Australian National University

15 September 2020

Committee Secretary
Senate Standing Committee on Rural & Regional Affairs & Transport
Joint Select Committee on Road Safety
Department of the Senate
PO Box 6100
Parliament House
Canberra ACT 2600
E: RRAT.Sen@aph.gov.au

Dear Committee Secretary

RE: Inquiry into the identification of leading practices in ensuring evidence-based regulation of farm practices that impact water quality outcomes in the Great Barrier Reef

Thank you for the opportunity for The Australian National University (ANU) to appear before the Committee on 28 August 2020.

A number of matters arose during the course of the Committee hearing to which we committed to provide responses. We also note correspondence from the Committee dated 2 September 2020 with a list of additional questions from Senator Rennick.

On a matter of clarification, there was discussion at the end of the appearance about land management. While land management includes farming, it is a much broader term that encompasses all land usage.

We note that as academics, the advice provided is evidence-based, grounded in rigorous science. Given the depth of information requested by the Committee, this is by necessity a long response. In our initial submission we sought to ensure the language we used was accessible to all readers. However, given the detailed requests from Committee members, this response is, in parts, more technical.

We have attached a number of papers for the benefit of Committee members, however we are cognisant that under copyright law some may not be republished on the website without approval of the publisher. We trust you will undertake appropriate action on this matter.

We would also direct the Committee to our initial submission that identified ways in which scientific advances can provide benefit both to farmers and to the health of the Great Barrier Reef. Research outcomes can empower farmers by supporting them to monitor crop growth, soil nitrogen levels and nitrogen levels in plant and riparian environments. Additionally, introducing beneficial soil bacteria to crops can improve nitrogen capture. These tools are either available now or can be developed and deployed in the coming years.

Available and future technologies include:

- High resolution monitoring of soil nitrogen and phosphorus status using hyperspectral imaging via drones and satellites to confine fertiliser application to sites that need additional nitrogen.
- Breeding of crops that need less fertiliser to produce higher yields.
- Increasing the ability of plants to capture and use nitrogen and phosphorus from soils through improved soil management, rotations or intercropping with legumes.
- Using beneficial soil bacteria to convert atmospheric nitrogen into fertiliser-like nitrogen inside the plant.

- Engineering or breeding non-legume plants to fix atmospheric nitrogen and significantly reduce or remove the need to apply fertilisers.

ANU research further indicates that replanting of terrestrial vegetation and coastal mangroves and seagrass beds along waterways and coastlines will trap soil, limit erosion and capture excess nutrients.

There are clear opportunities for a 'win-win' solution, where farmers can reduce their costs at the same time as protecting the Great Barrier Reef. We note that this is not a criticism of past or current farming practices; rather, even with the gains made by farmers, there is always the need and potential to increase farming profitability and if that can be achieved by practices that have environmental benefits we would argue they are worth pursuing.

Fertiliser to River to Reef Data

The Fertiliser to River to Reef Data requested is available in the Mallela 2013 (peer reviewed and published) paper, which is freely available here: https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0075663

Update on Proposed Research

In our original submission, we noted addition work is required to advance our capabilities to reduce the uncertainty of catchment water quality modelling. The submission of the ARC Linkage Project proposal on water quality has been delayed due to issues arising from the Covid-19 pandemic.

The current plan is to submit the first round next year. A draft proposal has been prepared and discussions with industry partners—WA Department of Water and Environmental Regulation, Qld Water Modelling Network, and possibly WaterNSW—are ongoing.

Paddock to Reef Program

The website below explains the relationship between the joint Reef 2050 Water Quality Improvement Plan management practice frameworks (water quality risk frameworks) and the Industry Best Management Practice (BMP) programs: https://www.reefplan.qld.gov.au/tracking-progress/reef-report-card/2017-2018/faqs#toc-19

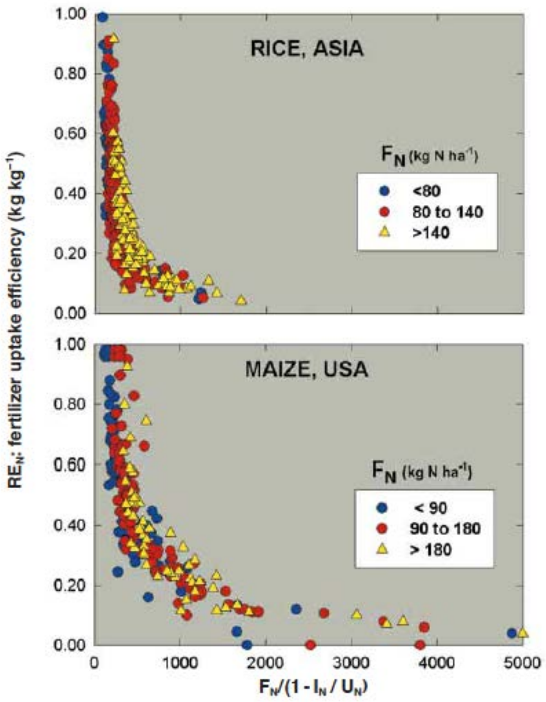
> *Progress towards the Reef 2050 Water Quality Improvement Plan management practice adoption target is reported using industry specific management practice frameworks (water quality risk frameworks). For sugarcane, horticulture and grains, practices are ranked from low risk (for innovative practices that pose the lowest water quality risk) to high risk (superseded practices that have the highest water quality risk). For grazing, they are ranked from very low soil erosion and water quality risk to moderate-to-high soil erosion and water quality risk. The frameworks allocate a percentage weighting to each practice, depending on its relative potential influence on off-farm water quality. They are based on evidence and backed by research.*
>
> *Industry BMP programs support individual landholders in assessing their own management and comparing it with commonly accepted industry standards. Under the industry BMPs, most practices that are described as 'at industry standard' align with moderate risk in the Reef 2050 Water Quality Improvement Plan risk framework. Practices that are 'above industry standard' generally align with the moderate–low or lowest risk in the framework. Over time, it is expected that the framework's best practices will become industry standard.*

Evidence around fertiliser take up

The following section presents some data on the efficiency of nitrogen uptake by crops, showing that estimated uptake of nitrogen from fertiliser applied to the field is on average between 20-50%. It can be lower or higher depending on environmental conditions and crops species.

Nitrogen use efficiency (NUE) has two main components: nitrogen (N) uptake efficiency (N harvested in crop/N applied to field) and nitrogen use efficiency (total crop yield/N applied to field). Nitrogen uptake efficiency is the ratio of nitrogen harvested in the tissue of the crop (e.g. per ha) compared to the soil nitrogen input (through fertilisers) into the same area. Some examples for these measurements are shown in figures below from Cassman et al. (2001).

Figure 5. Variation in nitrogen fertilizer uptake efficiency RE_N.



(RE_N: kg N fertilizer uptake kg^{-1} N applied) in relation to the degree of synchrony between crop N demand (U_N: in kg N ha^{-1} as measured by crop N accumulation in aboveground biomass at physiological maturity in N-fertilized plots) and the N supply from indigenous resources (I_N: in kg N ha^{-1} as measured by crop N uptake in control plots without applied N) and the amount of applied N fertilizer (F_N in kg N ha^{-1}). Smaller values on the abscissa indicate greater synchrony between N supply and demand. Data source for rice: C. Witt and A. Dobermann, On-Farm Monitoring Database, June 2000 release; IRRI, Los Banos, Philippines. Data source for maize: D. Walters, University of Nebraska; North Central Regional Research Project NC-218.

For Australian crops, nitrogen uptake efficiency varies depending on studies, with an example from Australian grain crops shown in the figure below (Angus and Grace, 2016). This study used ^{15}N-labelled fertiliser to trace its fate and found that, on average, 44% of applied N accumulate in the crop, 34% are retained in the soil and 22% are lost.

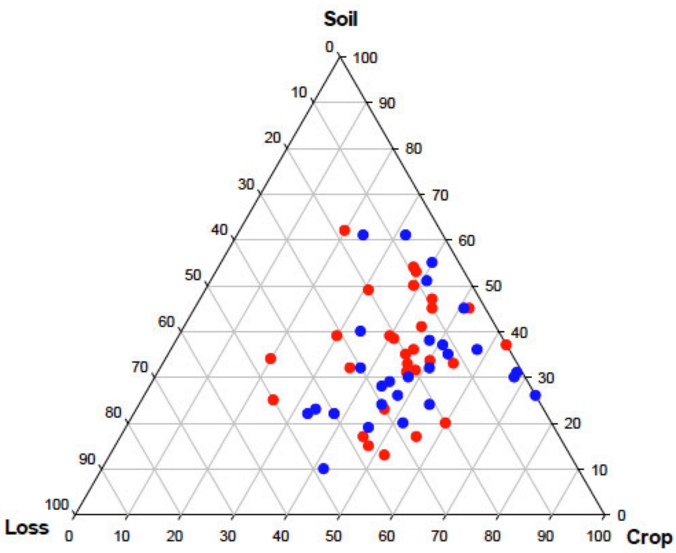


Fig. 2. Fate of ^{15}N fertiliser applied to Australian grain crops (red for duplex soils and blue for uniform clays). The ^{15}N was measured in above-ground plant parts and soil, both sampled at crop maturity. Unaccounted ^{15}N is reported as loss. The mean for all studies was 44% in crop, 34% in soil and 22% loss and there was little difference between duplex and clay soils. Data sources are Australian experiments reported by Pilbeam (1996) and Freney et al. (1992) and more recent studies by Lam et al. (2012), De Antoni et al. (2014), Bell et al. (2015), Harris et al. (2015), Schwenke and Haigh (2016) and Wallace et al. (2016).

In general, at low nitrogen application rates, the plant crop takes up a higher percentage of the nitrogen. The higher the nitrogen application per ha, the smaller the percentage that is taken up by the crop. In addition, this ratio depends on rainfall, temperature, presence of bacteria that convert different forms of N, soil properties, slope of terrain, the type of crop, presence of ground cover, intercropped plants or weeds (Lassaletta et al., 2014; Roy et al., 2006; Smil, 1999).

Nitrogen can be lost from the soil in a number of ways before plants take it up. (1) Organic N can be de-aminated into ammonia; ammonia can be converted to nitrate (by nitrifying bacteria), and nitrate is then easily leached from soil because of its high solubility. (2) Nitrate can be converted (by denitrifying soil bacteria) into nitrous oxide (volatile) or back into atmospheric nitrogen (Lassaletta et al., 2014; Smil, 1999).

We want to emphasize that the nitrogen uptake efficiency is clearly variable and measurements will have to be performed for specific areas, crops, soils and climate conditions to provide reliable estimates. There are ways to improve nitrogen use efficiency and nitrogen uptake efficiency though both management techniques, minimizing nitrogen fertiliser where economically viable, smart technologies for the targeted application of fertilisers, crop breeding efforts and use of nitrogen fixing bacteria that would increase the proportion of biologically fixed nitrogen (Swarbreck et al. 2019). Detailed recommendations for fertiliser use and estimates of N loss from the soil have been provided for the Australian sugarcane agriculture (Bell, 2014; Thorburn et al., 2017; Canegrowers, 2020).

Nitrogen-fixing bacteria

During the discussion about the use of nitrogen fixing bacteria, a question arose about nitrogen fixing bacteria that can improve nitrogen nutrition and yield of sugarcane. Here, we would like to provide some more background on this topic because we see this as a possible opportunity to further reduce the use of nitrogen fertiliser in agriculture, including the cultivation of sugarcane by partially replacing nitrogen fertiliser with biologically-fixed nitrogen.

The main points presented below are that:
(1) Nitrogen fixing bacteria can contribute nitrogen to plants from atmospheric nitrogen, this can save significant amounts of fertiliser if it is efficient.
(2) While the most efficient fixation of atmospheric nitrogen happens in legumes that form a symbiosis with rhizobia bacteria, a less efficient association exists between free-living nitrogen fixing bacteria and non-legumes like sugarcane.
(3) While current efficiency of nitrogen fixation in sugarcane is low, and use of nitrogen fixing bacteria in sugarcane not practiced in Australia, it could be a future opportunity to enhance plant growth and reduce nitrogen fertiliser with some rigorous research.

What is biological nitrogen fixation?
Plants require nitrogen from the soil, which is taken up mainly in the form of soluble forms of nitrogen like nitrate or ammonia. Input of soluble nitrogen into the soil is either via nitrogen fertilisers (the majority in agricultural systems), via lightning strikes that fix some of the atmospheric nitrogen into nitrate (small contribution), or through biological nitrogen fixation (Herridge et al., 2008). Only certain bacteria can convert atmospheric nitrogen into a soluble form (ammonia), which is then taken up by plants. This process is called biological nitrogen fixation. Some of these bacteria are free-living in the soil, some live in association with plants. Agronomically the most important group of nitrogen-fixing bacteria are rhizobia, which form a symbiosis with legumes, such as peas and chickpea. Rhizobia inocula (preparations of bacteria to be applied to seeds or the field) are routinely used in agriculture to improve legume nitrogen nutrition and reduce fertiliser application (Herridge et al., 2008) and Australia has a very successful practice in inoculation of legumes (Drew et al., 2019).

Benefits of symbiotic biological nitrogen fixation
Measurements of the contribution of biological nitrogen fixation in legumes have estimated that approximately 20-75% of legume nitrogen is derived from the atmosphere. This percentage varies from low values if N fertiliser is applied to the field, or in the presence of inefficient rhizobia, while it can also go up to >80% of total plant nitrogen under low nitrogen conditions with effective strains (Herridge et al., 2008). The following tables give an overview of the value of symbiotic nitrogen fixation in legumes in Australia, estimated to save Australian farmers ~$4.3 billion per year (Tables from Drew et al., 2019).

TABLE 6.1 Annual contribution of symbiotically (legume) fixed nitrogen.	Globally	Australia
Amount N fixed (million tonnes)	40	2.7
N fertiliser equivalent (million tonnes)	50	3.4
Economic value (billion dollars)	63	4.3

TABLE 6.2 Estimates of the amounts of N fixed annually by crop legumes in Australia.

Legume	% N fixed	Shoot dry matter (t/ha)	Shoot N (kg/ ha)	Root N (kg/ha)	Total crop N (kg/ ha)	Total N fixed[1] (kg/ha)
Lupin	75	5.0	125	51	176	130
Pea	66	4.8	115	47	162	105
Faba bean	65	4.3	122	50	172	110
Lentil	60	2.6	68	28	96	58
Soybean	48	10.8	250	123	373	180
Chickpea	41	5.0	85	85	170	70
Peanut	36	6.8	190	78	268	95
Mungbean	31	3.5	77	32	109	34
Navy bean	20	4.2	105	43	148	30

1 Total N fixed = per cent N fixed x total crop N; Data sourced primarily from Unkovich et al. 2010.

Legumes also provide effective improvement of yield of non-legumes when grown in rotation, as is often done in Australia. As an example, the benefits of rotating chickpea with wheat is shown in the table below, from Drew et al. (2019).

TABLE 6.10 Simple gross margin analysis of the N and yield benefits of a chickpea-wheat rotation compared with unfertilised or N-fertilised wheat-only sequences

	Chickpea/wheat (0 N)	Wheat (0 N)/ wheat (0 N)	Wheat (100 kg/ ha N)/wheat (0 N)
Year 1	Chickpea	Wheat	Wheat
Grain yield (t/ha)	2.3	2.3	3.2
Grain ($)[1]	920	575	800
Cost of production ($)[2]	465	270	400
Gross margin ($)	455	305	400
Year 2 (wheat only)	Wheat	Wheat	Wheat
Grain yield (t/ha)	2.8	1.7	1.8
Grain ($)	700	425	450
Cost of production ($)	270	270	270
Gross margin ($)	430	155	180
2-year gross margin ($)	885	460	580

Yields taken from Table 6.5 and are the means of no-tillage and cultivated treatments at two sites in northern NSW (source: unpublished data of WL Felton, H Marcellos, DF Herridge and GD Schwenke).
1 Chickpea at $400/t; wheat at $250/t; 2 NSW DPI figures

Rotations of legumes with sugarcane also provide additional soil nitrogen, potential yield benefits and protection from pathogens, e.g.
http://www.pulseaus.com.au/blog/post/sugarcane-fallow-options

https://www.farmonline.com.au/story/3609834/legume-rotation-benefits-cane/

https://grdc.com.au/resources-and-publications/groundcover/ground-cover-supplements/ground-cover-issue-86-collaboration-supplement/grain-legume-break-for-sugarcane

Benefit of nitrogen fixation by non-symbiotic bacteria associating with non-legumes
Some non-symbiotic nitrogen-fixing bacteria are also important as they associate with a number of non-legume species and can contribute fixed nitrogen to the plant (e.g. Franche et al., 2009; James and Olivares, 1998; James, 2000). These associations are not as efficient as the legume-rhizobia interactions but still can provide significant nitrogen inputs under the right conditions, most notably in tropical environments (Unkovich and Baldock, 2008). The most effective enhancement of nitrogen content in non-legumes through the use of nitrogen fixing bacteria has been reported in sugarcane with increases in N content of around 10-40% (e.g. Martins et al., 2020), but this depends on sugarcane cultivar, soil conditions and location. In addition, some of these bacteria are plant growth promoting, partly through nitrogen fixation and partly through their ability to enhance root growth and therefore indirectly enhance the capacity of plants to take up nutrients (Dobbelaere et al., 2003). Yield benefits of the use of these bacteria as inoculants for non-legume crops have been measured as up to 14-29% in corn, 14-31% in wheat (Sanchez Santos et al., 2019), and usually <10% in sugarcane in Brazil (de Oliveira et al., 2003, 2006; Martins et al., 2020).

Several species of nitrogen-fixing bacteria (e.g. *Azospirillum*, *Azetobacter* [*Gluconacetobacter*], *Beijerinckia*, *Burkholderia, Herbaspirillum*) have been found in association with sugarcane (Boddey, 1995; Martin et al., 2020). These and other bacteria are commonly used to enhance crop production and reduce fertiliser use in South America, where more than 100 products based on these bacteria have been commercialised by >70 companies and are used on various crops, including wheat, corn, soybean, cotton and rice (Cassan et al., 2020). Several of these species are being successfully used in Brazil for the inoculation and growth-promotion of sugarcane (Baldani et al., 2002). Some of their growth-promoting effects are likely due to biological nitrogen fixation inside stems of sugarcane (Martin et al., 2020; Otto et al., 2016) fertiliser. However, it is important to stress that nitrogen fixing bacteria do not fix nitrogen well if there is sufficient nitrogen in the environment, i.e. the effects of these bacteria are only seen in fields that receive low nitrogen fertiliser levels, and their contribution to nitrogen fixation in non-legumes requires rigorous controls (e.g. James, 2000; de Oliveira et al., 2003; Unkovich et al., 2020).

The figure below (Thornton et al., 2017) shows that Brazil achieves high sugarcane yields with low N fertiliser input. This has been at least in part achieved by replacing N fertiliser with the use of nitrogen-fixing bacteria (Baldani et al., 2002; Boddey et al., 1995; 2001). In comparison, Australia uses higher average N fertiliser inputs with lower nitrogen use efficiency than Brazil. However, this is also likely the result of different soil types, climate, terrain, sugarcane cultivars and management practices in both countries.

Data on NUE in the Australian Sugarcane industry (Thorburn et al., 2017) shows the relationship between N application and cane yield (in this figure, NUE is defines as yield cane/N application rate).

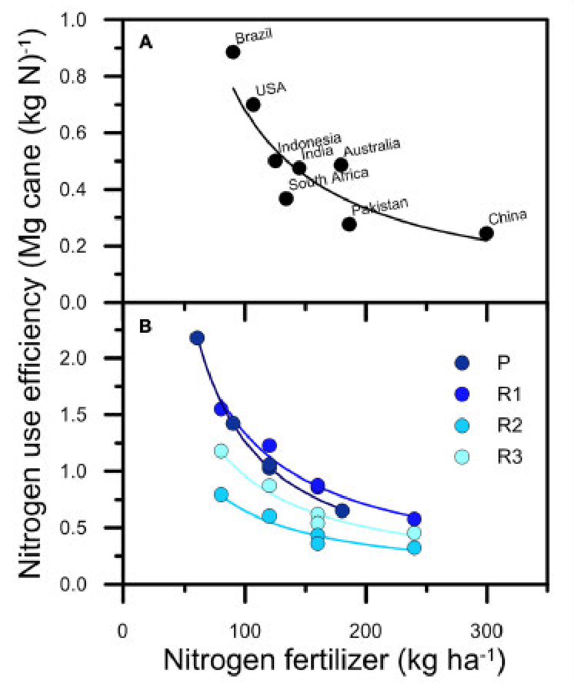


FIGURE 1 | Nitrogen use efficiency of sugarcane production in **(A)** eight countries and **(B)** four crops [plant (P) and three ratoons (R1–R3)] in an Australian field experiment. In **(A)**, the results are averages derived from data on total production sugarcane production and nitrogen applied (Robinson et al., 2011). The results in **(B)** were derived from data given by Thorburn et al. (2003b).

Figure from Thorburn et al. (2017). NB: Recommended N fertiliser amounts for sugarcane in Australia varies between sites but averages 140-200 kg/ha; Bell et al., 2014).

Use of nitrogen fixing bacteria in sugarcane in Australia
In Australia, there has not been, to our knowledge, a history of inoculating sugarcane with nitrogen-fixing bacteria to improve nitrogen nutrition nor was evidence of sustained nitrogen fixation found in sugarcane inoculated with a species of *Gluconacetobacter* that was shown to be beneficial in Brazil (Walsh et al., 2006). Similarly, Biggs and colleagues (2002) did not find evidence for sustained contribution of biological nitrogen fixation in Australian sugarcane. Unkovich and Baldock (2008) concluded 'On balance we would concur with the authors of several earlier global reviews of this topic and conclude that (in Australia) contributions of nitrogen to crop growth from asymbiotic N_2 fixation are likely to be <10 kg N ha^{-1} y^{-1} and generally not of agronomic significance under low rainfall conditions. In tropical environments where higher rainfall and temperatures coincide, rates are likely to be greater if soil mineral N is low and carbon substrates are available for N_2 fixing microorganisms. If asymbiotic N_2 fixation is to be encouraged or profitably managed, there is a need for more reliable field measurement and a combination of methodologies including ^{15}N might provide more definitive quantitative indications.'

One likely reason for the lack of success in using associative nitrogen fixing bacteria in Australia is that their effectiveness is not as reliable as the use of nitrogen fertiliser. Because of the relatively affordable cost of nitrogen fertiliser in Australia, and because of the more predictable success of using fertiliser compared to nitrogen-fixing bacteria, farmers likely are using fertiliser at levels that would inhibit the activity of nitrogen-fixing bacteria. In fact, nitrogen fertiliser use in the sugarcane industry in Australia is recommended at 140-200 kg N / ha (e.g. Bell, 2014). Estimations in Brazil have concluded that nitrogen addition to sugarcane fields at approximately 30-60 kg/ha for the first crop and 80-140 for ratoon crop subsequently (Martins et al. 2020) are conducive to successful use of nitrogen-fixing bacteria.

Opportunities for increasing the benefit of nitrogen fixing bacteria in the Australia sugarcane industry
There are Australian companies, for example New Edge Microbials (https://microbials.com.au/products/), which supply bacteria that improve the growth of non-legumes. This includes Azospirillum, one of the free-living,

nitrogen-fixing bacteria that could be used on sugarcane. Combinations of Azospirillum with other growth promoting bacteria may be even more beneficial.

It is possible that the use of nitrogen-fixing bacteria could be successful for sugarcane in Australia. This would require testing some of the successfully used strains of nitrogen-fixing bacteria that have been used in Brazil (de Oliveira et al., 2003; 2006), or the selection of effective strains present in Australian soils and currently present inside sugarcane cultivars. Their use would have to be strictly combined with very much reduced use of nitrogen fertiliser to prevent inhibition of biological nitrogen fixation at high nitrogen concentration. Famers would have to accept that effectiveness of these bacteria is more variable than fertiliser use, but this could be offset by reduced expense for fertiliser. The cost of inoculation with bacteria is significantly less than use of fertiliser (e.g. inoculating legumes with rhizobia in Australia has an estimated cost of $5/ha; https://www.dpi.nsw.gov.au/agriculture/soils/australian-inoculants-research-group) and would not result in nutrient run-off, as all the nitrogen is used directly by the plant. If there were sufficient monetary incentives for reduction of run-off, this might be a viable option.

It is also worth mentioning that the use of nitrogen-fixing bacteria can be extended to enhanced growth of micro algae for biotechnological applications, for remediation of contaminated soils and recovery of eroded soils (Cassan et al., 2020). This could add value to other efforts in minimising nutrient run-off.

The main recommendation would be to conduct rigorous, repeatable research to test the viability of using (mixtures of) nitrogen-fixing and other plant growth-promoting bacteria in Australian soils in the sugarcane growing regions under different climate and management scenarios.

Response to Senator Rennick's Questions

The Great Barrier Reef is composed of a number of different ecosystems. The inshore zone of the Great Barrier Reef includes coral reefs (composed of many reef organisms including, but NOT limited to, calcareous hard corals), mangroves and seagrass beds.

It is not possible to consider the health of the Great Barrier Reef without considering the health of these interconnected ecosystems - all of which may be impacted to varying degrees by elevated levels of sediments, nutrients and other contaminants that can be exacerbated by human activity, see review papers attached.

These ecosystems are home to many organisms that would also be pertinent to the questions detailed below: coralline algae (required for hard coral larval recruitment), mangroves, seagrass, turtles, dugongs, seabirds, shore birds, fish, sharks, rays. We recommend further reading e.g. the Great Barrier Reef Outlook Report 2019, which can be found here: http://elibrary.gbrmpa.gov.au/jspui/bitstream/11017/3474/10/Outlook-Report-2019-FINAL.pdf

As the questions we received focused primarily on the role of agricultural runoff on one taxonomic group (hard corals) the following responses are limited to that aspect only. We would however recommend consideration of the many other species of organisms and ecosystems in any decision making. Furthermore, given the interconnected nature of the greater terrestrial - aquatic ecosystem in central and northern Queensland we would view treating components in isolation as not being best practice.

As the questions are interrelated we have grouped our responses and used high quality, peer reviewed, published science to evidence our responses.

Unnatural levels of terrestrial runoff on to reef: A huge dump of sediment in the context we described is related to unnaturally high levels of sediment running off the land into the adjacent coastal environment. This is typically associated with landscape changes and loss of natural vegetation (e.g. land clearance, development) which can result in soil erosion and the runoff of other contaminants associated with the land use that the remaining vegetation cannot retain. This impacts marine water quality, sediment quality and the ecosystems and organisms that live, feed and reproduce there. These impacts can be acute (short but extreme) or chronic (occurring over long periods of time) depending on the system and event. This is a problem that is seen around the world. As evidence, we recommend the Committee read review papers on sediment impacts:

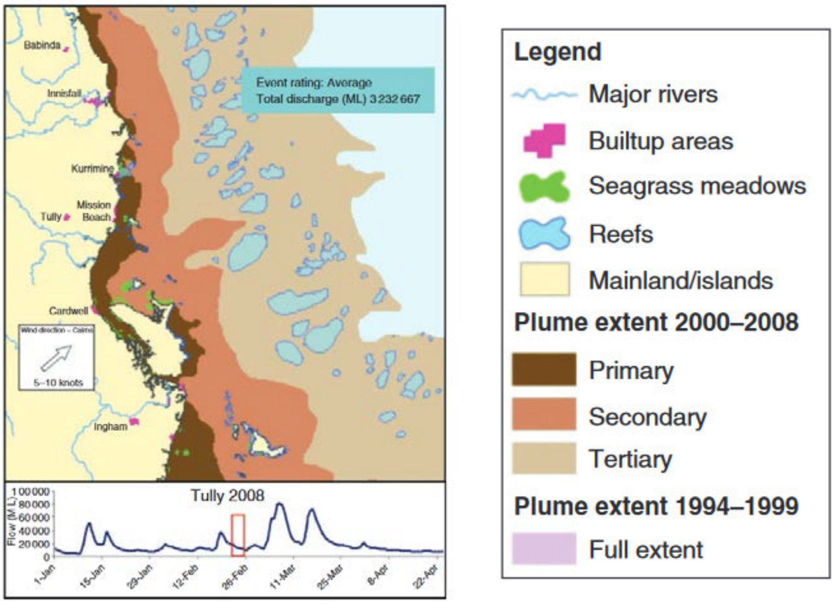
- Bainbridge, Z., S. Lewis, R. Bartley, K. Fabricius, C. Collier, J. Waterhouse, et al. 2018. Fine sediment and particulate organic matter: A review and case study on ridge-to-reef transport, transformations, fates, and impacts on marine ecosystems. Marine Pollution Bulletin 135: 1205-1220. doi:https://doi.org/10.1016/j.marpolbul.2018.08.002.
- Bartley, R., Z.T. Bainbridge, S.E. Lewis, F.J. Kroon, S.N. Wilkinson, J.E. Brodie, et al. 2014. Relating sediment impacts on coral reefs to watershed sources, processes and management: A review. Science of The Total Environment 468-469: 1138-1153. doi:https://doi.org/10.1016/j.scitotenv.2013.09.030.
- Erftemeijer, P.L.A., B. Riegl, B.W. Hoeksema and P.A. Todd. 2012. Environmental impacts of dredging and other sediment disturbances on corals: A review. Marine Pollution Bulletin 64: 1737-1765.
- Fabricius, K. 2005. Effects of terrestrial runoff on the ecology of corals and coral reefs: a review and synthesis. Marine Pollution Bulletin 50: 125-146.
- Risk, M.J. 2014. Assessing the effects of sediments and nutrients on coral reefs. Current Opinion in Environmental Sustainability 7: 108-117. doi:http://dx.doi.org/10.1016/j.cosust.2014.01.003.

Does catchment runoff only impact the nearshore Great Barrier Reef?

No—it can extend to the Coral Sea. River plumes (and the terrestrial contaminants associated with it) can reach the outer reef. For example, during some events, the maximum area influenced by the Tully River flood plumes extended into the Coral Sea. See (full paper attached):

Source: Devlin, M. and B. Schaffelke. 2009. Spatial extent of riverine flood plumes and exposure of marine ecosystems in the Tully coastal region, Great Barrier Reef. Marine and Freshwater Research 60: 1109-1122. doi:10.1071/mf08343.

Also, the impacts to the outer reef may be indirect, due to changes in the coastal, estuarine and inner reef ecosystems. For example, marine species that can be found in mangroves include birds, crabs, prawns, fish, dolphins and reptiles such as sea turtles.



The above image gives an example of plume extent stretching across the Great Barrier Reef from the Tully River in the wet tropics (source Devlin and Schaffelke 2009).

Does catchment runoff affect the (hard) corals? Is there a link between catchment-river runoff and reef contaminants? Using evidence from long-lived coral cores.

Yes, coral cores clearly capture how changing land use has resulted in increased sediment and nutrient loads on the reef. Coral cannot move, they calcify in one location on the reef. Their skeletons reflect the water quality that they grow in. *Porities* (massive corals) corals can live for hundreds of years and can provide a record of site-specific water quality.

Please see the following Great Barrier reef case studies from 1) the Burdekin which documents increased sediment on the reef in response to European settlement and 2) The Tully river, where fertiliser-P use is linked to river runoff and uptake by corals (seen in the skeletal records).

Both papers are attached:

- McCulloch, M., S. Fallon, T. Wyndham, E. Hendy, J. Lough and D. Barnes. 2003. Coral record of increased sediment flux to the inner Great Barrier Reef since European settlement. Nature 421: 727-730.
- Mallela, J., S. Lewis, E. and B. Croke. 2013. Coral skeletons provide historical records of phosphorus runoff on the Great Barrier Reef. PLoS ONE 8(3): e60010. doi:10.1371/journal.pone.0060010.

Coral Cores reflect river flood plumes and terrestrial sediment (Ba/Ca is a sediment proxy):

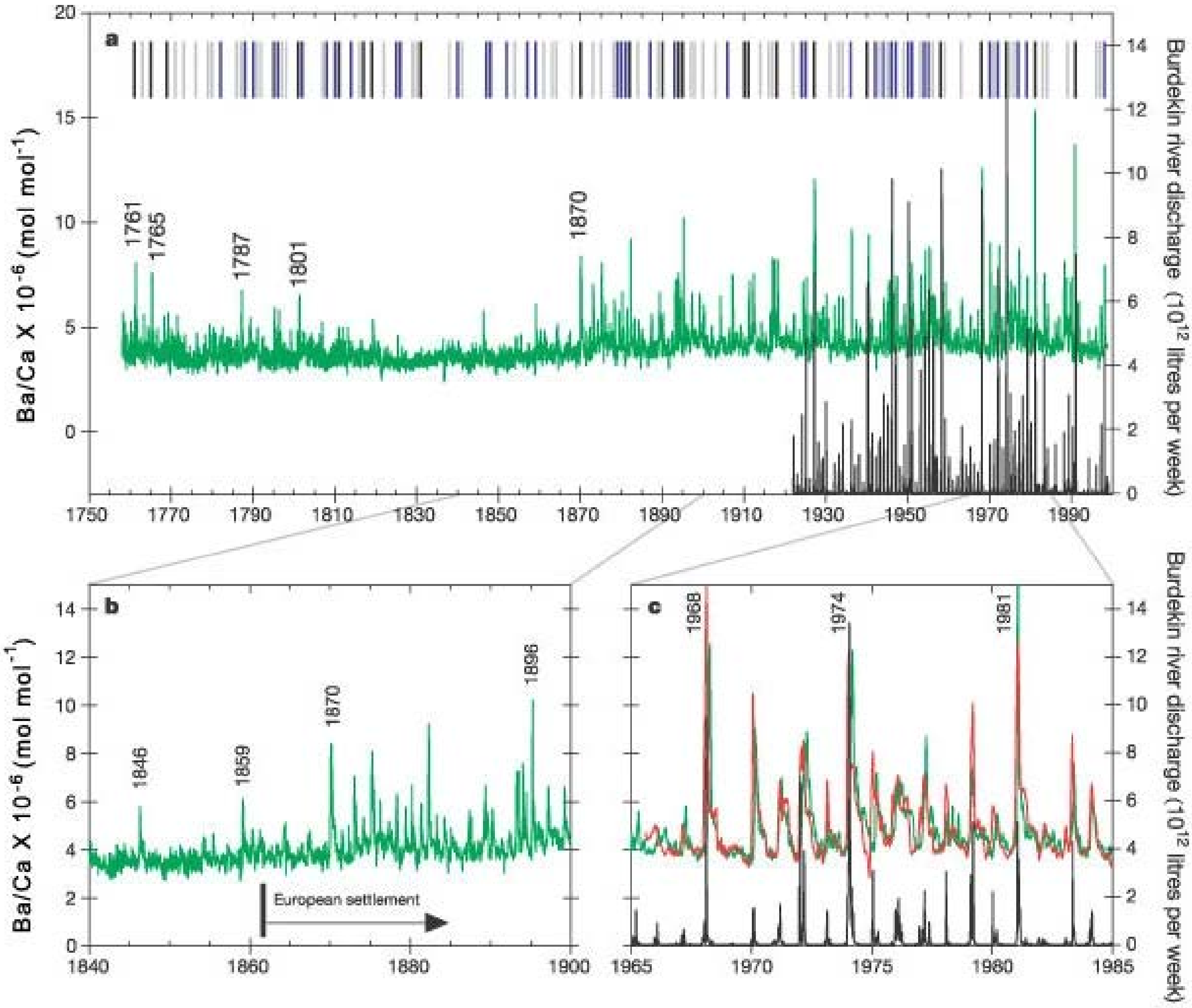


Figure 1 The Burdekin River: Barium provides a proxy for suspended sediments as it is desorbed from flood plume sediments21 and quantitatively partitioned into the corals, calcium carbonate skeleton22. a, Coral record from Havannah Reef (green line) for the period from 1760 to 1998 (Source McCulloch 2003, paper attached)

Coral cores from the Tully River capture sediment and fertiliser-P records:

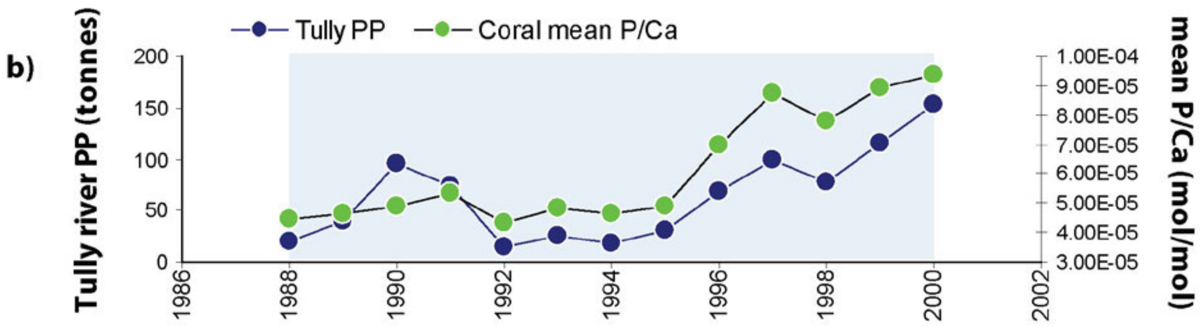


Figure 2 Particulate phosphorous (PP) in the Tully River and phosphorus levels in coral cores (P/Ca) from nearshore Dunk Island (Mallela et al 2013)

We also recommend the following book that gives an excellent overview and case studies on a river catchment and explains the first principals of sediment runoff and nutrient impacts on the Great Barrier Reef: Furnas, M. 2003. Catchments and corals: Terrestrial runoff to the Great Barrier Reef. Australian Institute of Marine Science.

We also recommend (attached): Risk, M.J. 2014. Assessing the effects of sediments and nutrients on coral reefs. Current Opinion in Environmental Sustainability 7: 108-117. doi: http://dx.doi.org/10.1016/j.cosust.2014.01.003.

We further recommend the Great Barrier Reef Outlook Report 2019, which can be found here: http://elibrary.gbrmpa.gov.au/jspui/bitstream/11017/3474/10/Outlook-Report-2019-FINAL.pdf and the scientific consensus statement: "Land use impacts on Great Barrier Reef water quality and ecosystem condition"

The evidence base supporting this consensus is provided in a series of four supporting chapters. The main conclusions were:

1. The decline of marine water quality associated with land-based run-off from the adjacent catchments is a major cause of the current poor state of many of the coastal and marine ecosystems of the Great Barrier Reef. Water quality improvement has an important role in ecosystem resilience.
2. The main source of the primary pollutants (nutrients, fine sediments and pesticides) from Great Barrier Reef catchments is diffuse source pollution from agriculture. These pollutants pose a risk to Great Barrier Reef coastal and marine ecosystems.
3. Progress towards the water quality targets has been slow and the present trajectory suggests these targets will not be met.
4. Greater effort to improve water quality is urgently required to progress substantial pollutant reductions using an expanded scope of tailored and innovative solutions. Climate change adaptation and mitigation, cumulative impact assessment for major projects and better policy coordination are also required to protect the Great Barrier Reef.
5. There is an urgent need for greater investment in voluntary practice change programs, the use of regulatory tools and other policy mechanisms to accelerate the adoption of practice change, and robust monitoring and evaluation programs to measure the rate and effectiveness of adoption.
6. Strengthened and more effective coordination of Australian and Queensland government policies and programs, further collaboration with farmers and other stakeholders, and strong evaluation systems are critical to the success of Great Barrier Reef water quality initiatives.
7. Priorities for reducing pollutant loads are now established at a catchment scale, based on the exposure of coastal and marine ecosystems to land-based pollutants, and should be used to guide investment.

8. A greater focus on experimentation, prioritisation and evaluation at different scales, coupled with the use of modelling and other approaches to understand future scenarios, could further improve water quality programs.

Yours sincerely

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