Support for improved quality control but misplaced criticism of GBR science reply to viewpoint “The need for a formalised system of Quality Control for environmental policy-science” by P. Larcombe and P. Ridd (Marine Pollution Bulletin 126:449–461, 2018)

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Viewpoint

Support for improved quality control but misplaced criticism of GBR science. Reply to viewpoint "The need for a formalised system of Quality Control for environmental policy-science" by P. Larcombe and P. Ridd (Marine Pollution Bulletin 126: 449–461, 2018)

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ABSTRACT

This is a response to the published Viewpoint by Larcombe and Ridd (2018). We agree with Larcombe and Ridd (2018) that scientific merit goes hand in hand with rigorous quality control. However, we are responding here to several points raised by Larcombe and Ridd (2018) which in our view were misrepresented. We describe the formal and effective science review, synthesis and advice processes that are in place for science supporting decision-making in the Great Barrier Reef. We also respond in detail to critiques of selected publications that were used by Larcombe and Ridd (2018) as a case study to illustrate shortcomings in science quality control. We provide evidence that their representation of the published research and arguments to support the statement that "many (…) conclusions are demonstrably incorrect" is based on misinterpretation, selective use of data and over-simplification, and also ignores formal responses to previously published critiques.

1. Introduction

Over the past years, shortfalls in the reproducibility of research results and other quality control criteria have been debated in the biomedical sciences, and this has led to constructive changes, e.g. in editorial procedures.[1] In their recent Viewpoint, Larcombe and Ridd (2018) argue that systemic failings occur in the quality control in environmental sciences, especially in what they call "policy-science", which they define as science used to inform government policy. In a case study, they examine nine journal publications selected from the extensive[2] literature on the condition of the Great Barrier Reef (GBR) and its responses to environmental and human pressures. The authors conclude that some of the GBR "policy-science" appears to be invalid, driven by an ideological agenda, and overstating the pressures and observed declines in ecosystem condition. Based on this, they question the effectiveness of quality control processes for research results that have informed policy.

We fully support the view that stringent quality control procedures are key to the responsible conduct of research, in particular the need for transparency, rigorous peer review, better and explicit representation of uncertainty, avoidance of over-simplification, and sharing of data and statistical code for analyses. We welcome critical assessment and re-appraisal of scientific publications as this is part of the scientific method. However, we contend that Larcombe and Ridd (2018) make a series of points that warrant rebuttal. First, we outline that for the GBR, formal and effective science review, synthesis and advice processes are

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[1] For example: https://www.nature.com/articles/nmeth.2471 (viewed 11 December 2017).

[2] A simple search in Web of Science (www.webofknowledge.com, accessed 10/12/2017) using the keywords 'Great Barrier Reef', 'impact', 'water quality', 'condition', 'decline' resulted in ca. 1000 publications during 2003–2013 (the same period selected in the case study of Larcombe and Ridd (2018).

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in place and do in fact support policy and decision makers. Second, we question the value and validity of Larcombe and Ridd's (2018) proposed concept of "policy-science", as it disregards the boundary that separates science and policy. And last, we comprehensively rebut their criticisms of the publications they believe underpin "*much government policy and spending*" on the GBR. We argue that their critiques demonstrate biases, misinterpretation, selective use of data and over-simplification, and also ignore previous responses to their already published claims. We acknowledge that Larcombe and Ridd (2018) is a "Viewpoint" rather than an original study. Nevertheless, scientists expect any article published in a scientific journal to pass the same stringent quality controls as those so strongly advocated in Larcombe and Ridd (2018).

2. Review and synthesis processes for GBR science

Understanding large, complex and interconnected ecosystems like the GBR is challenging. However, the knowledge base, including large-scale observational datasets, constantly evolves and advanced statistical and process models are increasingly developed and applied. Models, such as the new eReefs[3] suite of models, have improved the ability to e.g., predict system responses, analyse and attribute spatio-temporal changes, and include estimates of uncertainty.

Compared to many other tropical marine ecosystems, the GBR is relatively well studied, and its management and policies are supported by a comprehensive body of science, generally published in the peer-reviewed, international scientific literature. While we acknowledge that peer-review processes could be improved, it is our opinion and that of the French Academy of Sciences, the German Leopoldina and the UK Royal Society (Catlow, 2017) that peer review should remain the cornerstone of the evaluation of science quality.

Peer review by itself does not facilitate the use and application of research outcomes (Elliott et al., 2017). To regularly provide science updates to policy makers and GBR stakeholders such as Traditional Owners, industry sectors, and the broader community, publications are regularly[4] reviewed, synthesised and interpreted by scientists in collaboration with natural resource managers (most recent major syntheses: Great Barrier Reef Marine Park Authority, 2014a; Hairsine, 2017; Waterhouse et al., 2017). In addition, multidisciplinary groups of scientists are regularly requested to provide specific advice to policy makers (for example: Great Barrier Reef Water Science Taskforce, 2016).

The current overarching policy framework for the management of the Great Barrier Reef is the Reef 2050 Long-term Sustainability Plan (Commonwealth of Australia, 2015), which incorporates the Draft Reef 2050 Water Quality Improvement Plan (The State of Queensland, 2017) that was recently updated for the third time since its initial release in 2003 (The State of Queensland and Commonwealth of Australia, 2003). Core principles of these plans are adaptive management and decision-making based on best available science (Great Barrier Reef Marine Park Authority, 2014b, 2014c). The adaptive management strategies for the GBR, like for most other natural resources, includes the monitoring, reporting and assessment of the resource condition and of success or failure of adopted policies. An important component of this are various, peer-reviewed, annual report cards that synthesise observational and modelled data for ecosystem health and socio-economic indicators, extending from the upper catchment to the outer GBR.[5] Adaptive management and decision-making is also supported by several formal independent advisory bodies,[6] chaired by eminent Australians, providing publicly reported scientific advice by recognised experts in their field, review of developing policy and cross-sectoral stakeholder input.

Larcombe and Ridd's statement "*that there appears to be no effective mechanism of robust technical scrutiny of policy-science regarding the GBR*" does not reflect existing processes. Based on the above we argue that review and synthesis processes for GBR science are in line with good practices to provide science for evidence-based decision making (Elliott et al., 2017), including peer review, effective dissemination and fit-for-purpose interpretation.

3. Maintaining a distinction between science and policy

The concept of "policy-science" as proposed by Larcombe and Ridd (2018) is misleading. Scientific studies are, and should remain conducted and reviewed based on their scientific merit, not their policy relevance or conformation with current hypotheses, paradigms or policies. We argue that science that may be used to inform policies, guidelines and management decisions is no different from any other scientific research. Results of such studies are generally published in the international scientific literature, and the requirements for rigour in experimental design, execution, analysis, interpretation and peer review are exactly the same as for studies that may not inform policy. Larcombe and Ridd's argument might lead to indiscriminately questioning the rigour of any science that underpinned policies - such as research identifying man-made ozone-depleting substances (that led to their ban under the Montreal Protocol), research on the toxicology of pharmaceuticals and pesticides (e.g. that led to the ban of persistent organic pollutants under the Stockholm Convention), or research identifying the emission of greenhouse gases as the dominant cause of observed warming (that underpins the climate change policies of many nations, including the Paris agreement).

For the GBR, and elsewhere, the effective use of science in policy development and implementation is based on the consideration of multiple lines of evidence from a broad range of studies, whether carried out in response to an articulated policy-relevant knowledge gap or not. Scientific hypotheses and theories as well as regulations, legislation and policy are rarely, if ever, based on the findings of a single publication. The multiple-lines-of-evidence approach permits ALL relevant science to be used in setting policy.

Application of science in policy development benefits from timely access to information, synthesis and contextualisation of information and knowledge, including the interpretation of seemingly contradictory results, and from diverse expert advice. The challenge of managing complex ecosystems, such as the GBR, in a future of intensifying multiple and cumulative pressures, is often considered a "wicked problem" (e.g. Chapman, 2017); partly because it requires the resolution of "conflicting human wants or needs", but also because future states can only be predicted with high uncertainty. Resource management under these circumstances requires the integration of knowledge from social and biophysical science with socio-economic and cultural aspirations and political considerations (Chapman, 2017; Batie, 2008) - exactly what is in place for supporting the use, management and conservation of the GBR.

4. Clarifying some quality control issues

Very few scientists would argue with the call by Larcombe and Ridd (2018) to improve quality control procedures. But these authors make a series of points that warrant rebuttal. Larcombe and Ridd (2018) argue that a major failing of quality control procedures is that studies

[3] http://ereefs.org.au/ereefs, https://research.csiro.au/ereefs/.

[4] For a history of syntheses related to GBR water quality see: http://www.reefplan.qld.gov.au/about/history/.

[5] http://www.reefplan.qld.gov.au/measuring-success/report-cards/; http://healthyriverstoreef.org.au/report-card-results/; http://riverhealth.org.au/report_card/ehi/; http://ghhp.org.au/report-cards/2016.

[6] For example: Independent Expert Panel, Reef Advisory Committee: http://www.environment.gov.au/marine/gbr/reef2050/advisory-bodies; Independent Science Panel: http://www.reefplan.qld.gov.au/about/committees/science-panel/.

(footnote continued)

designed to replicate a publication's findings are "rarely funded". While this is true, direct replication is by no means the only method by which published results can be validated or refuted. Other, indirect methods include, e.g., empirical testing if findings apply in other locations or ecosystems; building upon the findings using additional data or data produced by different techniques; meta-analyses to test whether findings do or do not apply as widely as originally thought or interpretation needs refinement. Challenging accepted paradigms is important, however, only empirical research can provide new evidence that either confirms findings or supports alternative hypotheses. This is at the heart of the scientific method, the essence of which "*is to continually update, challenge, improve and refine, using as much evidence as possible*".[7]

Larcombe and Ridd (2018) state that there is little incentive for critical assessment of published works stating that "*such critiques have been largely ignored in the subsequent literature*". Given their sincere call to improve quality control processes in science it is interesting that nowhere in their 2018 Viewpoint do Larcombe and Ridd make it clear to readers that many of their criticisms of the nine GBR papers have been raised previously (i.e., Ridd, 2007; Ridd et al., 2011, 2013a, 2013b), and have been thoroughly addressed by the original authors (De'ath and Fabricius, 2011; De'ath et al., 2013; Kroon, 2013). To re-publish previous claims that have been addressed and refuted appears to be selecting information to support their statements and an example of the very issue Larcombe and Ridd (2018) are criticising.

Larcombe and Ridd (2018) argue that, due to the potential financial liabilities, research conducted by industry "*is likely*" to use more rigorous quality control procedures. This, however, does not seem supported by the fact that two fields of science where major credibility problems have arisen are medicine and biomedical science (Larcombe and Ridd, 2018 and references therein), both with a considerable proportion of industry-funded research.

5. Alleged flaws in the analyses and representation of the GBR case study

Larcombe and Ridd (2018) selected nine papers, published between 2003 and 2013, that they believe underpin "*much government policy and spending*" on the GBR. They further state that they have identified issues that "*appear to be of a gravity to completely invalidate some of the papers' stated conclusions*". They continue that "*although our analysis indicates that many of the above conclusions are demonstrably incorrect, the crucial question here is not whether the conclusions are right or wrong, but whether the suite of QC processes applied to the work were effective in ensuring that the findings were defensible. Here the answer is clearly in the negative.*" In our detailed responses to these criticisms (Appendix A) we refute their criticisms for seven of the more recent publications, and in doing so also show that the quality control procedures that are applied to the GBR science are appropriate and fit for purpose.

A large body of research on the condition of the GBR by many scientists from various organisations consistently shows that the GBR is under pressure from past and ongoing human activities, that the pressure varies regionally, and that the GBR still retains some level of resilience. Larcombe and Ridd (2018) consider the selected nine publications of their GBR case study to be motivated by an agenda; i.e. that "*These papers form part of a body of work that has built up substantial momentum over a decade or more, and their combined agenda is now effectively set in policy and spending frameworks*". The nine selected studies are part of a larger literature[2] – subsequent research has either corroborated the main findings or incrementally built on them to advance the understanding of the condition of GBR ecosystems and their responses to environmental and human pressures. The accumulated scientific knowledge of the various pressures on the GBR and the potential solutions have informed both policy and research investment, as they should.

Continuous improvements in the quality control of science are being made. The sharing of data and statistical code is now more common and is increasingly a requirement of many scientific journals and funding bodies. Many science organisations and large observational programs invest in the non-trivial task of providing and maintaining access to complex datasets.[8] This will enhance the reproducibility and transparency of research, and will also facilitate greater and more rapid scientific progress. This is important given the fast pace of change currently observed in the GBR (e.g. Hughes et al., 2017, 2018) and in other ecosystems, as pressures on the natural environment continue to intensify due to a growing human population, intensifying resource use and increasing concentrations of atmospheric carbon dioxide.

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Appendix A

Rebuttal of Larcombe and Ridd's (2018) criticism of recent influential publications on the GBR. We did not address the criticisms of the Pandolfi et al. (2003) and the Bellwood et al. (2004) papers here, not because we agree with their criticisms but we felt it more appropriate for the authors of these earlier studies to write such response.

Fabricius et al. (2013): Intra-annual variation in turbidity is related to terrestrial runoff on inner-shelf coral reefs of the Great Barrier Reef

Fabricius et al. (2013) use instrumental turbidity (water clarity) records from 14 reefs and show that GBR turbidity is significantly related to riverine inputs of fine sediment, bottom sediment resuspension, and bathymetry. They show that averaged over all 14 reefs, turbidity was 13% (range: 5–37%) greater in weeks with higher vs lower river discharges, and that turbidity remained increased for up to 250 days after floods on the more turbid inshore reefs. They also showed that within regions, turbidity was up to 10-fold higher on inshore reefs nearer a river mouth compared to those away from rivers.

Larcombe and Ridd's (2018) claim that "*using the figures they present, the increase appears to be no more than 1 NTU rise in turbidity for perhaps a few days of each year, so is very small indeed*" (p. 459). This is unsubstantiated – no evidence is provided about how they come to this conclusion. Moreover, two additional publications based on decadal time series of remote sensing-derived water clarity data have now been published and found similar relationships for the wider GBR (Fabricius et al., 2014, 2016; both not cited by Larcombe and Ridd, 2018). We conclude that the finding that GBR water turbidity is significantly related to riverine discharges holds and is further validated by more recent data.

De'ath et al. (2012): The 27-year decline (1985–2011) of coral cover on the Great Barrier Reef and its causes

De'ath et al. (2012) showed a 50% decline in coral cover on the GBR, and quantified the causes for this decline, attributing it to the combined effect of tropical cyclones, outbreaks of crown-of-thorns starfish and thermal coral bleaching. Larcombe and Ridd (2018) state that the impact of the extreme Tropical Cyclone (TC) Hamish in 2009 "*was not mentioned by De'ath et al. (2012)*" (p. 458), and that the circumstances leading to the reported decline in coral cover were due to

[7] Article by M. Grubb https://theconversation.com/were-climate-researchers-and-our-work-was-turned-into-fake-news-89999.

[8] For example: https://portal.aodn.org.au/; https://www.aims.gov.au/docs/data/data.html.

"special environmental conditions" from TC Hamish and TC Yasi in 2011.

In fact, De'ath et al. (2012) identified tropical cyclones as the major cause of coral loss in the GBR in their analysis, which included the detailed path, duration and strength of all 36 cyclones (including TC Hamish and TC Yasi) that affected the GBR during the observation period 1985–2011.

Larcombe and Ridd (2018) also summarised the De'ath et al. (2012) conclusion as "*Coral cover will fall to 5%–10% by 2022*" (p. 453). This statement is both incomplete and an over-simplification of the De'ath et al. (2012) study: the full sentence from the discussion in De'ath et al. (2012) reads "*Without significant changes to the rates of disturbance and coral growth, coral cover in the central and southern regions of the GBR is likely to decline to 5–10% by 2022*". Other sections in the De'ath et al. (2012) publication provide regionally explicit data on the effect sizes of the three forms of disturbance.

Coral cover trends, based on standardised survey methods by the long-term coral monitoring program of the Australian Institute of Marine Science, are now reported annually [1]. The significant decline in coral cover reported in De'ath et al. (2012) was followed by a period of recovery (2012 to 2016), due to an absence of disturbances that had driven the 50% decline, and fast growth rates of one type of corals – tabulate *Acropora* spp. that dominate early successional reefs in the central and southern GBR. Further significant loss in coral cover was observed in the northern and central GBR in 2016 and 2017 due to extreme temperature stress (Hughes et al., 2017) and a new population outbreak of crown-of-thorns starfish. Greater warming (Brown and Caldeira, 2017) and more extreme weather (Fischer and Knutti, 2015; Wang et al., 2017) are predicted globally. Coral abundance and recovery are expected to be adversely affected under the predicted future regime of chronic pressure and more frequent and severe disturbances (e.g. Cheal et al., 2017; Osborne et al., 2017).

Kroon (2012): Towards ecologically relevant targets for river pollutant loads to the Great Barrier Reef

Kroon (2012) provided first-order estimates of ecologically relevant targets for river pollutant loads for six regions in the GBR catchment. The study showed that to achieve GBR water quality guidelines for total suspended solids and chlorophyll concentrations, current mean annual loads of total suspended solids (TSS) and dissolved inorganic nitrogen (DIN) at end-of-catchment would have to be reduced by approximately 41% and 38%, respectively, with most reductions in the Wet Tropics and Burdekin regions.

Larcombe and Ridd (2018) simplified and misrepresented this study, by summarising its conclusions as "*Halving river-borne nutrient and sediment concentrations will halve concentrations of nutrient and sediments in the Great Barrier Reef waters*" (p. 453). Kroon (2012) does not make this specific conclusion. Larcombe and Ridd (2018) also state that "*the journal comment-and-reply process is stymied by lack of easy access to the original data*" (p. 453). While the data for Kroon (2012) were not made publicly available as part of the publication (e.g. through Supplementary Material), the data were always available upon request to the author or the CSIRO - Larcombe and Ridd never requested these data. Larcombe and Ridd (2018) only cite their own previous critique of Kroon (2012) (Ridd et al., 2013b), but not the subsequent response (Kroon, 2013) where their criticisms were comprehensively addressed. Finally, Kroon (2012) states upfront that exact estimates of targets were not the aim of that study, but rather that "*first-order estimates of river loads at end-of catchment are quantified for total suspended sediment (TSS) and dissolved inorganic nitrogen (DIN) that would achieve GBR water quality guidelines (i.e. sustainable loads)*", and that these "*sustainable loads are compared with the best estimates of current and pre-European river loads for TSS and DIN (Kroon et al., 2012), to highlight the approximate reductions in river loads required to protect GBR marine ecosystems from exposure to TSS and DIN*".

To calculate the first-order estimates of ecologically relevant targets for river pollutant loads, Kroon (2012) used published information on river pollutant loads (Kroon et al., 2012), marine monitoring data (De'ath and Fabricius, 2008), and GBR water quality guidelines (Great Barrier Reef Marine Park Authority, 2010). Subsequent studies have improved river pollutant load estimates (e.g. Bartley et al., 2017; Waters et al., 2014) and used Kroon's (2012) approach to achieve stepwise improvement of target setting and management prioritisation. This includes Water Quality Improvement Planning for four Natural Resource Management regions in the GBR (Brodie et al., 2014, 2015a, 2015b; Wooldridge et al., 2015). In addition, basin scale targets have now been set for all GBR river basins (Brodie et al., 2016, 2017a, 2017b) based on defined ecosystem outcomes using improved modelling capability such as the eReefs framework and more complete data sets. In conclusion, the main aim of Kroon (2012), to progress GBR science towards estimating targets for river pollutant loads that are ecologically relevant, has been achieved.

De'ath and Fabricius (2010): Evidence that water quality is an important driver of reef health

De'ath and Fabricius (2010) investigated how GBR indicators of reef health (macroalgae cover and coral species richness) were related to water clarity, water column chlorophyll, and spatial patterns. They demonstrated strong spatial variation in the indicators, and additionally also strong relationships between the indicators and water clarity and chlorophyll.

Larcombe and Ridd's (2018) critique of that study, which was already stated before in Ridd et al. (2011), is flawed, as outlined previously by De'ath and Fabricius (2011): the analyses were not based on a regional comparison between northern and southern sectors of the GBR, and hence did not "proverbially compare apples with oranges". Instead, De'ath and Fabricius (2010) show the effects of water quality and chlorophyll on these indicators as being additional to the spatial changes in the biota along latitudinal and cross-shelf gradients. Macroalgae and coral richness naturally decline with latitude away from the equator, and across the continental shelf, and these relationships were accounted for by adding the spatial predictors in the models. The flaws of this argument have already been explained in greater detail in a previous response (De'ath and Fabricius, 2011) to an earlier iteration of this critique (Ridd et al., 2011). Hence the conclusion by De'ath and Fabricius (2010) that minimizing pollution from agricultural runoff would reduce macroalgal cover and increase the taxonomic richness of hard corals and phototrophic octocorals holds.

De'ath et al. (2009): Evidence for declining coral calcification on the Great Barrier Reef

De'ath et al. (2009) report a significant 14.2% decline in the rate of calcification in massive *Porites* corals from 68 reefs spanning the entire GBR between 1990 and 2005. This decline was unprecedented for at least the previous 400 years for which calcification records existed.

Ridd et al. (2013a) pointed out an error in the original data set, as some outer-most bands in some corals were incompletely formed. De'ath et al. (2013) have subsequently corrected the rate of decline, from 14.2% in the 2009 study, to 11.4% [95% CI = (10.4, 12.4)]. This rate of decline is marginally reduced, yet it is still unprecedented. Larcombe and Ridd (2018) repeat the critique of Ridd et al. (2013a), but do not cite the responses and corrections (De'ath et al., 2013; also published in Science[9]), and continue to ignore the fact that there are is no evidence for ontogenetic changes in Porites growth rates.

We maintain that the initial finding of slowing of coral growth rates,

[9] Science (2013) Vol 342: p 559. Corrections and Clarifications to "Declining coral calcification on the Great Barrier Reef" by G. De'ath et al. (2 January 2009, p. 116).

possibly attributable to climate change, are valid and supported by other studies reporting similar responses for several other reef regions around the world, including the Caribbean, SE Asia and the eastern equatorial Pacific (reviewed in Lough and Cantin, 2014). A separate analysis of *Porites* growth records from seven reefs in the central GBR (D'Olivo et al., 2013) over a longer time period than in De'ath et al. (2009) shows a significant decline in calcification on three inshore reefs, and attributes this decline to river discharges. Calcification on four mid- and outer-shelf reefs increased over six decades, but decreased from 1990 to 2008 on midshelf reefs, which D'Olivo et al. (2013) interpret as an indication of recovery from a coral bleaching event in 1998. A subsequent study demonstrated how coral bleaching associated with major thermal stress events on the GBR suppressed coral calcification for four years, followed by recovery (Cantin and Lough, 2014) thus providing a mechanism of action to support the observed decreases.

Brodie et al. (2007), Fabricius et al. (2010): Nutrients from agricultural runoff are largely responsible for Crown-of-Thorns starfish plagues

Increased survivorship of crown-of-thorns starfish (CoTS) larvae in response to elevated availability of phytoplankton (indicated by elevated chlorophyll *a* concentrations) after extreme river discharges is recognised as a key mechanism that triggers outbreaks of CoTS, a significant coral predator (Uthicke et al., 2015; Mellin et al., 2017; Pratchett et al., 2017b, 2017a; Brodie et al., 2017c). This link was explored in (Fabricius et al., 2010), building on the descriptions of strong temporal, regional and cross-shelf patterns in chlorophyll *a* concentrations reported in (Brodie et al., 2007).

Larcombe and Ridd (2018) question results of data analyses in these two publications that show higher chlorophyll *a* concentrations in the inshore central GBR compared to the northern GBR, stating three reasons:

1. “rapid flushing must reduce system-wide long-term nutrient enhancement to very low levels.” (p. 455).
2. “river discharge of nutrients is only a very small component of the GBR nutrient cycle” (p. 456).
3. The location of regional chlorophyll monitoring transects biasing the chlorophyll data analysed in Brodie et al. (2007) and Fabricius et al. (2010).

Both Brodie et al. (2007) and Fabricius et al. (2010) analysed a large long-term dataset[10] of chlorophyll *a* concentrations from ~monthly water sampling within nine regional clusters (or transects) along the whole GBR. Brodie et al.'s (2007) analysis included data over the entire year, while Fabricius et al. (2010) analysed only summer data (November–March) from the long-term dataset. Relevant to Larcombe and Ridd's (2018) critique, both analyses showed that, averaged over all years in the long-term dataset, chlorophyll *a* concentrations in the inshore central region (south of 15°S or 16°S, respectively, to about 19°S) were about twice as high compared to the data from inshore waters in the more northern region. Offshore chlorophyll *a* concentrations were similar in both regions.

In questioning these observational results, Larcombe and Ridd (2018) quote short water retention times on the GBR shelf (Choukroun et al., 2010) but ignore evidence of long nutrient retention times (Brodie et al., 2012). A nutrient budget for the GBR (Furnas et al., 2011) showed that riverine inputs are the largest sources of new nutrients for the inner GBR lagoon during the summer wet season, and that nutrient recycling fluxes dominate in both wet and dry season and sustain productivity. While water may be rapidly exchanged between the GBR lagoon and the Coral Sea (Choukroun et al., 2010), dissolved inorganic nutrients discharged from rivers are rapidly assimilated by phytoplankton on time scales of days to weeks (Devlin and Brodie, 2005; Furnas et al., 2005, 2011). Higher concentrations of suspended sediments, nutrients as well as phytoplankton blooms, indicated by higher chlorophyll *a* concentrations, are generally observed following large river discharge events (e.g. Devlin et al., 2001; Devlin and Brodie, 2005; Devlin and Schaffelke, 2009; Devlin et al., 2012, 2013, 2015; Petus et al., 2016). The nutrients in the phytoplankton are being recycled and remain in the GBR lagoon for much longer periods than the water exchange rate suggest (Furnas et al., 2011; Brodie et al., 2012). Most of the suspended sediment and associated particulate nutrients from river inputs initially remain in the inshore zones, with only a small proportion transported further into the lagoon zone (Furnas et al., 2011). However, turbidity (as a proxy for particulate nutrients and suspended sediments) is strongly related to river discharges in the region where crown-of-thorns starfish (CoTS) outbreaks originate, and remains elevated in the GBR for 4–8 months after major river floods (Fabricius et al., 2016). Nitrogen removal from the GBR lagoon is mainly via denitrification from sediments although some flushing to the Coral Sea can occur after mineralization in the sediment and release to the water column (Alongi and McKinnon, 2005; Alongi et al., 2007; Furnas et al., 2011). Phosphorus is removed from the water column by burial (Monbet et al., 2007). Sediment-associated nutrients can become available again during major resuspension events, e.g. storms and tropical cyclones, again leading to phytoplankton blooms (Furnas, 1989). It is also known that only a small proportion of the fine sediment (and the associated particulate nutrients) discharged from GBR rivers is ever exported to the Coral Sea (Francis et al., 2007), the rest remains in the GBR lagoon, mostly within the inner-shelf (Lewis et al., 2014b).

Larcombe and Ridd's (2018) re-drawing (Fig. 5 on p. 457) of the measured chlorophyll levels from Brodie et al. (2007) shows that inshore and offshore chlorophyll *a* concentrations at the northern sampling sites are similar to offshore data from the central GBR sampling sites, but lower than inshore chlorophyll *a* concentrations in the central region, a finding clearly presented in Brodie et al. (2007). Because shelf-width is different between the region, which Larcombe and Ridd (2018) rightly point out, Brodie et al. (2007) and Fabricius et al. (2010) chose to use for their graphical representation a relative ‘distance across the shelf’ scale to allow more meaningful comparisons between regions. For example, inshore sites in the northern regions are located in comparable water depth regardless of their actual distance to the Coral Sea. Larcombe and Ridd (2018) highlight faster flushing times due to the narrow shelf in the northern region. We suggest that this is one of the reasons why there is only a small cross-shelf gradient in chlorophyll *a* concentration, in addition to different inputs (as described above).

The sampling program which data were analysed in Brodie et al. (2007) and Fabricius et al. (2010) was conducted from 1992 to 2008 and is still the most comprehensive dataset of broad-scale chlorophyll *a* data. As with any in situ monitoring, the spatial representativeness may be limited by the location of sampling sites. Modelled water quality data (incl. chlorophyll *a* concentrations) have recently become available. These provide additional evidence of increased chlorophyll concentrations in the GBR lagoon following river discharge events and of chlorophyll *a* concentrations considerably higher than they would have been before catchment development occurred from about 1850 (Baird et al., 2016; Brodie et al., 2017a, 2017b; Walshe et al., 2017).

It is also important to note that only in the latitudes between Lizard Island and Townsville are the mid-shelf reefal areas of the GBR exposed regularly (almost annually) to enhanced nutrient loading from rivers with increased amounts of DIN discharge associated with sugarcane and banana cultivation fertiliser use (Brodie et al., 2005; Brodie et al., 2017c) and that this increased DIN loading has been in place only since about 1950 (Lewis et al., 2014a). These are the areas where CoTS outbreaks occur in the central GBR.

[10] Data are available upon request via https://apps.aims.gov.au/metadata/view/eb16c150-c7b4-11dc-b99b-00008a07204e.

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