdekin-Townsville and Mackay Whitsunday regions. Also shown are the mean concentrations (µg.L<sup>-1</sup>) of the N species for each land use site.

Further analysis of nitrogen sourced from sugarcane shows that nitrogen surpluses and nitrogen fertiliser application rates are correlated with nitrogen losses (in both dissolved and particulate forms) from GBR catchments (Bell et al., 2016; Thorburn and Wilkinson, 2013; Thorburn et al., 2013) (Figure 6.9). The relationships in the GBR are similar to catchments in the northern hemisphere and the USA (Thorburn et al., 2013). Conversely, lowered nitrogen fertiliser usage leads to smaller losses of nitrogen as seen in fertiliser trials (Rohde et al., 2013; Webster et al., 2012).



**Figure 6.9. Relationship between total nitrogen input (fertiliser and legumes) and total wet season nitrogen in run-off (total nitrogen, particulate nitrogen and dissolved inorganic nitrogen) from >20 sugarcane sites in GBR catchments. Data points indicate TN losses, while fitted regressions are shown for PN and DIN from the same sites. Source: Reproduced from Bell et al. (2016).**

### *Summary of new evidence*

The research project *RP178a Transitional work program for bioavailable nutrients* led by Dr Joanne Burton and Dr Alexandra Garzon-Garcia from the Queensland Department of Environment and Science has led the contributions to the new evidence base associated with understanding sediment particle and the contribution of eroded soils to DIN export in the GBR catchments (Garzon-Garcia et al., 2018b; Garzon-Garcia et al. *in prep*). While the highlights of this work are extracted from this report here, the final report should be consulted for further detail.

## **6.2 Improved understanding of bioavailable particulate nutrients in catchments**

### **6.2.1 Understanding of sediment particle size exported from GBR catchments during high flow**

The existing sediment particle size GBRCLMP monitoring data (2005-2017) was analysed for temporal and spatial representivity and the dominant particle size classes were assessed to understand variability by region and catchment for all end of system and sub-catchment sites. The current monitoring methods were assessed.

The key outcomes and conclusions for the contribution of eroded soils to particle size export:

- **The majority of the sediment monitored at end-of-system (EoS) sites in the GBR catchments is in the <63 µm particle size range (silt and clay) (~ >90%).**
- **Greater than 90% of sediment exported from the larger, predominately grazed dry catchments (Normanby, Burdekin, Burnett and Fitzroy) is <16 µm (clay and fine silt),**

although there is large variability between samples that may be related to the timing of sampling during events, the variability of sampled flows and sediment source. **In contrast, suspended sediment samples collected in the coastal wet catchments have a lower fine silt and clay content (<16 µm, <2 µm) and higher coarse fraction content (≥63µm).**

- **There is an appreciable fraction of the fine sediment (i.e. <63 µm) leaving the GBR catchments at EoS that is larger than 16 µm (from 5 to 29%),** particularly in the Wet Tropics and Mackay-Whitsunday regions. This is important to note considering that the size range that is modelled in P2R Dynamic SedNet (within Source) is the <20 µm fraction and **should be taken into account as part of the validation of suspended sediment models with monitored data.** Additionally, it is important to take into account that **fractions of fine sediment larger than 16 µm would have water quality effects in the river estuaries that need to be assessed,** including the generation of DIN (see section on the contribution of eroded soils to DIN export).
- To be conclusive about these findings **an understanding of the true representativeness of the data is necessary,** including how representative the flow conditions sampled are with respect to historical flow, and inter and intra annual variability. Additionally, it is important to **demonstrate the influence of organic content in sediment particle size determination.** Organic content appears to be higher in wet smaller coastal catchments marine plumes and this may be having a role in the binding of smaller particle sizes and consequently affecting particle size determination (Lewis et al., 2018).
- **It is recommended that the reported particle size distribution continues to use a percent volume basis and the ultra-dispersion method** (that measures absolute particle size distribution).
- **Further and broader discussions are necessary to define the particle size classes to report particle size distribution.** Particle size datasets are currently being collected and analysed at paddock, sub-catchment, end of system and in marine plumes. It would be useful to do a full source to sink assessment of the particle size data before finalising recommendations for reporting size classes.
- **Monitoring of particle size should be included as a standard parameter in the GBRCLMP** at least for the catchments where sediment and particulate nutrient management is prioritised (e.g., grazing catchments).

### **6.2.2 Generation of DIN from eroded soils**

Our current understanding of the main biogeochemical processes and associated N pools that produce DIN when soil is eroded, fractionated into fine sediment (<20 µm) and transported in rivers was applied to quantify the DIN produced from eroded soils in the Bowen and Johnstone catchments using the P2R Source Catchments based modelling framework (Ellis and Searle, 2014). Additionally, the model was run for PN using bioavailable nutrient datasets gathered in RP128G phases 1 and 2 (Garzon-Garcia et al., 2017a) and compared the results with the PN estimates from the existing P2R platform. The proposed new method accounts for the variability in enrichment between the bulk soil and the <20 µm fine sediment for different soil types, land uses and erosion processes. Spatial layers for PN and DIN generation from sediment for the identified processes were created and supplied to the P2R modellers. The 'SedNet Particulate Nutrient Generation Model' was replaced with a new model that allows for

the fine sediment generation model (unmodified) to interact with the supplied layers to generate a load of each of the N pools from each hydrounit and eroding process in the catchments. We refer to these set of models as Bioavailable Particulate Nitrogen models (**BPN models**).

The key outcomes and conclusions for the contribution of eroded soils to PN modelling and DIN generation from sediment:

- **A proposed new method for modelling PN and DIN generated from sediment was successfully tested under the P2R modelling platform.** PN modelling can be improved to account for the variability in fine sediment (<20 µm) characteristics in the catchments including the variability in enrichment ratios of particulate nutrients in sediment from that of their parent soils.
- **In the Bowen River catchment pilot study all of the end-of-catchment exported DIN currently modelled could be accounted for by the DIN generated from sediment. Likewise, it is hypothesised that a significant fraction of DIN would also be generated from the erosion of soils and their associated fine sediment in other grazing catchments of the GBR where DIN yields from fertiliser use are not relatively high.**
- **DIN generation associated with sediment erosion and transport was not significant in the Johnstone River catchment** (around 3% the currently modelled DIN load at the Johnstone River end-of-catchment).
- **Although ‘DIN from sediment’ yields** (kg DIN generated per kg of eroded sediment per hectare per year) **were much higher in the Johnstone than in the Bowen River catchment, the very large modelled yields of ‘DIN from fertiliser’ dominated the DIN source to end of system in the former. However, sediment will likely continue to generate DIN from PON mineralisation as it is transported further in the estuary and the marine environment. This needs to be quantified before final conclusions are drawn about the contribution of eroded sediment in the Johnstone to the marine environment are made.**
- **A large part of the DIN generation associated with sediment erosion and transport is of anthropogenic origin and it is not targeted as such. Considering its significance, identifying, modelling and targeting this fraction in grazing catchments is important.**
- **The main sources of sediment in a catchment are not necessarily the main sources of DIN-producing sediment.** For example, modelling in the Bowen River catchment indicated that although gully erosion is the main source of sediment, hillslope erosion is the main source of PN and ‘DIN generation from sediment’. Our findings highlight the **disproportionate contribution of hillslope erosion to particulate and bioavailable nutrient catchment export per unit mass of eroded sediment**, when compared to subsurface erosion (gully and streambank). In the Johnstone River catchment, although conservation and sugarcane dominated sediment export, and sugarcane alone dominated PN export, BPN modelling results indicated that dairy may be an important source of ‘DIN from sediment’ at the end-of catchment (39% contribution) together with sugarcane (44% contribution).
- **Sediment source contribution (surface versus subsurface erosion) is an important determinant of the total DIN load generated from sediment in the catchment and of the source contributions to these loads.** Calculations using tracing data as a second line

of evidence for the Bowen River catchment indicated large variability in surface versus subsurface source contributions to 'DIN generation from sediment' with changes in the proportion of sediment sourced from subsurface sources. Under a scenario with subsurface sediment contribution >93%, subsurface sediment would be an equally important source to 'DIN generation from sediment' as surface erosion. These findings highlight the **importance of accurately modelling the distribution between surface and subsurface sediment sources in catchments to accurately model 'DIN generation from sediment' and also PN loads.**

- **It is fundamental to increase understanding of how land-use change and management (including vegetation type) have modified the quality of sediment (e.g. 'DIN generation from sediment') exported to the Reef relative to pre-development conditions.**

## 7. MANAGEMENT OPTIONS FOR REDUCING LAND-DERIVED PARTICULATE NUTRIENTS

The current evidence on land management practices for minimising losses of land-derived particulate nutrients has recently been collated in the 2017 Scientific Consensus Statement, Chapter 4 (Eberhard et al., 2017). Much of this information was also established in the 2013 Scientific Consensus Statement (Thorburn et al., 2013), with the exception of the management of gully and streambank erosion where the knowledge is constantly and necessarily improving to target these high sediment and particulate nutrient contributing erosion features.

As described in Section 0 and 0, the relative importance of specific management of particulate nutrients in the catchment is boosted due to knowledge of more rapid timeframes for the bioavailability of particulate nutrients than was previously assumed. In grazing and dryland cropping catchments, we can now view eroded sediments as a significant source of bioavailable particulate nutrients.

### 7.1 Land management practices

#### *Summary of established evidence*

Based on the understanding that particulate nutrients are contained in fine sediments, particulate nutrients have been treated as being mainly lost through erosion (Thorburn and Wilkinson, 2013), and management of sediment loads is important in determining particulate nutrient loads. Key points of this evidence are summarised below, and have been extracted from the 2017 Scientific Consensus Statement, Chapter 4 (Eberhard et al., 2017).

#### **Grazing**

- In grazing lands of GBR catchments, the principles of land management for reducing run-off and sediment loss include (i) reducing forage utilisation (which is heavily influenced by stocking rates) to increase ground cover, and (ii) redistributing grazing pressure away from areas vulnerable to erosion such as gullies and streambanks (; Hunt et al., 2014; McIvor, 2010; Thorburn and Wilkinson, 2013).
- Several studies have found that levels of livestock forage utilisation of 25–30% (of maximum annual biomass) are required to ensure that the pasture productivity and erosion control functions of rangeland vegetation are sustained (Ash et al., 2011). More recently Wilkinson et al. (2014) determined that animal equivalent stocking rates were inversely correlated with historical cover levels, with low-cover properties having typically two to four times the stocking rates of high-cover properties. High-cover properties also had a much higher proportion of 3P (palatable, productive, perennial) grasses than the medium- and low-cover sites, irrespective of soil type. Land condition assessments were consistently higher and less variable on the high-cover sites. The study also found that while forage productivity and hydrologic function are related to historical cover levels over decades, grazing management in the shorter term must consider more than just ground cover. For example, the widespread dominance of the

exotic grass Indian couch in degrading pastures can give rise to high cover but low productivity and poor soil infiltration capacity.

- It is unlikely that pasture management alone will be sufficient to reduce sediment yields to ecologically sustainable levels for the GBR due to increased contribution of sediment sources from channel (gully and streambank) sources. The Paddock to Reef Water Quality Risk Framework for Grazing (Australian and Queensland governments, 2013) now includes explicit targeting of gully and streambank erosion as a means to reduce the water quality risk from grazing land management.
- Current understanding of the degree of alteration of bank erosion with the introduction of agriculture, and the success of methods for remediating bank erosion sites, is limited. There are no known published studies on the effectiveness of reinstating riparian zones on the erosion, sediment loss or water quality in the GBR catchments.

### **Cropping:**

- The principles for managing nutrients to reduce their losses from GBR catchments apply to dissolved and particulate nutrients in fertilised crops and pastures. The concepts have generally been developed and tested in the context of managing losses of dissolved nutrients from crops because of (i) the widespread use of fertiliser in crop production, and (ii) common adoption of erosion reducing measures in cropped lands.
- Management systems that reduce or eliminate tillage, reduce soil compaction (e.g. controlled traffic) and maximise cropping opportunities and soil cover (by crop residue retention) reduce nutrient losses in a wide variety of cropping systems, including grain (Thomas et al., 1990), cotton (Silburn and Hunter, 2009) and sugarcane (Agnew et al., 2011; DNRM, 2016; Masters et al., 2008). Contour embankments are essential for reducing loss of sediments and associated particulate nutrients from cropping lands in large storms, particularly in rainfed cropping (Murphy et al., 2013). These principles also apply to reducing nutrient losses from fallows in cropping systems (DNRM, 2016).

### *Summary of new evidence*

Several studies in recent years have trialled a range of remediation options for reducing soil loss from gully erosion, e.g.:

- Wilkinson et al. (2013) demonstrated that gully check dams (constructed of sticks wired together) and controlling livestock access are effective ways to trap fine sediment on the gully bed, initiate revegetation of the gully bed and walls and reduce gully sediment yield. For this method to be effective, the remediation design must be appropriately scaled to the run-off volumes.
- A companion study by Wilkinson et al. (2014) determined that the soil and vegetation condition of the hillslope above the gully was important for reducing run-off into hillslope drainage line gullies. Soil infiltration capacity of high-cover sites was measured to be four times that of low-cover sites for both Chromosol and Sodosol soils, indicating that high-cover sites could absorb and retain more water in the root zone of the soil profile for supporting forage production and reduce the amount of run-off fuelling channel erosion downslope.
- More recently, studies by Brooks et al. (2016) investigated (i) the influence of grazing exclusion, (ii) the contribution of bioavailable nutrients, and (iii) the effectiveness of engineering works to support revegetation and control erosion of large gullies in alluvial soil. This study also showed that as gully systems

erode back into the alluvium they contribute nutrient-rich sediments, largely from terrace features, to stream systems. This reinforces the importance of all fine sediment sources as contributors of bioavailable nutrients.

- Wilkinson et al. (2015a, 2015b) provide a collation of options for managing gully erosion in the GBR catchments.
- A pilot study in alluvial gullies in the Normanby catchment (Garzon-Garcia et al., 2016) demonstrated that the main source of bioavailable PN, bioavailable PP and Carbon varied with the stage of gully evolution between surface and subsurface. This study also demonstrated that bioavailable PN and bioavailable PP concentrations are enriched in the <10 µm fraction compared to the <63 µm fraction (as mentioned above).

The following key points relevant to managing particulate bioavailable nutrients are extracted from Eberhard et al. (2017):

- There is increased confidence that reduced stocking rates will improve ground cover and water quality from hillslopes.
- There is increased confidence that cover provided by invasive grass species is less effective in helping productivity and soil infiltration capacity than are perennials.
- The importance of sediments from gully and streambank sources is clearer. And sediments from these sources can contain high concentrations of bioavailable nutrients.
- There is increased confidence that maintaining land condition on hillslopes above gullies helps reduce gully erosion.
- Effective remediation of gullies requires substantial actions such as excluding stock and engineering (e.g. check dams) or bioengineering (slope battering, seed, mulch, gypsum and fertiliser) approaches.
- The effectiveness of managing streambank erosion has still not been demonstrated in GBR catchments.
- The effect of vegetation type will be important to consider when doing landscape restoration due to the link between the carbon – nutrient interaction identified in the marine environment (Section 4.3.1). This requires specific monitoring and management of carbon inputs from both soil and vegetation in the catchment.

## 8. CATCHMENT INTERACTIONS: PRIORITY KNOWLEDGE GAPS AND MANAGEMENT IMPLICATIONS

### *Priority knowledge gaps*

Greater understanding of **bioavailable particulate nutrient source and delivery in the catchment** to optimise the benefits of management interventions (i.e. reduce fine sediment and bioavailable particulate nutrients collectively). This will require:

- Specific studies to understand the generation of bioavailable particulate nutrients under different land management conditions are required, specifically for hillslope erosion. Focus catchments could include continuation of the current efforts in the Johnstone and Bowen/Burdekin catchments, plus addition of the Olive Pascoe basin for end of system and native paddock scale sites.
- Monitor and calibrate DIN reduction from erosion management. This needs to be carried out to cover different erosion management techniques for comparison, different soil types and at least until a stable state has been achieved (could be >10 years for gully rehabilitation works) including paddock scale, monitoring of rehabilitation projects and end of system sites.
- Greater confidence in the knowledge of pre-development sources (reference conditions) linked to soil types, land use and erosion processes through establishment of a catchment to marine monitoring program in a relatively pristine area such as the Olive Pascoe Basins, based on the design of the NESP Project 2.1.5 design. Tracing and dating in sediment cores could also be examined to look at the end of different catchments to examine shifts in sources and nutrient regimes.
- Assessment of existing knowledge of the sources of bioavailable nutrients in the context of particle size ('clean and dirty' sediment) to select areas where there is likely to be fine sediment and potentially bioavailable nutrient benefits (overlay maps) from erosion management. Use this to assess potential sources of 'ecologically relevant' fine sediment (organic matter and flocs) (depending on whether they stay in that form in transport).
- Identification of priority areas for soil mapping and ground truthing. This needs to be supported by improved methods for capturing and measuring particle size distributions (and ensure comparable datasets).
- Acquisition of higher resolution soils data (initially water dispersible silt and clay, POC, PN, PP, adsorbed ammonium, SOC, SON, DRP). To be verified with development of pedo-transfer functions as part of RP178a) and classification of soils (disaggregate into finer scale) to provide better estimate of bioavailable nutrient delivery in the models.
- Development of nutrient budget from all sources (e.g. Johnstone bioavailable particulate nutrient from grazing versus sugarcane; for grazing lands bioavailable particulate nutrients, cattle, rainfall [Packett et al., 2018]). Could be progressed with existing information in 2 case studies. E.g. test the model data with multiple lines of evidence and trialling in the 2 Major Integrated Project (MIP) locations. Use to evaluate end of system loads, accounting for bioavailable particulate nutrient inputs.

- Finer scale validation of the study of bioavailable nutrient catchment modelling study (RP178a Burton, Garzon-Garcia, Ellis) – this will assist to assess evaluation outcomes from management practice improvement, plume sourcing information and better marine risk assessment, and could be undertaken by analysis of multiple lines of evidence (existing monitoring data, tracing and experimental results). Investigation of the effect of vegetation type (i.e. carbon) on the bioavailability of particulate nutrients in-situ and as they are transported through catchments. This may influence on ground management practices such as trash blanketing and choosing species and tree density to be used in rehabilitation.
- Assessment of the contribution of organic sources of nutrients (e.g. nitrogen from legumes, nitrogen and phosphorus from mill mud) to nutrient losses (both dissolved and particulate). If the contribution is significant, methods to manage those losses (e.g. better managing supplementary fertiliser in these situations) need to be developed.
- Assessment of the effect of mill mud/mud ash application on bioavailable P forms at block (runoff/deep drainage) and catchment scale.
- Determination of the relationship between phosphorus surpluses, soil phosphorus concentrations and phosphorus lost to the environment in both particulate and dissolved forms.
- Investigation of how bioavailable particulate nutrients interact in wetlands and the role of riparian areas in trapping or processing bioavailable nutrients. Quantification of the potential wetland treatment efficacy needs to take these particulate nutrient processing factors into account. Both N and P will be important to investigate in wetlands as freshwater algae respond to both. Residence times are vital to the efficacy of wetland treatment and in some catchments, it will not be possible to achieve appropriate residence times.

#### Specific monitoring and modelling needs:

- Monitor bioavailable properties (at least PIN, POC, SOC/DOC, adsorbed ammonium, particle size distribution) at Paddock to Reef program monitoring locations (paddock, sub catchment and end of system sites) and specific project areas (e.g. rehabilitation treatments) to be able to assess the bioavailability of particulate nutrients to phytoplankton using indicators of bioavailability. This will also improve modelled equations for bioavailable nutrient delivery.
- High resolution soil mapping to support improved modelling (Extend soil database). This will include the addition of additional soil parameters that will be required to use pedotransfer functions to estimate sediment properties. The list of parameters will be provided in the final report from RP178a.
- Undertake high resolution mapping (e.g. repeat LiDAR) of channel processes and deposition—in strategic locations to inform bioavailable nutrient contributions from different erosion processes.
- Improved representation of particulate nutrients (PN, PP and POC) and bioavailable particulate nutrients (DIN from mineralisation, DIN from desorption, solubilised DIN, DRP, bioavailable DON and DOC) in the catchment models. This must be coupled with improved sediment modelling. Intrinsic soil property data will be required for catchments other than the Bowen and Johnstone. Improve the catchment modelling to:

- Account for pre-development and current bioavailable nutrients in catchments will support the targeting and management of DIN from erosion. This will allow reporting on DIN reductions associated with erosion mitigation.
- Provide greater resolution of the model outputs and fine scale validation of the model outputs.
- Improve the distinction of PP and PN pathways between hillslopes and gullies.
- Develop pedo-transfer functions from intrinsic soil properties for finer scale analysis of bioavailable nutrient sources and delivery (longer term needs).

### *Management implications*

The new evidence highlights that:

- The relative importance of specific management of particulate nutrients in the catchment is boosted due to knowledge of more rapid timeframes for the bioavailability of particulate nutrients than previous assumed. The extent of influence is inshore and midshelf areas.
- In grazing and dryland cropping catchments, eroded sediments can now be viewed as a significant source of bioavailable particulate nutrients (DIN in the marine environment).
- Different management practices will target different erosion processes and should be considered in the context of generation of fine sediment and particulate bioavailable nutrient yields per unit area. There is a need to develop and promote land management practices that reduce loss of nutrient-rich fine sediments.
- Nutrient markets/offsets and trading for nitrogen forms should take into account the bioavailability of the different pools of particulate nutrients.
- It is important to communicate that our understanding of nutrient budgets has changed and that this improved knowledge may influence (within) catchment prioritisation.
- Adding the bioavailability of particulate nutrients to the prioritisation of erosion management will accelerate the benefit to water quality of these investments. However, assessment of the time lags of managing DIN from fertiliser versus soil erosion is important, especially if the relative importance of DIN and PN is assessed.
- Further targeting of effort to manage DIN from erosion requires additional information for refinement (see priority knowledge gaps).
- The 2017 GBR end of catchment load targets for PN and PP mirror the fine sediment reductions for each basin. There is a need to specifically address bioavailable particulate nutrients when the targets are revised for the WQIP update in 2022 (need to be prepared to do that in 4 years time). This would require further quantification of DIN from erosion and quantification of the bioavailability of particulate nutrients in more catchments (both during transport to end-of-catchment and in the estuarine/marine receiving water columns). *This requires a combined catchment to reef approach.*
- Setting ecologically relevant end of catchment load targets for P is important and should be progressed for definition by 2022. *This requires a combined catchment to reef approach.*

## **PART III: MANAGEMENT IMPLICATIONS**

## 9. IMPLICATIONS FOR MANAGEMENT AND SUPPORTING INFORMATION NEEDS

### *Summary of previous conclusions*

#### ***Previous conclusion from Brodie et al. (2015)***

- Comprehensive management of water quality within the GBR system, particularly of anthropogenically influenced nutrient inputs, requires consideration of the full range of nutrient elements and nutrient species. While the GBR appears to be primarily N-limited, the availability of P (and possibly Fe) may exert a significant influence on regional- or reef-scale N-fixation. Most terrestrial N enters the GBR lagoon in organic form (DON, PN). While most of this N is not immediately bio-available to support algal growth, it does eventually and significantly influence reef-scale water quality as it is progressively mineralized and recycled within pelagic and benthic food webs.
- Given our conclusions that almost all the PN discharged from rivers to the GBR is likely to become bioavailable within its residence time in the GBR lagoon, we suggest management of anthropogenic sources of PN (mainly erosion) may be important to the health of the GBR as is management of anthropogenic sources of DIN. However, given that much of the PON discharged is likely converted to N<sub>2</sub> (see above) and hence does not become available for primary production it is most likely that PON is not as important source of nitrification effects in the GBR lagoon as is DIN. The relative importance of DON is also difficult to accurately assess but given that, at best, only a proportion of the discharged DON is likely to become bioavailable our best assessment is that DON is less important than DIN. Direct runoff of urea from fertiliser application is a specific issue that needs to be managed given both the waste of fertiliser implied as well as the lack of current recognition that this form of DON is completely bioavailable.

### *Conclusions from new evidence*

The new knowledge of the bioavailability of particulate nutrients has implications for management in several areas including the selection of management options, prioritisation and target setting. There are also implications for monitoring, modelling and future information needs. These have been captured from the supporting documentation, the workshop and further discussion with workshop participants and are summarised below.

| Management area    | Implications  |
|--------------------|---|
| Management options | <ul style="list-style-type: none"><li>• The relative importance of specific management of particulate nutrients in the catchment is boosted due to knowledge of more rapid timeframes for the bioavailability of particulate nutrients than previous assumed. The extent of influence is inshore and midshelf areas.</li><li>• The carbon – nutrient interaction in the marine environment is important, which requires specific monitoring and management of carbon inputs from both soil and vegetation in the catchment. The effect of vegetation type will be important to consider when doing landscape restoration.</li></ul> |

| Management area        | Implications  |
|------------------------|---|
|                        | <ul style="list-style-type: none"> <li>• In grazing and dryland cropping catchments, we can now view eroded sediments as a significant source of bioavailable particulate nutrients (DIN in the marine environment).</li> <li>• Different management practices will target different erosion processes and should be considered in the context of generation of fine sediment and particulate bioavailable nutrient yields per unit area. There is a need to develop and promote land management practices that reduce loss of nutrient-rich fine sediments.</li> <li>• Nutrient markets/offsets and trading for nitrogen forms should take into account the bioavailability of the different pools of particulate nutrients.</li> <li>• It is important to communicate that our understanding of nutrient budgets has changed and that this improved knowledge may influence (within) catchment prioritisation.</li> </ul>   |
| <b>Prioritisation</b>  | <ul style="list-style-type: none"> <li>• Adding the bioavailability of particulate nutrients to the prioritisation of erosion management will accelerate the benefit to water quality of these investments. However, assessment of the time lags of managing DIN from fertiliser versus soil erosion is important, especially if the relative importance of DIN and PN is assessed.</li> <li>• Further targeting of effort to manage DIN from erosion requires additional information for refinement (see 'Information needs').</li> <li>• Explicit addition of particulate nutrient loads and assessment of their bioavailability (e.g., by catchment, sediment type in plume) is required for future marine nutrient risk assessments – both in the marine modelling and in linking to end of catchment loads.</li> </ul>   |
| <b>Target setting</b>  | <ul style="list-style-type: none"> <li>• The 2017 GBR end of catchment load targets for PN and PP mirror the fine sediment reductions for each basin. There is a need to specifically address bioavailable particulate nutrients when the targets are revised for the WQIP update in 2022 (need to be prepared to do that in 4 years time). This would require further quantification of DIN from erosion and quantification of the bioavailability of particulate nutrients in more catchments (both during transport to end-of-catchment and in the estuarine/marine receiving water columns).</li> <li>• Setting ecologically relevant P targets is important and should be progressed for definition by 2022.</li> </ul>  |
| <b>Modelling needs</b> | <ul style="list-style-type: none"> <li>• Improved representation of particulate nutrients (PN, PP and POC) and bioavailable particulate nutrients (DIN from mineralisation, DIN from desorption, solubilised DIN, DRP, bioavailable DON and DOC) in the catchment models. This must be coupled with improved sediment modelling. Intrinsic soil property data will be required for catchments other than the Bowen and Johnstone. Improve the catchment modelling to: <ul style="list-style-type: none"> <li>– Account for pre-development and current bioavailable nutrients in catchments will support the targeting and management of DIN from erosion. This will allow reporting on DIN reductions associated with erosion mitigation.</li> <li>– Provide greater resolution of the model outputs and fine scale validation of the model outputs.</li> <li>– Improve the distinction of PP and PN pathways between hillslopes and gullies.</li> <li>– Develop pedo-transfer functions from intrinsic soil properties for finer scale analysis of bioavailable nutrient sources and delivery (longer term needs).</li> </ul> </li> </ul> |

| Management area    | Implications   |
|--------------------|--|
|                    | <ul style="list-style-type: none"> <li>• Improve marine modelling (eReefs) capability to: <ul style="list-style-type: none"> <li>– Simulate dissolved and particulate organic matter decay rates that vary as a function of stoichiometry and/or origin, incorporating knowledge of decay rates and POM composition gained from catchment and marine studies of particulate organic matter.</li> <li>– Adjust parameterisation of inorganic nutrient adsorption/desorption from suspended mineral sediments as information regarding these processes becomes available. Incorporate improved understanding of benthic sediment contributions in the eReefs model.</li> </ul> </li> </ul>   |
| • Monitoring needs | <ul style="list-style-type: none"> <li>• Monitor bioavailable properties (at least PIN, POC, SOC/DOC, adsorbed ammonium, particle size distribution) at Paddock to Reef program monitoring locations (paddock, sub catchment and end of system sites) and specific project areas (e.g. rehabilitation treatments) to be able to assess the bioavailability of particulate nutrients to phytoplankton using indicators of bioavailability. This will also improve modelled equations for bioavailable nutrient delivery</li> <li>• High resolution soil mapping to support improved modelling (Extend soil database). This will include the addition of additional soil parameters that will be required to use pedotransfer functions to estimate sediment properties. The list of parameters will be provided in the final report from RP178a.</li> <li>• Undertake high resolution mapping (e.g. repeat LiDAR) of channel processes and deposition—in strategic locations to inform bioavailable nutrient contributions from different erosion processes.</li> <li>• Extend routine measurement of nutrients (including PIN, DOC and POC) in the MMP and include monitoring of midshelf areas in strategic locations where bioavailable nutrient sources may be important or where existing knowledge can be extended, e.g. link to crown-of-thorns starfish initiation in the Wet Tropics transects.</li> </ul> |

The following **information needs and dependencies** have been identified through this process (these are in addition to the supporting monitoring and modelling needs identified above):

1. Greater understanding of **bioavailable particulate nutrient source and delivery in the catchment** to optimise the benefits of management interventions (i.e. reduce fine sediment and bioavailable particulate nutrients collectively). This will require:
  - Specific studies to understand the generation of bioavailable particulate nutrients under different land management conditions are required, specifically for hillslope erosion. Focus catchments could include continuation of the current efforts in the Johnstone and Bowen/Burdekin catchments, plus addition of the Olive Pascoe basin for end of system and native paddock scale sites.
  - Monitor and calibrate DIN reduction from erosion management. This needs to be carried out to cover different erosion management techniques for comparison, different soil types and at least until a stable state has been achieved (could be >10 years for gully rehabilitation works) including paddock scale, monitoring of rehabilitation projects and end of system sites.

- Greater confidence in the knowledge of pre-development sources (reference conditions) linked to soil types, land use and erosion processes through establishment of a catchment to marine monitoring program in a relatively pristine area such as the Olive Pascoe Basins, based on the design of the NESP Project 2.5.1 design. Tracing and dating in sediment cores could also be examined to look at the end of different catchments to examine shifts in sources and nutrient regimes.
- Assessment of existing knowledge of the sources of bioavailable nutrients in the context of particle size ('clean and dirty' sediment) to select areas where there is likely to be fine sediment and potentially bioavailable nutrient benefits (overlay maps) from erosion management. Use this to assess potential sources of 'ecologically relevant' fine sediment (organic matter and flocs) (depending on whether they stay in that form in transport).
- Identification of priority areas for soil mapping and ground truthing. This needs to be supported by improved methods for capturing and measuring particle size distributions (and ensure comparable datasets).
- Acquisition of higher resolution soils data (initially water dispersible silt and clay, POC, PN, PP, adsorbed ammonium, SOC, SON, DRP). To be verified with development of pedo-transfer functions as part of RP178a) and classification of soils (disaggregate into finer scale) to provide better estimate of bioavailable nutrient delivery in the models.
- Development of nutrient budget from all sources (e.g. Johnstone bioavailable particulate nutrient from grazing versus sugarcane; for grazing lands bioavailable particulate nutrients, cattle, rainfall [Packett et al., 2018]). Could be progressed with existing information in 2 case studies. E.g. test the model data with multiple lines of evidence and trialling in the 2 Major Integrated Project (MIP) locations. Use to evaluate end of system loads, accounting for bioavailable particulate nutrient inputs.
- Finer scale validation of the study of bioavailable nutrient catchment modelling study (RP178a Burton, Garzon-Garcia, Ellis) – this will assist to assess evaluation outcomes from management practice improvement, plume sourcing information and better marine risk assessment, and could be undertaken by analysis of multiple lines of evidence (existing monitoring data, tracing and experimental results).
- Investigation of the effect of vegetation type (i.e. carbon) on the bioavailability of particulate nutrients in-situ and as they are transported through catchments. This may influence on ground management practices such as trash blanketing and choosing species and tree density to be used in rehabilitation.
- Assessment of the contribution of organic sources of nutrients (e.g. nitrogen from legumes, nitrogen and phosphorus from mill mud) to nutrient losses (both dissolved and particulate). If the contribution is significant, methods to manage those losses (e.g. better managing supplementary fertiliser in these situations) need to be developed.
- Assessment of the effect of mill mud/mud ash application on bioavailable P forms at block (runoff/deep drainage) and catchment scale.

- Determination of the relationship between phosphorus surpluses, soil phosphorus concentrations and phosphorus lost to the environment in both particulate and dissolved forms.
  - Investigation of how bioavailable particulate nutrients interact in wetlands and the role of riparian areas in trapping or processing bioavailable nutrients. Quantification of the potential wetland treatment efficacy needs to take these particulate nutrient processing factors into account. Both N and P will be important to investigate in wetlands as freshwater algae respond to both. Residence times are vital to the efficacy of wetland treatment and in some catchments, it will not be possible to achieve appropriate residence times.
2. Further investigation of the rates and processes that influence nutrient **bioavailability in the marine environment**, including assessment of:
- Remineralisation rates of particulate organic material derived from terrestrial versus marine sources.
  - The role of resuspension in injecting DIN and PON from sediment pools into the water column and implications for remineralisation. These factors should be considered in the assessment of the risk of particulate bioavailable nutrients to the GBR.
  - The interaction of fine sediment, bioavailable nutrients and Chlorophyll in the central midshelf areas of the GBR. This will require frequent measurement of these parameters and analysis of the data correlations.
  - The role of phosphorus in supporting phytoplankton growth, relative to nitrogen. This can be explored in more detail using the eReefs biogeochemical models, supported with marine process studies to confirm model results and improve parameterisation and representation of phosphorus and nitrogen fixation processes in the model.
  - The effect of carbon on nutrient bioavailability (combined laboratory and field analysis).
  - The differential and combined effects of bioavailable nutrients (N, P, C) on algal groups and linking to COTS initiation and survival.
  - Phytoplankton dynamics in times of river discharge on the midshelf areas of the GBR, and measurement of nutrient enrichment across the GBR, especially in the midshelf and outer shelf between Townsville and Cairns where river discharge extends beyond inshore areas.
  - Cumulative impacts of multiple nutrient stressors on GBR ecosystems.
3. **Integrated assessment** of the catchment to reef interactions of fine sediment and bioavailable nutrients, drawing on the above information. This could include:
- Extension of the research effort to other systems (getting a good picture for the Burdekin, and some in the Tully / Johnstone) to differentiate between land use and the distinction of anthropogenic influences. In particular it is important to get a better understanding of pre-development loads of bioavailable nitrogen and phosphorus by studying pristine / conservation catchments or long-term rehabilitation sites (e.g. Weany Creek). This information can also be obtained by examining nutrient regime shifts in sediment cores from receiving waters.

- Extended application of the approach adopted in NESP Project 2.1.5 to other catchments (e.g. Herbert, Johnstone, Olive-Pascoe). This would need to be supported by laboratory based analysis of bioavailable nutrient processing from soils in different locations, experimental manipulation of carbon (build on DES/Griffith Uni indicator work) and extension of the monitoring in existing locations (Burdekin, Tully) to incorporate midshelf areas.

### *Main differences to our previous thinking*

Brodie et al. (2015) concluded: *Overall, we suggest management of anthropogenic sources of PN (mainly erosion) is likely to be very important to the health of the GBR (particularly the inshore GBR) but not as important as the management of anthropogenic sources of DIN (mostly fertiliser use). This finding is **based on our current assumptions that almost all the PN discharged from rivers to the GBR is likely to be bioavailable within its residence time in the GBR lagoon (Brodie et al., 2012), but PN is likely to be dispersed over a much smaller area than DIN.***

We now have case study evidence of how much of the PN becomes bioavailable once it enters the lagoon, and in what timeframes. In the Burdekin River in Cyclone Debbie, experimental results indicate that the bioavailable nutrients from PN is in the same order of magnitude as the end of system DIN load (from the Burdekin River itself not including discharge from Barratta Creek and the Haughton River). This is a greater proportion of bioavailable nutrients than previously assumed, and with a more rapid mineralisation rate than previously assumed. A case study using catchment model improvements also highlights the importance of the variability in particulate nutrient generation and the need for much finer scale prioritisation using available digital soil constraints mapping.

**The new evidence strengthens the case for specifically targeting the management of particulate nutrients in the GBR catchments for minimising risks to the GBR from anthropogenic land-based nutrient inputs as the timeframes of bioavailability in the marine environment can be within a few days.**

### *Concluding remarks*

The outcomes of the workshop and associated discussions are compelling for re-assessing the relative importance of the role of land-derived particulate nutrients to GBR health, highlighting that targeted management of particulate nutrients in the GBR catchments is warranted. However, this requires improved knowledge of the sources and delivery of particulate nutrients in specific locations, supported by improvements in catchment and marine modelling capability. These needs have been identified through the workshop and supporting work.

The project has demonstrated the value of greater collaboration between the catchment and marine research teams, and between these teams and the modellers. A majority of the outcomes of this project are hinged on this extremely positive collaboration. It is recommended that a forum is established for regular communication between experts in this field and across the paddock to reef landscape. The participants at the workshop indicated a willingness to support this kind of initiative. It would be beneficial to facilitate additional discussion among participants to refine the timelines required for delivering the key information needs.

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# **ATTACHMENT 1: EXTRACT FROM BRODIE ET AL. (2015), BRIEFING AND TECHNICAL SUMMARY**

Brodie, J., Burford, M., Davis, A., da Silva, E., Devlin, M., Furnas, M., Kroon, F., Lewis, S., Lønborg, C., O'Brien, D., Schaffelke, B., Bainbridge, Z. 2015. The relative risks to water quality from particulate nitrogen discharged from rivers to the Great Barrier Reef in comparison to other forms of nitrogen. TropWATER Report 14/31, Centre for Tropical Water & Aquatic Ecosystem Research, James Cook University, Townsville, 98 pp.

## **Briefing summary**

Discharge of nitrogen to the Great Barrier Reef (GBR) from rivers has increased greatly associated with agricultural development of the GBR catchment over the last 180 years. Increases in the discharge of dissolved inorganic nitrogen (DIN - nitrate and ammonium) are largely associated with increased use of inorganic nitrogen fertilisers in crops such as sugarcane. Increases in the discharge of particulate nitrogen (PN) resulted from increased erosion associated with grazing and cropping and to a smaller extent urban development in the catchment. It is not fully understood whether dissolved organic nitrogen (DON) loads have increased except where urea fertiliser is lost directly as urea.

Increased loads of nitrogen discharged to the GBR have had serious effects on GBR ecosystems including:

1. Increasing the severity of crown of thorns starfish outbreaks leading to large losses of coral over the last 60 years
2. Increasing the severity of coral bleaching where nitrogen enrichment is present
3. Increasing the growth of macroalgae compared to coral in nitrogen enriched conditions
4. Increasing the incidence of coral diseases

Discharge of DIN from rivers in high flow conditions disperses widely in the GBR lagoon (over 100s of km) before being taken up by marine plants including phytoplankton, macroalgae and corals. PN disperses to much less distances as most of the sediment and particulate nutrients sediment from river plumes close to the river mouth. The deposited PN may then be mineralised by bacteria to DIN and disperse more widely in the period after high discharge but the dynamics of this process are not fully understood. Much of the deposited PN may quickly be removed from the GBR all together by denitrification to nitrogen gas. While DON is also dispersed widely in the GBR lagoon during flood plume conditions its final fate is very poorly understood.

PN derived from erosion in grazing lands is well understood to derive from all forms of erosion - gully, streambank and hillslope, but recent studies suggest the proportion from channel erosion (gullies and streambanks) is much greater, compared to from hillslope sources, than was understood 10 years ago. However, as surface soils are enriched in nitrogen compared to sub-surface soils contributions of PN from hillslope erosion (where erosion is primarily of the surface soils) may be an, as yet, fully understood factor in prioritizing hillslope erosion management compared to the priorities set if only erosion of sediment itself is considered.

In conclusion while there is no doubt management of fertiliser derived DIN, given its complete bioavailability, is the highest priority for nitrogen management of the GBR, PN is also critical to manage as some/much of this nitrogen component may also become bioavailable in the

GBR lagoon after discharge. Management of the urea component of DON discharge from urea fertiliser use is also a priority as urea becomes fully bioavailable in the GBR lagoon very easily.

## Technical Summary

The development of the Great Barrier Reef Catchment for agriculture over the last 160 years has resulted in large increases in the loads of suspended sediments, nutrients and pesticides discharging to the Great Barrier Reef (GBR) lagoon. The increased loads of nitrogen, along with increased loads of phosphorus, are believed to be responsible for a range of damaging impacts on the ecosystems of the GBR associated with nutrient enrichment. In response to the documented damage caused to the GBR from increased river discharge of sediments, nutrients and pesticides the Australian and Queensland Governments developed Reef Plan 2003 (Queensland Department of the Premier and Cabinet, 2003). This plan aimed to halt and reverse the decline in water quality entering the GBR within 10 years (i.e. by 2013), by reducing diffuse pollution from agriculture. For nitrogen considerable uncertainty surrounds the relative importance of river discharged forms of nitrogen i.e. particulate nitrogen (PN) versus dissolved inorganic nitrogen (DIN) versus dissolved organic nitrogen (DON). While it is clear that ammonium and nitrate (the main components of DIN) are completely bioavailable when discharged from rivers into the GBR lagoon, the degree of bioavailability of terrestrially sourced DON and PN is largely unknown.

The diverse forms of nitrogen in the environment exhibit a wide spectrum of sources and transport and have different fates. Riverine PN, largely in organic forms, is primarily derived from erosion of GBR catchment soils. The supply of PN to the Great Barrier Reef (GBR) has increased over the last 150 years in line with increasing erosion due to widespread grazing activity and cropping. Inputs of DIN have increased primarily through the increasing application of fertiliser in cropping, particularly of sugarcane. The extent to which inputs and composition of DON have changed with catchment development and the processes leading to such change are less well understood (there are many different species of DON which have variable rates of bioavailability).

The sources of the different forms of nitrogen from different land uses can be partially estimated, for DIN but not for PN or DON, from the Source Catchments modelling results. For DIN 68% of the anthropogenic load comes from sugarcane lands. Accurate knowledge on the relative contribution of different N forms to nutrient cycling in GBR is essential for improving the water quality and this is currently a major research gap. We need to know about the relative bioavailability's of the different forms of N to design the most effective policies for water quality improvement. Most anthropogenic PN comes from erosion (primarily in grazing lands) whereas most anthropogenic DIN comes from fertiliser loss in cropping (predominantly in sugarcane lands). DON (except for urea fertiliser in runoff) is the natural form of N in catchments. If DIN and PN were known to be equally a risk factor in effects of the GBR such as COTs both nitrogen load reduction from grazing and sugarcane lands might well become equal priorities. This issue of relative importance is also a major research gap.

As PN is sourced from erosion, it is critical to management as to whether the largest sources are associated with hillslope erosion (and rill erosion), gully erosion or streambank erosion. It is reasonably well known that surface soils are richer in nitrogen (and phosphorus and organic

matter) than subsurface soils. Thus, while all erosion types may deliver particulate matter, surface soil erosion (e.g. hillslope) is likely to deliver higher amounts of PN (and PP). In contrast sub-surface erosion (rill at depths below 20cm, gully and streambank) will deliver relatively lower amounts of PN per unit of sediment. Thus, in some circumstances while hillslope erosion may be a smaller contributor to the overall sediment load it may be a bigger contributor to the PN load. The actual reality of these different delivery mechanisms is a major research gap.

Terrestrial nitrogen discharged into the GBR during riverine floods can spread widely in the GBR lagoon. DIN is taken up by plants (phytoplankton, macroalgae, turf algae, algal symbionts in corals and other organisms, benthic microflora), especially once water clarity improves through sedimentation of suspended sediment in the flood plume such that sufficient light is available for algal photosynthesis throughout the water column. It is unlikely that the chemical form of DIN (nitrate vs nitrite vs ammonium) has a large effect on algal demand and we can assume both forms are equally and fully bioavailable. Nitrogen in particulate forms (PN) may be deposited near the river mouth within sediments, or, alternatively, incorporated into suspended organic aggregates which can be dispersed over wider areas. A portion of the terrestrial DON (e.g. amino acids and urea) may be directly bio-available for biological uptake, but our understanding of the bioavailability of DON once discharged into GBR waters is very limited. Most DON and all PN needs to be mineralized to bioavailable forms such as nitrate before it can be “used” by biota.

Large pools of nitrogen exist in different compartments of the GBR – in the water column as ammonium and nitrate in normally very low concentrations; as PN also in low concentrations and; as DON in relatively higher concentrations. In ambient GBR lagoon waters DON comprises more than 95% of the nitrogen pool. While the total bioavailability (i.e. ability to be immediately taken up by plants for growth) of the ammonium and nitrate is not in question, the relative bioavailability (i.e. the ability to be taken up by plants after an initial mineralisation step) of the PN and particularly the DON is still undecided and should be the subject of further investigation.

The relative risk to GBR ecosystems from the various forms of nitrogen depends on the size of the input, the dispersal ‘footprint’ of the material and the degree of bioavailability of the different nitrogen forms over time. DIN is essentially 100 percent bioavailable. A large portion of both marine and terrestrial-sourced PN is potentially bioavailable (time frame days to months) after bacterial mineralization to DIN or ingestion by filter feeders. However, a significant fraction may be removed through denitrification in sediments (nearly all nitrogen is ultimately returned to the atmosphere via denitrification). The bioavailability of DON spans a wide spectrum. A significant proportion of DON, however, may be unavailable over timeframes longer than water residence times in the GBR system. Given our conclusions that almost all the PN discharged from rivers to the GBR and some of the DON is likely to be bioavailable within its residence time in the GBR lagoon, we suggest management of anthropogenic sources of PN (mainly fine sediment erosion) may be equally important to the health of the GBR as is management of anthropogenic sources of DIN. Furthermore, the PN (and PP) may drive the formation of sediment flocs and floc aggregates (i.e. ‘marine snow’) that, in turn, may influence turbidity/resuspension regimes along the inshore GBR. However, the extent and fate of the PN (and PP) delivered in the GBR lagoon is largely unknown and requires further study (i.e. there is potential that a high proportion of PN delivered is deposited near the river mouth

(although largely unquantified) and hence in this situation the effects would be more confined to localised areas. Direct runoff of urea from fertiliser application is a specific issue that needs to be managed given both the waste of fertiliser implied as well as the lack of current recognition that this form of DON is completely bioavailable.

Our current understanding is that nutrient enrichment from terrestrial runoff is driving increased frequency of crown of thorns starfish (COTs) outbreaks. While it is not known for certain yet (this is a major research gap) as to whether nitrogen inputs are more important than phosphorus inputs in driving this process our current consensus is that nitrogen is more likely the primary driver. Given this, the relative importance of PN and DIN in driving COTs, becomes a major question. Again our current consensus is that DIN is more important than PN in this process given that DIN is completely bioavailable after discharge while PN takes time to become bioavailable. In addition, DIN is able to disperse widely after river discharge in the GBR lagoon whereas much of the discharged PN is known to be trapped near the river mouth and the contained nitrogen may never reach the mid-shelf areas where COTs initiation is known to occur.

Thus managing the different forms of nitrogen involves quite different management practices on the catchment from fertiliser management (primarily in sugarcane cultivation with the highest total usage of nitrogen fertiliser in the GBR catchment) to various erosion controls (i.e. hillslope versus gully versus streambank) in grazing lands (and to a lesser extent in cropping lands) to providing better vegetation trapping capacity on floodplains and in riparian vegetation.

The review of nitrogen speciation and inputs herein in no way suggests that anthropogenic phosphorus discharges are unimportant to the health of the GBR, or even necessarily that anthropogenic nitrogen discharges are known with a high degree of certainty to be more important than phosphorus. While nitrogen is generally considered the major limiting nutrient in marine waters, both globally and in the GBR, limitation among nitrogen, phosphorus and silica vary, even in marine waters, in time and space. Thus, it is quite possible that phosphorus can limit primary productivity at certain times in the GBR and at certain locations. This is a major research gap for the GBR. For this report, the issue of large PN load increases and potential transformation to bio-available N is the primary concern.

Assessing the loading of nitrogen across the GBR from river discharge (and compared to currently available stocks) is important and in an Appendix we have included a draft paper which attempts to do this. As it yet to be peer reviewed we have kept it as an appendix pending its completion and before using the results more fully.

# **ATTACHMENT 2: WORKSHOP NOTES BIOAVAILABLE NUTRIENTS: SOURCES, DELIVERY AND IMPACTS IN THE GREAT BARRIER REEF: WORKSHOP, 15 MARCH 2018**

## **Purpose**

On behalf of the Office of the Great Barrier Reef (OGBR), C2O Consulting will coordinate, facilitate and document a stakeholder workshop. The workshop aims to deliver outcomes that provide clearer direction for future efforts to support improved understanding and management of bioavailable nutrient sources, pathways and impacts in the Great Barrier Reef. The outcomes will guide investment in management responses associated with bioavailable nutrients for achieving outcomes for the health of the Reef.

## **Invites**

A list of attendees is provided at Attachment 1.

## **Venue**

Department of Environment and Science, Level 3, Gondwana Room, 400 George Street, Brisbane

## **Outputs from the workshop and supporting work**

1. An agreed conceptual model of the delivery, transformation and fate of bioavailable nutrients from their source to the Reef. This will help communicate this complex issue for management, policy and modelling and support understanding of where future research investments need to focus.
2. A clear picture of current knowledge and additional research required to determine: what happens to particulate nutrients in the marine environment; what are the risks of particulate nutrients on varying timescales in the GBR lagoon; what is the contribution of particulate nutrients to bioavailable nutrients in the GBR lagoon relative to the bioavailable nutrients (primarily dissolved inorganic nitrogen) discharged directly from agriculture; and what are the management options for managing bioavailable nutrients. Ultimately, identify the key research required, how much funding that research requires, and who can undertake the research.
3. An indication of the effort required and the benefits of including new information into Source Catchment and eReefs modelling.
4. Consensus of the potential management implications of new evidence related to bioavailable nutrient delivery, transport and fate.

## **Workshop Notes and Discussion**

Presentations from the workshop are available on the shared Dropbox folder, or on request. The following notes capture the key points of the presentations and discussions, and will be used to review the supporting key messages and concept papers.

### **The risk and impacts of particulate nutrients to the marine environment -Jane Waterhouse**

#### *Impacts of increased nutrients in GBR*

- Elevated nutrients in marine waters has been demonstrated to lead to increased:
  - Macroalgal growth leading to reduced diversity
  - Survival of COTS larvae and secondary outbreaks
  - Susceptibility to bleaching
  - Coral disease

- Bioerosion
- Also interact with other stressors (e.g. fine sediment, temperature) to influence cumulative responses – typically exacerbates response.
- Different communities with different risks and responses - between regions, across shelf, with increasing depth.
- The nutrient form generated in the catchment is not necessarily the same as the form once it enters the GBR...it's complicated!

It's the bioavailability of the land-derived materials and timing that is important:

- DIN immediately bioavailable (very important).
- Particulate nutrients become bioavailable either instream or in marine system i.e. a portion is very important but how much – refer to later presentations.
- It appears that DIP from fertiliser becomes tightly bound to soils and is measured as particulate inorganic P (DIP release varies with soil types & geologies). Relative importance is not known.
- Land-derived dissolved organic nutrients are – to our current knowledge – relatively less important due to smaller proportions becoming bioavailable. *W*

#### *DIN exposure and risk*

- Exposure to DIN is significant to all inner shelf areas and the midshelf area between Lizard Island and Townsville adjacent to basins with high anthropogenic DIN loads.
- The relative importance of DIN to seagrass ecosystems is still uncertain, but it may influence light availability for deepwater seagrass in areas deeper than 10 to 15 m due to increased phytoplankton growth.
- The greatest coral reef and seagrass exposure to DIN is from the Herbert, Haughton, Johnstone, Russell-Mulgrave, Tully, Plane and Murray Basins.
- Anthropogenic PN is also likely to be of some importance in the same areas, as well as the Fitzroy Basin – but knowledge on the bioavailability of particulate nitrogen to marine ecosystems relative to that of DIN is still limited.

#### Discussion:

- Jon emphasised the importance of timing of discharge and risk to GBR ecosystems.
- Nutrient effects on seagrass are less well known – especially in deepwater systems where light reduction might be an issue further offshore.

#### **Partitioning and fate of particulate nutrients in the GBR - *what happens to land-derived contributions?* Jon Brodie and Steve Lewis**

- Jon ran through conceptual diagrams circulated in the key messages paper prior to the workshop.
- Steve showed some examples of data to illustrate differences between Tully and Burdekin
  - SPM– Burdekin starts much higher and then settles out around 10 psu and eventually depleted, Tully – starts much lower and much more gradual depleted
  - PN – similar to SPM story
  - DIN – Tully starts higher but both conservative mixing pattern
  - DON – much more variable – stays about the same all the time

#### Discussion of the conceptual models (consider for modification):

- Michele Burford working in SEQ on organic matter – including DON – which differentially affects phytoplankton and can be toxic to the algae in freshwater – and not sure how much impact in marine (phytotoxic effect on algae) – from leaf litter.

- Urea – measured urea uptake rates and equivalent to nitrate and ammonia – and quantity is as much. Mark Silburn includes urea in paddock modelling – covered in a paper. Understanding of urea – measured in top inch of soil – transformation period – ammonium there 3 months with large spread over time (dry layer and limited biological activity). If rained it would have runoff. Phil – what happens to urea is dependent on fertiliser band.
- DOP – a range of those compounds used in marine ecosystem – just as important where not much DIP in marine.
- Would be useful to consider various source s- e.g. what we do we know re: cattle sources (feedlots, manure)
- Could use size of circles to represent confidence levels in each part of the diagram.
- Use C2R diagram approach which provides simple versions and then develop case studies to incorporate details.

### **How the biogeochemical model handles the bioavailability of nutrients – Barbara Robson**

- eReefs biogeochemical model built on complex conceptual understanding.
- Model represents various marine parameters – can show ‘real time’ simulation of freshwater and sediment, DIN, DON (so much DON, transported further).
- Can distinguish likely influence periods from resuspension.
- Phytoplankton respond very quickly to DIN.
- Can produce vertical transects out from the coast – DIN, DON, phytoplankton N, zooplankton N.
- How could we use the models now?
  - Analysis of nutrient budgets – importance of different constituents at different times and events - including scenarios to test sensitivity
  - Scenarios of reducing the effects of different nutrient forms

### **Questions:**

- Benthic sediments – what does it mean for illustrating DIN resuspension events? Can model against regular monitoring sites and opportunistic sampling – but not much data for individual events and lower confidence. Could use aggregated data from water type mapping and analysis over different events.
- How handle catchment derived sources versus marine sources? Karen Wild-Allen – paper on nutrient budgets – upwelling quite important, N fixation is accounting for about 10-20% N out there, catchments are smaller component than upwelling but in terms of impact is much greater influence.
- How represent legacy effects of floods and resuspension of material? How incorporated into model e.g. longer-term influence? Model keeps track of sediment store and models resuspension events – but not enough sediment process and concentration data to validate over time to assess model performance.

### **Partitioning and fate of particulate nutrients in the GBR – new NESP and RWQP field and experimental results**

#### *What's really damaging the reef? The role of biogenic sediments – Steve Lewis*

- Focus on processing in the marine zone, plume dynamics and transformation.
- Flood plume- determine origin of flocc aggregates (tracing), characterising sediment that is dispersed in the inshore area (2 floods over 2 years).
- Cyclone Debbie (primarily BBB source) – rapid deposition around 11psu, then gradual depletion.
- March 2018 – primarily Upper Burdekin source – sampled but no results yet.

- Sediment traps – resuspension events; showing timeframes of sediment ‘availability’ and correlation between discharge and wave events after discharge influence.

#### *Indicators of particulate nutrient bioavailability for GBR – Michele Burford*

- What impact is particulate material having on the marine system, and what does it mean biologically?
- How determine direct effect of particulate nutrients on marine ecosystem using phytoplankton as the measure? Test indicators of bioavailability on phytoplankton growth and develop new assay to test linkage.
- Soil sampling in Bowen and Johnstone catchments to represent soil types and conditions.
- Marine - identified importance of adsorbed ammonium, PON and ratio of C to N as explanatory parameters (not necessarily causal); in freshwater same but DRP also important. Phytoplankton yield better measure than Chl – shorter response.
- Based on algal bioassay, particulate nutrients are potentially bioavailable, and indicated algal response. Carbon also important.
- Implications – current monitored parameters insufficient to understand the effect of bioavailable nutrients, not accounted for in target setting.
- Gaps – role of carbon in the system, why and how do particulate nutrients affect the algae, work closely with the modelling to ensure that improving predictions.

#### *DIN generation in river plumes - Alex Garzon-Garcia*

- Samples taken across the salinity gradient in the Cyclone Debbie Burdekin plume and incubated to measure DIN generation.
- DIN generation increased linearly – did not slow down towards the end of the incubation.
- Showed that DIN generation in the plume is significant.
- Implications – need targets for DIN produced from PN? We are not measuring DIN produced from PN.
- Gaps – what happens when sediment settles and further DIN generation, risk assessment of DIN from PN to the reef, testing model in other catchments, what is a reference for bioavailable PN (pristine) and role of carbon quality and quantity.

#### Questions:

- Role of ammonium and where does it come from – rapid turnover and rapid uptake by the phytoplankton.
- Jon – the DIN measured in plumes is probably not representing the transformation between PN and DIN – hard to show with monitoring data.
- Steve – add to gap – length of time in the plume – is it the persistence of the plume water out there that’s more important? Barbara – model includes remineralisation but not adsorption.
- Barbara – rapid generation of DIN from PIN - does the filtering process make a difference? Subtracted the DIN that was already present in solution from the DIN extracted with strong salts from sediment.
- Bec- a large proportion – up to 30% of DIN measured - is colloidal – but that doesn’t mean that the phytoplankton isn’t taking it up.

#### **Discussion to summarise ‘marine’ story and identify priority knowledge gaps**

##### *Knowledge gaps identified in presentations:*

##### Risks and impacts

- Representation of nutrients – spatially and temporally

- Impacts and risk of P – relative importance of N and P and relationships between them and C
- Timing and inputs – representation and processing
- Role of organic flocs

#### Marine models

- N fixation seems important – makes P as important as N – need to understand better
- Benthic sediments processes - model represents sediment nutrient processes similar to water column nutrient processes but it's actually much more complex. Almost no data to check. Timing of mineralisation and bioavailability.
- Simple representation of organic nutrients – are they different from different catchments and flood events?
- How do organic aggregates form and how does this affect transport of nutrients? Could be important in driving transport.

#### Plumes tracing and transport

- yet to observe influence of Burdekin event on sediment trap sites – large event
- what does a pristine flood plume look like (e.g. Olive-Pascoe)
- influence of new sediment in midshelf sites (relative risk of sediment across shelf)
- characterising SPM of most risk and tracing back to source
- Processes of sediment transport and resuspension in GBR

#### Indicators of bioavailability

- role of carbon in the system
- why and how do particulate nutrients affect the algae
- variation between years not accounted for, and limited spatial coverage
- work closely with the modelling to ensure that we are improving predictions

#### DIN generation in plumes

- What happens when sediment settles and further DIN generation
- Risk assessment of DIN from PN to the reef, testing model in other catchments
- What is a reference for bioavailable PN (pristine) and role of carbon quality and quantity

#### *Key messages, modified from summary paper:*

- Nutrient inputs are most important during river discharge events and for a period of time afterwards. For the Wet Tropics rivers – that is every year. For the Burdekin and Fitzroy – that is every 3 to 5 years (or less). This is when the availability of bioavailable nutrients can influence adverse ecosystem effects e.g. COTS larval survivorship (Nov to Feb), bleaching susceptibility (coupled with temperature – Jan-Mar), coral disease (coupled with temperature – Jan-Mar). Effects of nutrients on seagrass in areas of resuspension (leading to reduced light) may be important throughout the year. During discharge periods, nutrient inputs may be important in deeper areas (>15m) – associated with phytoplankton growth and reduced light (knowledge is less certain).
- Outside of those times, terrestrial influences are small and nutrient requirements for productivity are dominated by recycling in the GBR lagoon or from water column PON/DON. Resuspension of material outside of discharge periods is thought to be less important for nutrient bioavailability, but this is yet to be quantified. Upwelling mostly restricted to some outer shelf areas (e.g. Swains, Palm Passage, far northern GBR). PON may be more available than DON.

- Marine risk is assessed as DIN only at this stage – so does not fully capture the bioavailable component of particulate nutrients or dissolved organic nutrients (except perhaps indirectly in the Chlorophyll and light attenuation input data). Currently only linked back to end of catchment DIN loads for basin scale prioritisation.
- Strong evidence of these nutrient inputs exists for N, with less knowledge about P inputs and the interactions between N, P and C.
- The eReefs biogeochemical model captures the delivery and transformation of particulate nutrients through labile and refractory detritus to dissolved forms. This representation works at the regional scale but additional evidence from process-based studies provide a new opportunity to improve parameterisation of the model at local scales and get better performance at the river mouth. Examples include the DES/NESP experimental data.
- PON is mineralised in the water column to bioavailable form (e.g. DIN) and we have some idea of the rates. PON can be mineralised to ammonium in the sediment matrix and transformed to either nitrate (nitrification) or  $N_2$  (nitrification coupled with denitrification), or  $N_2O$ . The relative proportion of the rates of these two processes will vary depending on the redox conditions within the sediment matrix. Studies using  $^{15}N$  in the Brunswick River NSW with microphytobenthos (MPB) present showed that thirty-three days after the  $^{15}N$  was assimilated by MPB, 27% remained in the sediment, 16.5% had been effluxed as  $NO_3^-$ , 20.8% had been effluxed as  $NH_4^+$ , 20.7% had been effluxed as  $N_2$  and 15.1% was not accounted for. It is predicted that most (12.6%) of the  $^{15}N$  label that was not accounted for was probably lost as dissolved organic N (DON) fluxes. However, this is for the specific conditions of the Brunswick River estuary. The eReefs model handles mineralisation as a simple function of organic N concentrations and temperature, and denitrification as a function of nitrate concentrations, temperature and dissolved oxygen. It is still believed that between 10 and 30% of the DON from the river is bioavailable after discharge into the lagoon.
- Studies in Moreton Bay have shown that P fluxes into bottom sediments, not out of sediment, even when fine transported sediment deposits on the surface of the sediment. However, the role of resuspension due to wind mixing in releasing P into the water column is poorly understood.
- Some forms of terrestrial organic matter from riparian vegetation have been shown to inhibit algal growth, especially cyanobacteria. The effect of these forms of DOM on marine species is unknown.
- Organic and inorganic phosphorus is likely also important. The eReefs biogeochemical model indicates that: (1) though nitrogen is more often limiting, phosphorus does sometimes limit phytoplankton and coral symbiont growth in the GBR, and (2) nitrogen fixation by *Trichodesmium* makes an important contribution to the nitrogen supply. Nitrogen fixation is in turn limited by the phosphorus supply. Recent process studies in marine waters also show that nitrogen and phosphorus often co-limit production, contrary to previous assumptions.
- We have improved understanding of how much of the particulate nitrogen becomes bioavailable once it enters the lagoon. In the case study of the Burdekin River in Cyclone Debbie, experimental results indicate that 25% of the end of system DIN load was generated in the plume (from the Burdekin River itself not including discharge from Barratta Creek and the Haughton River). Had the event been large enough to trigger a plume that travelled to Palm Island (i.e. an additional 9 days of travel time) it is estimated that the same order of magnitude as the end of system DIN load would have been generated.
- Algae consumes DIN that has been derived from sediment in marine conditions. Both DIN and DRP derived from sediments is consumed by algae in freshwater conditions. Carbon has an

important influence in mediating this process in both fresh and marine waters (Garzon-Garcia et al. 2018a; Franklin et al. 2018).

- A new rapid bioassay technique has been developed that allows testing of catchment derived sediment nutrient bioavailability. Key sediment indicators have been identified including organic carbon, organic nitrogen, adsorbed ammonium and C:N ratios.
- Temporal and spatial variables need to be considered when examining the amount of DIN being generated from particulate sources. PIN (adsorbed ammonium) is an important source of DIN from plume sediment, this tends to occur in short timeframes (hours) at low salinity (<6 PSU). DIN can also be generated by the mineralisation of PON. This process occurs in longer timeframes (days) as the sediment is being transported.

*Marine 'so what'?*

- Reinforced that particulate nutrients matter – and needs to be considered in risk and prioritisation
- New pool of bioavailable nutrients at end of system that may not have been accounted for as a contribution to the marine environment before (and it's a lot – so it's worth investigating!)
- Shift conceptual understanding of cycling and how represented – changes framework of how measure, model and account for them to reflect that
- Adjusts the assumptions in the model...
- Highlights need for further monitoring in mixing zone
- Influence of carbon on processing needs further investigation
- Is the DIN offshore in the plume derived from the catchment particulate nutrients?

### **Sources and end of catchment nutrient budgets**

*Sources and end of catchment nutrient budgets – Cameron Dougall*

- Cameron presented an overview of end of catchment loads – by parameter, by basin, by land use (new load data).
- Demonstrated the application of the model and role of integrated monitoring and modelling approach.

Monitoring data:

- When assessing fine sediment and PN loads as annual averages – the contributions look reasonably similar – however, when assess the PN load per unit of sediment, some rivers are much richer than others in PN and PP, e.g. Kalpower = 0.7 kg of PP per ton of sediment and South Johnstone = 1.8 kg of PP per ton of sediment; more so for PN North Johnstone to Upper Burdekin (~5 to 1 ratio).
- Calculated the proportion of different nutrient forms from monitoring data – highlights some high differences between DIP and DOP proportions between basins.

Modelling data:

- Limited temporal and spatial water quality dataset, therefore a need to extrapolate and estimate the manageable component with catchment modelling.
- Greatest contributions PN and PP from the Burdekin (almost 30% total GBR load) and Fitzroy (~12%) basins, and then Herbert, Mary, Johnstone (all around 3-5% each).
- Loads by land use shows a large proportion total PN loads coming from grazing lands and conservation areas, and streambank erosion. In coastal catchments – also cane. Similar story for PP.

- Loads by erosion sources shows differences in losses by gully or hillslope erosion processes between fine sediment and PN with more PN from hillslope erosion – most probably because surface soils are generally richer in particulate nutrient compared to sub surface soils. Area for future work.

Limitations to modelled DIN and particulate nutrient transport:

- Refer to Limitations in McCloskey et al 2017. Includes over targeting and moving targets, rapidly evolving knowledge space, data poor environments - many spatial and temporal considerations, only prioritise to the scale of the limits of the input data (in grazing scale of soil mapping is a major limitation). Accuracy assessment never one size fits all – soils data often inhibiting better modelling (e.g. People wish to target at 1:25k scale yet soils data often at 1 to 500k).
- Summary – no plans to introduce new constituents into modelling, if demonstrated that sediment-attributed DIN is important then ramifications for prioritisation, smaller scale modelling (presented as example by Alex) is still proof of concept. A sensible prioritisation approach using local knowledge and common sense may effectively capture the BAN/DIN story - although it appears complex with many unknowns, so the spatial and temporal scale would be extremely broad, and the confidence levels inherently low...

Paddock and plot scale loads modelling:

- Brigalow catchment study -wealth of knowledge. Shows that dissolved N is dominant, the dissolved fraction under brigalow and freshly planted lightly grazed legume is dominated by inorganic N; however, as the grass component of the pasture increases the dissolved fraction becomes dominated by DON, the dissolved inorganic fraction is dominated by NO<sub>x</sub> but NH<sub>4</sub> N increases with increasing grass component of the pasture.
- Cattle pathways – 11.3kg/ha/yr N deposited in landscape from cattle via dung and urine to the soil surface at the Brigalow catchment study. Pathways to streams largely unknown.
- Rainfall simulator work (Matt Eyles) – assessed enrichment ratios based on particle size analysis – where and how generated and what influences those in practices. Also looking at erodibility and how that relates to bioavailable nutrients. Preliminary results - found an enrichment of finer particle sizes between the parent soil and sediments generated in runoff under simulated rainfall, with an increase in the <10µm fraction from ~8% to 30-45%.
- Further rainfall simulator work for nutrients - comparing bioavailable NH<sub>4</sub>-N concentrations with fine particle fractions to identify if a relationship is present between particle size and bioavailable nutrient parameters; assessing enrichment ratios of different soil types and soil surface conditions, developing a method to assess N speciation changes over time in frozen runoff samples, inputting data into the bioavailable nutrient indicator equations.
- Gaps – processing in reservoirs, what happens between surface and subsurface erosion, soil mapping and enrichment ratios.

*Discussion (mostly about gaps):*

- Could take some of basic soils data and use pedo-transfer functions to turn into better indicators of bioavailable nutrients. It's the nutrient enrichment and delivery ratios that are most important.
- Use existing QG datasets to progress the soils analysis.
- The more we look at gullies and association with nutrients we are understanding the large variability – and still many soil types where gullies are not even mapped. Can't use existing soil maps to extrapolate about key source areas. Strathalbyn – high variability and not well represented by traditional soil classes – so need other metric to describe soil characteristics.
- Gully workshop run by Ian Prosser identified concerns regarding appropriate application of the scale of the model – agreed that about 10,000km<sup>2</sup> is a good point of reference for how small to use for prioritisation...or as a minimum where a gauge is. Fine sediment deposition and

residence time turnovers in the model aren't well covered – *cross reference to the modelling network workshop results.*

### **Catchment generation, delivery and transformation processes**

*Improved understanding of bioavailable particulate nutrients in catchments – Jo Burton*

- Processes associated with DIN from erosion – DIN from solubilisation (immediate), DIN from desorption (in marine) and DIN mineralisation (in catchment and marine).
- Eroded soil is a source of bioavailable nutrients (i.e. DIN and DRP).
- Pathway of generation is complex and needs to account for soil type, carbon, hydrology, wetting and drying cycles, transport time.
- N and P and C are important in freshwater systems, and N and C are important in marine systems.
- Key concepts – role of particle size and link to enrichment, timeframes, link between soil properties and bioavailable particulate nutrients and eroded sediment.

Particle size data:

- Analysed particle size results from monitoring data – shows that a majority of the sediment being measured at end of system is <63µm.
- Larger proportion of <20µm reaching end of system in grazing catchments than in coastal catchments.
- Finer particles more enriched than larger particles.

Timeframes for DIN from PN:

- Not accounted for in the model.
- Transport time from catchment to marine influences the quantity of DIN generated by mineralisation of PON – mineralised between the generation point and the end of catchment.

Link between soil properties and bioavailable particulate nutrients and eroded sediment:

- Bioavailable particulate nutrients vary with soil type and erosion process, and land use.

This complexity creates lots of challenges! Exploring the use of pedo-transfer functions to predict Bioavailable particulate nutrients in sediments from intrinsic soil properties (see next presentation from Alex).

*Contribution of sediments to bioavailable nutrients from source to end of catchments – Alex Garzon-Garcia*

- A significant fraction of DIN is generated from eroded sediment and this is not quantified (1.2 to 1.5 times the Bowen EoS DIN load).
- A part of this DIN is of anthropogenic origin and is not presently targeted. Currently considered as natural / pre-development load.
- Getting sediment source contributions right in models (surface and subsurface) is key to accurate modelling of DIN at EoS.
- Prioritisation for sediment is not the same as prioritisation for bioavailable particulate nutrients.

This study:

- Quantified PN and bioavailable particulate nutrient pools in fine sediment (<20µm) from eroded soil from key soil types, land uses and erosion processes (subsurface and surface erosion) for the Bowen River catchment

- Used '*pedo-transfer functions*' to integrate into P2R modelling and run a case study for the Bowen River catchment

Model results:

- Assessed potential changes to P2R model – changed enrichment factors, only modelled fine sediment (<20 µm).
- PN enrichment varies widely across the catchment – much greater enrichment in surface soils.
- Prioritisation for sediment not the same as bioavailable particulate nutrients – this will vary depending on soil types and land use.
- Implications – targets for DIN from PN required?, modelling and modelling - currently not measuring or predicting DIN from PN, improve models/monitoring to predict reductions in DIN from erosion management, improve sediment targeting. Trading for nitrogen forms should take into account the bioavailability of the different bioavailable nutrient pools.

Discussion:

- Contributions from streambank erosion seem low – check the data that is used.
- Recommend calculating a budget estimate outside of the model – confounding all potential errors by incorporating to the model.

## **Discussion to summarise 'catchment' story and identify priority knowledge gaps**

*Knowledge gaps identified by presenters:*

Link between soil properties and bioavailable nutrients

- What particle size should be measured and modelled? Is it the same across all catchments?
- Is it important to monitor and model Bioavailable particulate nutrients at end of system?
- Can we improve the way that we currently model enrichment?
- What would bioavailable particulate concentrations have been in predevelopment scenario?

Contribution of sediments to bioavailable nutrients

- Testing BPN model in other catchments
- Extend soil database as necessary – might need more parameters than in SALI database
- Need reference conditions for anthropogenic estimates (predevelopment estimates)
- Accurate sediment modelling that represents erosion source contributions
- Include BPN to prioritise sediment management
- Monitor and calibrate DIN reduction from erosion management (paddock scale modelling)
- Linking prioritisation of sediment delivered to the reef, to the sediments that are producing DIN in the catchment.
- Compare anthropogenic DIN from grazing erosion compared to cane and bananas – South Johnstone a good example.

*Key messages, modified from summary paper:*

- A combined catchment monitoring and modelling approach produces annual average estimates of end of catchment loads of dissolved and particulate nutrient forms for the GBR 35 major basins. The greatest contributions of PN and PP are from the Burdekin (almost 30% total GBR load) and Fitzroy (~12%) basins, and then the Herbert, Mary, Johnstone basins (all around 3-5% each). Analysis of modelled loads by land use shows that a large proportion of total PN loads is generated from grazing lands and conservation areas, and streambank erosion. In

coastal catchments sugar cane also generates large proportions. These results are similar for PP.

- Analysis of modelled loads by erosion sources shows differences in losses by gully or hillslope erosion processes for fine sediment and PN, with more PN from hillslope erosion. This is because surface soils are generally richer in particulate nutrient compared to sub surface soils. Further work is required to provide improved quantification of erosion sources of particulate nutrients.
- DIN and DRP are generated from eroded soil/sediment, and can be managed through erosion management.
- New knowledge of DIN generation from PN can be used to improve how DIN is modelled in the Source Catchments model. Improvements to the sediment modelling are also required to provide more accurate estimates of end of system PN and DIN generated from PN (and corresponding P).
- In a case study of the Bowen catchment, the SOURCE Catchment model was run using new bioavailable PN data. DIN generated from eroded sediment (i.e. PN) using this new data can account for all of the end of system load of DIN modelled using the traditional method. DIN generation from PN is not currently accounted for in the SOURCE catchments model.
- The Bowen catchment case study also indicates that prioritisation for sediment management is not the same as prioritisation for bioavailable PN management. This has implications for finer scale spatial priorities for reducing sediment versus bioavailable PN yield, and also where hillslope and sub-surface erosion processes are targeted.
- Based on the modelling in the Bowen catchment (model run 28 years), there is more bioavailable PN coming from hillslope erosion than gully or streambank erosion. However, calculations made using tracing data as a second line of evidence indicate that after several years of above average rainfall (tracing data from 2011/12) subsurface sources contributed more bioavailable nutrients than surface sources.
- A pilot study in alluvial gullies in the Normanby catchment demonstrated that the main source of bioavailable PN, bioavailable PP and Carbon varied with the stage of gully evolution between surface and subsurface. This study also demonstrated that bioavailable PN and bioavailable PP concentrations are enriched in the <10 um fraction compared to the <63 um fraction.
- Variation in intrinsic soil properties (i.e. TOC, water dispersible clay) is an important factor for the estimation of PN and bioavailable PN because these properties impact delivery and enrichment ratios. The same is true for PP and bioavailable PP. These properties have been measured in key soil type and land use combinations in the Bowen and Johnstone catchments. There are also relevant soil properties that are not currently measured and included in the modelling (e.g. adsorbed ammonium, DRP). Development of pedo-transfer functions for BPN pools is necessary to determine which properties are most important.
- These findings have implications for management prioritisation, particularly at a smaller scale (hydrounits used in SOURCE Catchment modelling and individual alluvial gullies), as well as end of system target setting and tracking.
- The new evidence indicates that DIN is generated from eroded sediment, both during transport to end-of-catchment and in the estuarine/marine receiving water columns. This will be true for all catchments although the amount will vary with soil type, land use, time in transport etc.

### *Catchment 'so what'?*

- There are limits to spatial prioritisation using the Source model that should be considered – multiple lines of evidence should be used to do smaller scale prioritisation. Essential to calculate budgets outside of the models.
- The areas for investment come down to what is being delivered (not just generated).
- DIN from erosion is an important contribution to end of system DIN loads and to model it correctly we need the more accurate sediment source distribution in the catchment. This is the same case for PN.
- Understanding anthropogenic DIN from grazing lands is important for target setting – currently assumes its limited
- In the Burdekin we presently manage soil erosion for reducing fine sediment loads, and then cane for DIN – so we are doing both anyway...but in other catchments like the Johnstone, what are the actions for reducing PN??

### **Does this knowledge change what we do on-ground? What are the options? What are the management options? Are particulate nutrients manageable?**

The participants broke into 3 groups for discussing the following 6 questions for Management Practices, Catchment Processes and Marine Processes

1. What are the most relevant management implications from new evidence? (3 points)
2. How does the new evidence influence the prioritisation of management options?
3. What are the implications for target setting?
4. What are the associated modelling needs?
5. What are the associated monitoring and evaluation needs?
6. What are the critical information needs and dependencies?

### ***Management practices***

*What are the most relevant management implications from new evidence? (3 points)*

- Re-emphasising the importance of hillslope and gully erosion.
- Develop and promote management practices that reduce nutrient rich fine sediments.

*How does the new evidence influence the prioritisation of management options?*

- Revise communication regarding gully and hillslope and bioavailable particulate nutrients.

*What are the implications for target setting?*

- Next gen targets need to fully consider bioavailable particulate nutrients.

*What are the associated modelling needs?*

- Particle size fraction for % fines sediment and NP+C on fines.
- Better soil and subsoil data.

*What are the associated monitoring and evaluation needs?*

- Loads monitoring and paddock monitoring measure bioavailable properties for equations.
- Monitor carbon and SOC etc.
- Some more sediment size measuring (strategic) – specific.

*What are the critical information needs and dependencies?*

- Prediction of fine sediment and N+P+C erodibility and particle size distribution of eroded materials.
- Addition of carbon and BPN analyses in paddock studies.
- Identify areas for priority soil mapping- ground truthing.
- How do bioavailable particulate nutrients interact in wetlands? Use of freshwater bioavailable particulate nutrients equations to inform management.
- Methods for capturing and measuring particle size distributions (comparable datasets).
- Communication and language – refining reference to fines (e.g.16um), sediment, bioavailable nutrients.

### **Catchment processes**

*What are the most relevant management implications from new evidence? (3 points)*

- Concepts are good and it's important to investigate further.

*How does the new evidence influence the prioritisation of management options?*

- In grazing catchments, we can now view eroded sediments as a significant source of bioavailable particulate nutrients (DIN in the marine environment).
- At catchment scale – PN is an important source of DIN in catchments that we need to consider, but based on current knowledge, further targeting of management effort would require additional information to support refinement of priority areas.

*What are the implications for target setting?*

- This work will have implications for targets and need to consider bioavailable particulate nutrients when setting next targets.

*What are the associated modelling needs?*

- Development of pedo-transfer functions from intrinsic soil properties (longer term needs).
- PP and PN pathways between hillslopes and gullies.
- Soils data / classifying soils (disaggregate into finer scale) – better estimate of nutrient delivery.
- Improved resolution of models.
- Better modelling of bioavailable particulate nutrients into the marine environment.
- Fine scale validation of the model outputs.

*What are the associated monitoring and evaluation needs?*

- High resolution soil mapping (Alex and Cameron) (Extend soil database)
- High resolution channel processes and deposition– repeat LiDAR.
- Include carbon in GBRCLMP.
- Identify bioavailable particulate nutrient contribution of cattle – nutrient budget from all sources (e.g. Johnston bioavailable particulate nutrient from grazing versus cane; for grazing lands bioavailable particulate nutrients, cattle, rainfall (Packett et al)). Can do with existing info in 2 case studies. E.g. test the model data with multiple lines of evidence and trialling in the 2 MIPs locations. Use to evaluate end of system loads, accounting for BPN inputs.
- Monitor and calibrate DIN reduction from erosion management.
- Measuring PIN in catchment.

*What are the critical information needs and dependencies?*

- We want to know more about the bioavailable particulate nutrients sources to marine to optimise benefits of management interventions (i.e. reduce fine sediment and bioavailable particulate nutrients). Also need pre-development sources – reference conditions. Need to understand soil types, land use, erosion processes.
- Fine scale validation – test against data layers to assess evaluation outcomes, plume sourcing information and better marine risk assessment.
- Better understanding sources BPN from all particle sizes – select areas where fine sediment and potentially BPN benefits – overlay maps.
- Riparian areas?? (frontage country) – turn over and cycling – not just what's going through but cycling and residence times (incl. wetlands).
- 'Clean and dirty sediment' – and sources – do they stay in that form in transport?? Marry up the source with the ecologically relevant sediment (organic matter and flocs).

### **Marine processes**

*What are the most relevant management implications from new evidence?*

- Timeframes for bioavailability of particulate nutrients is much faster than we previously thought – and for a while after delivery = particulate nutrients matter! Relative importance is boosted. Extent of influence is inshore and midshelf areas
- Carbon – nutrient interaction is important (monitoring and management of soil carbon).

*How does the new evidence influence the prioritisation of management options?*

- Link particulate nutrients from catchment into risk assessment.
- Investment in soil erosion will also benefit bioavailable particulate nutrient management for marine outcomes.
- Time lags of managing DIN from fertiliser versus soil erosion is important.
- Understanding of nutrient budgets has changed.

*What are the implications for target setting?*

- Quantify DIN from sediment and bioavailability.

*What are the associated modelling needs?*

- Model (eReefs) actually combined DIN and PN for targets.
- Linking back to catchment loads need to account for DIN and bioavailable PN explicitly.
- Test different decay rates.
- Sort out the benthic sediment contributions.

*What are the associated monitoring and evaluation needs?*

- Extend NESP work to other catchments.
- Real time monitoring in events
- Nutrients in midshelf areas – link to CoTS = WT bioavailable nutrient sources
- Measuring highest priorities – Herbert, Johnstone
- Extended measurement PIN and DOC and POC

*What are the critical information needs and dependencies?*

- Effect of carbon on nutrient bioavailability.
- In-situ data at high frequency in discharge event.
- Benthic sediment generation...

- Differential effect of bioavailable nutrients (N, P, C) on algal groups and linking to COTS.
- Midshelf story – sediment, bioavailable nutrients, Chl, - needs to be measured!!
- Model developments – transport of flocs, N fixation, test sensitivity to P inputs.
- Extend NESP – Olive Pascoe – other catchments plus lab based work of bioavailable processes from soil in different locations, also manipulate C (build in DES/Griffith Uni indicator work) AND extend existing locations into midshelf in existing areas.
- Dependencies: Linking to each other! Ensure paddock to reef projects meet each other's needs across the landscape...

#### **Prioritising future research, management and policy direction**

- Explore if there is a link to RIMReP, and MMP inputs.
- Reef Plan RD&I prioritisation – how align with that – what are the things that need to happen in parallel in marine and catchment end?
- Link to P2R Review.
- Identify MIP opportunities.
- Establish a road map for how the information needs will inform target setting and priorities.
- NESP project led by Michele Burford includes literature review on carbon in the GBR (<http://nesptropical.edu.au/index.php/round-4-projects/project-4-11/>)
- Follow up meeting – linking from catchment to reef – consider a subgroup of the Sediment Working Group.
- Simplify communication and language – clear messages!

## Workshop participants

| Participant and Organisation   | Role                                    |
|--|---|
| Lex Cogle, OGBR DES  | Science delivery / policy               |
| Leigh Smith, OGBR DES  | Science delivery / policy               |
| Jean Erbacher, DES   | Science delivery / policy               |
| Rae Schlecht, OGBR DES   | Science delivery / policy               |
| Nyssa Henry, OGBR DES  | Science delivery / policy               |
| Jo Burton, DES   | Research - Catchment                    |
| Alex Garzon-Garcia, DES  | Research - Catchment                    |
| Stephen Lewis, TropWATER JCU   | Research – Catchment to Reef            |
| Jon Brodie, C2O Consulting   | Research – Catchment to Reef            |
| Zoe Bainbridge, TropWATER JCU  | Research – Catchment to Reef            |
| Michele Burford, Griffith University   | Research - Marine                       |
| Barbara Robson, AIMS   | Marine modelling                        |
| Rebecca Bartley, CSIRO   | Research - Catchment                    |
| Andrew Brooks, Griffith University   | Research - Catchment                    |
| Cameron Dougall, DNRME   | Catchment modelling                     |
| Mark Silburn, DNRME  | Paddock modelling / management practice |
| Phil Moody, DES  | Paddock research / management practice  |
| Matthew Eyles / Bruce Cowie, DNRME   | Paddock research / management practice  |
| Jane Waterhouse, C2O Consulting  | Coordination                            |
| Johanna Johnson, C2O Consulting  | Facilitation                            |
| <b>Apologies:</b> Mark Baird, Rob Ellis, Dave Waters, Kevin Gale / Giles West, Damien Burrows, Leigh Gray, Carol Honchin, Kev McCosker, Shawn Darr |   |

