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Viewpoint

The need for a formalised system of Quality Control for environmental policy-science

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ABSTRACT

Research science used to inform public policy decisions, herein defined as "Policy-Science", is rarely subjected to rigorous checking, testing and replication. Studies of biomedical and other sciences indicate that a considerable fraction of published peer-reviewed scientific literature, perhaps half, has significant flaws. To demonstrate the potential failings of the present approaches to scientific Quality Control (QC), we describe examples of science associated with perceived threats to the Great Barrier Reef (GBR), Australia. There appears a serious risk of efforts to improve the health of the GBR being directed inefficiently and/or away from the more serious threats. We suggest the need for a new organisation to undertake quality reviews and audits of important scientific results that underpin government spending decisions on the environment. Logically, such a body could also examine policy science in other key areas where governments rely heavily upon scientific results, such as education, health and criminology.

1. Introduction

Since the early beginnings of Science in the time of the ancient Greeks, the scientific method has completely revolutionized human existence and almost always for the better. Science has progressed by constant checking, replication, argument and improvement. In some areas of science, such as Newton's Laws of Motion, checks are effectively done billions of times every day when people fly in a plane, drive a car or walk across a bridge. Newton's Laws of Motion are so well tested, checked and replicated that we stake our lives on them. But most science is not massively validated in this way and is thus not as reliable. Here we focus on the extent to which policy-science is checked, tested and replicated, and we define the term "policy-science" to mean all science used as the basis for making expensive or important decisions by governments to make and deliver their policies. Note that "policy-science" as defined here does not refer to the science of making good policy, but rather the science upon which particular policies are to be based. So, we join these words together for convenience only, and emphasise that good science is different and clearly distinct from policy-making processes and the resulting policy itself. The connections between science and policy are complex. Although science forms only one of the wide range of inputs to policy-making (e.g. Fig. 1), a policy is likely to be worse if the science is itself less than credible and defensible. Scientists play the key role of ensuring that this input is objective and of the highest quality, so that policy-makers and politicians alike can be best informed of the scope and strength of the knowledge and also, importantly, of the key uncertainties (Rutter and Gold, 2015). Recent examination of policy proposals in the UK indicate that there is a deal of work left to do before it is clear exactly how Government policy has used science and evidence in policy formulation (Sense About Science, 2016).

Policy-science is also in a different category to the science which may ultimately be used by commercial companies for industrial applications, where it is up to the company to determine and test its reliability, because the company is taking the risk. Thus, the critical distinction between policy-science and the rest of science is the active use by government, often to make expensive and important decisions on behalf of the public. It is therefore vital to understand what measures governments take to make sure they are basing decisions on well tested, checked, replicated, sound science, and in our case, the environmental sciences.

One of the motivations for this work has been the revelations from other parts of the scientific literature that there may be major systemic failing in science Quality Assurance (Ioannidis, 2005, 2014). (To clarify the terminology, in quality management terms, the term Quality Control (QC) is used to verify the quality of the output, through inspection

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Fig. 1. A graphic illustrating 22 factors that can influence the decisions taken by UK government ministers (after Larcombe, 2007).

and testing, whereas Quality Assurance (QA) is the process of managing for quality. In the ISO 9000 standard (ISO, 2005), clause 3.2.10 defines Quality Control as: "A part of quality management focused on fulfilling quality requirements" and Clause 3.2.11 defines Quality Assurance as: "A part of quality management focused on providing confidence that quality requirements will be fulfilled".) Perhaps the most high-profile example of systemic failure comes from the biomedical sciences, where checks made on peer-reviewed science indicate that a large number of important papers are found to be wrong. Prinz et al. (2011) of the German drug company Bayer, writing in the journal 'Nature Reviews Drug Discovery' claimed that 75% of the literature used for potential drug discovery targets is unreliable. This issue has come to some international prominence:

> "*A rule of thumb among biotechnology venture-capitalists is that half of published research cannot be replicated. Even that may be optimistic. Last year researchers at one biotech firm, Amgen, found they could reproduce just six of 53 "landmark" studies in cancer research.*"
>
> (The Economist, 19/10/2013)

Other authors have reported the frequency of irreproducibility at around 50% (Hartshorne and Schachner, 2012; Vasilevsky et al., 2013). It has also been suggested that false or exaggerated findings in the literature are partly responsible for up to 85% of research funding resources being wasted (Chalmers and Glasziou, 2009; Ioannidis, 2014; Macleod et al., 2014). Despite replication studies being fundamental to establishing science reliability, such studies are rarely funded, and are not generally seen as a way of advancing a scientific career (Ioannidis, 2014).

A concern over reproducibility is shared by some editors of major journals. Marcia Angell, a former editor of the New England Journal of Medicine, stated

> "*It is simply no longer possible to believe much of the clinical research that is published, or to rely on the judgment of trusted physicians or authoritative medical guidelines. I take no pleasure in this conclusion, which I reached slowly and reluctantly over my two decades as an editor of The New England Journal of Medicine.*"
>
> (Angell, 2009)

The editor of *The Lancet* stated that

> "*The case against science is straightforward: much of the scientific literature, perhaps half, may simply be untrue. Afflicted by studies with small sample sizes, tiny effects, invalid exploratory analyses, and flagrant conflicts of interest, together with an obsession for pursuing fashionable trends of dubious importance, science has taken a turn towards darkness.*"
>
> (Horton, 2015)

The financial costs of irreproducible biomedical research are significant. Freedman et al. (2015) estimated that the cumulative prevalence of irreproducible preclinical research exceeds 50%, which in the United States alone, results in approximately US$28 billion per annum spent on research that is not reproducible. Similar concerns about QC occur in other areas, and in particular psychology, where there is

> "*growing concern regarding the replicability of findings in psychology, including a mounting number of prominent findings that have failed to replicate via high-powered independent replication attempts.*"
>
> (LeBel, 2015)

In introducing a special edition on "Replicability in Psychological Science: A Crisis of Confidence", the editors ask the question

> "*is there currently a crisis of confidence in psychological science reflecting an unprecedented level of doubt among practitioners about the reliability of research findings in the field?*"
>
> (Pashler and Wagenmakers, 2012; see also Wagenmakers et al., 2012)

and answer themselves in the affirmative, warning that

> "*Research findings that do not replicate are worse than fairy tales; with fairy tales the reader is at least aware that the work is fictional.*"

Doubts about the validity of published literature have also spread to research in special education, where problems with replication are also evident. Cook (2014) specifically notes the problems in bio-medical science and psychology, and asked whether similar issues would be evident in educational research, concluding that

> "*To avoid leaving policy makers and practitioners between a rock (making decisions without empirical evidence) and a hard place (making*

decisions based on invalid research), *the special education research community should systematically examine the degree to which research in the field is unreplicated, biased, or both*".

Whilst it might be hoped that problems of experiment replication and bias are confined to the bio-medical, psychology and education fields of research,the evidence is that such a hope would be wrong (BBC, 2017). It is prudent to examine whether similar problems occur in the environmental sciences. It is particularly important that portion of the environmental science intended to be used for major government decisions be soundly based upon quality-controlled science. Indeed, a call for "organised skepticism" to improve the reliability of the environmental marine sciences has already been made by Duarte et al. (2015) and Browman (2016). In particular, Duarte et al. (2015) argue that some of the major threats to ocean ecosystems may not be as severe as is portrayed in some scientific accounts, and that

"*the scientific community concerned with problems in the marine ecosystem* [*should*] *undertake a rigorous and systematic audit of ocean calamities, with the aim of assessing their generality, severity, and immediacy. Such an audit of ocean calamities would involve a large contingent of scientists coordinated by a global program set to assess ocean health.*"

In this paper we discuss the QC measures, or lack thereof, used in much environmental science and we highlight some deficiencies. In addition, a case study of the Great Barrier Reef is presented which demonstrates how these QC problems can flow through to important environmental (and economic) issues. Our review indicates significant doubts about whether much of the claimed anthropogenic damage to the GBR system is based upon quality-assured science and thus whether damage mitigation schemes are fully appropriate. We conclude that better Quality Control processes are essential for such environmental policy-science, and suggest, based on the proposal of Duarte et al. (2015), how this might be achieved.

2. What Quality Control processes are used in environmental sciences?

For many laboratory procedures, such as measuring concentrations of chemicals in a water sample, there are established protocols and calibration procedures. Laboratories may gain national accreditation from organisations whose role is to ensure that member facilities comply with relevant national and international standards and are thus competent to produce consistently reliable testing, calibration and measurement data. These aspects are QA, because they are part of the process of managing for quality, and the QA processes for these measurements are relatively straightforward. However, the conclusions of a scientific paper, and our confidence in them, generally rest upon more than measurement accuracy. For example, one might examine whether the experimental design is adequate, assumptions made are reasonable, statistical methods are appropriate, alternative interpretations are possible, and conclusions are transferable. These aspects of inspection and testing are QC, and the QC process is difficult and explicitly includes elements of judgment.

For most science, including environmental science, the two routine QC processes that occur outside the author's institution are peer review of submitted manuscripts, and the journal comment-and-reply process where scientists may be able to highlight problems with a recently published article. We question whether these processes are adequate QC for policy-science used to support important public policy decisions.

2.1. Peer Review

Much has been written elsewhere on the strengths and weaknesses of peer review and considerable effort has recently been expended in improving the process (e.g. Hettyey et al., 2012; Fresco-Santalla and Hernández-Pérez, 2014). Whilst peer review is certainly an excellent filter to make sure that published results are readable, that glaring errors are relatively few, and is generally helpful in improving the final work, it can also be a relatively cursory process, and there is also no guarantee that the reviewer is entirely unbiased. The appraisal of Horton (2000) is that.

"*we know that the system of peer review is biased, unjust, unaccountable, incomplete, easily fixed, often insulting, usually ignorant, occasionally foolish, and frequently wrong*"

Whilst this may read as an over-dramatic appraisal, the general point is clear. From our own first-hand experience in all aspects and from all viewpoints of the review process, we know that all Horton's adjectives are sometimes true, and should be taken seriously. Despite its long-recognised shortcomings (e.g. BBC, 2017), peer review generally functions acceptably for general science, but we question whether it is delivering and can deliver the far greater accuracy we believe is required for policy-science.

2.2. Journal comment-and-reply process

Very occasionally, a journal publishes a (generally critical) comment on a journal paper, with a reply to the comment from the original authors. This is a very ad-hoc QC process because it is based upon the willingness of those readers who doubt the paper's conclusions to take the time and effort to write a critical comment. If a paper is based on large datasets, it is highly unlikely that another scientist would volunteer the time to analyse the data thoroughly to test for errors and alternative interpretations. Such an effort can take months and, as noted above, is rarely funded by the normal science-funding agencies. Further, it is clear that most comments are ignored in the literature (Banobi et al., 2011) so that the effort involved far outweighs the positive impact for science. Finally, it is an unfortunate reality that writing critical commentaries, especially of the work of the eminent and influential, can damage a career, and this risk reduces further the likelihood of the necessary critique being undertaken and published. Therefore, overall, there is little incentive for scientists to publish a critical comment, indeed the incentives are largely to not do so. Worse, there is no resulting guarantee that important papers are subject to rigorous technical scrutiny.

2.3. "Industry Science" QC processes

Policy science which provides information on threats to the environment is unlikely to use such rigorous QC systems as science applied to industrial applications, such as when a private company uses some fundamental research to develop a product for economic gain. Whilst both may use peer review and the journal comment-and-reply process, the possibility of considerable financial losses arising from an ill-informed decision is likely to drive a rigorous analysis to check the data and replicate results. Consider a pharmaceuticals company wishing to develop a promising laboratory discovery to produce a new prescription drug for the market. On average, this costs 2.5 billion US dollars (figures for 2014) and takes a decade or more (DiMasi et al., 2016), so drug companies take great care at the beginning of a programme to make sure the initial information upon which they are basing the investment is sound. It is not accepted that a peer-reviewed journal article is adequate, partly because, when checks are made, the original work is found to be wrong at least half the time (Prinz et al., 2011), and so by identifying the errors early, any waste of resources is minimised. Given the level of government spending and significance of associated policy decisions, we believe that it is pertinent and responsible to ask whether governments need to subject policy-science to greater scrutiny than the standard peer-review processes. Below we consider some published policy-science relating to the Great Barrier Reef.

3. Great Barrier Reef policy-science

Both the Queensland and Australian Governments have already spent considerable sums on the Great Barrier Reef region, including AUD $375 million between 2008 and 2013 (Brodie et al., 2013; Commonwealth of Australia, 2015), and are expected to spend a further AUD $575 million in water quality initiatives between 2015 and 2020 (Great Barrier Reef Water Science Taskforce, 2015; Great Barrier Reef Marine Park Authority and Queensland Government, 2015; Kroon et al., 2016). Much of this is based on science which indicates 'damage' to the GBR system. More recently, it has been proposed that AUD $8 billion be spent in order to ensure water-quality targets are met (Alluvium Consulting Australia, 2016). These costs do not include those borne by industry in meeting environmental legislation or the opportunity costs of preventing some forms of development in GBR river catchments or at the coast. Such costs are difficult to estimate, but by itself, the government expenditure of AUD $1 billion or more warrants rigorous scrutiny of the science.

The iconic nature of the GBR has legitimately led to concern about its future since the early days of the conservation movement in the 1960s. Early conservation campaigns focussed on preventing the mining of coral for calcium carbonate and exploration for oil. In addition, the mortality of corals on a large number of reefs due to the Crown of Thorns Starfish (COTS), discovered in the 1960s (Pearson and Endean, 1969) triggered speculation that human activity was adversely affecting large tracts of the reef system, which continued despite geological evidence of the past presence of COTS (e.g. Walbran et al., 1989; Henderson and Walbran, 1992; Fabricius and Fabricius, 1992). By the 1990s, attention was starting to focus on the influence of river runoff, and especially the increased loads of rivers due to agriculture (e.g. Brodie, 1992; McCook, 2003). The year 1998 saw a worldwide coral bleaching event (Hoegh-Guldberg, 1999) which also impacted the GBR. A further bleaching event in 2002 saw the focus of concern move to the role of temperatures, pH and cyclone frequency and intensity, under the general umbrella of 'climate change'. At this time, the role of COTS as a stressor to the GBR system was perhaps not the primary focus, but this changed with the subsequent hypothesis that nutrient enrichment of the water facilitated the survival of larval stages of COTS (Brodie et al., 2007; Fabricius et al., 2010). In the last decade, dredging in the GBR region has become a focus of increased concern, associated with the expansion of Queensland's ports. Previously, dredging was certainly regarded as a local issue, affecting regions within a few tens of kilometres from various ports, but recently port expansion has also been linked to system-wide decline of the entire GBR (UNESCO, 2012; but also see Larcombe and Ridd, 2015). Most recently, coral bleaching events have occurred in the northern and some central parts of the GBR in 2016 and 2017, which have led to national and international concern (Hughes et al., 2017). The understandable emotion that sometimes accompanies such observations means that it is more important than ever to ensure that a dispassionate scientific view is taken.

With the likely exception of a few small corners of fringing reefs directly affected by past dredging activity (Morton, 2014), live coral remains on all of the ~3000 reefs of the GBR marine park. However, specific questions exist, such as whether the coral is growing more slowly than before, or is less healthy, or if the coral coverage on a particular reef has been reduced. These form some of the issues which lead to people raising the question of whether the GBR system is 'under increased threat'. In the marine environment, answering these specific questions and general issues are far more difficult than demonstrating the wholesale destruction of terrestrial habitats for agriculture. Perhaps most significantly, demonstrating 'change' in the GBR is made extremely difficult by the naturally high temporal variability of the physical system (e.g. Larcombe and Woolfe, 1999b; Larcombe and Carter, 2004; Larcombe, 2007; Larcombe and Ridd, 2015; Lewis et al., 2007; Liu et al., 2014). A particular reef can appear devastated due to a COTS outbreak, the passage of a cyclone (e.g. Perry et al., 2014) and/or thermal bleaching. However, reef surfaces subjected to such episodic impacts have been observed to fully recover in a decade or two, as documented by the Australian Institute of Marine Science Long Term Coral Monitoring Programme (AIMS LTMP) (Sweatman et al., 2011) and most recently for the southern region of the GBR (AIMS, 2016; Hughes et al., 2017). Similar cycles of change and resetting are perhaps less well acknowledged, but as documented by the sedimentary record, appear to occur in many other GBR coastal and marine habitats, such as beaches, intertidal mudflats, fringing and estuarine mangroves, seagrass meadows and the various habitats of the mid-shelf seabed (Hopley, 1982; Gagan et al., 1988; Nott and Hayne, 2001; Nott et al., 2013; Liu et al., 2014; Larcombe and Ridd, 2015).

The natural variability of the entire GBR system, coupled with the vast extent of the relevant components, which include river catchments through to the continental slope, means that scientists are forced to use indirect measures of the system (e.g. Laurance et al., 2011), or to perform analysis of datasets where complex statistical techniques are used to try and discern a weak signal from the background noise. Inevitably, this can leave considerable scope for misinterpretation of the data, and, we believe, risk an unwarranted level of significance being ascribed to the work. Duarte et al. (2015) noted:

> "*the marine research community may not have remained sufficiently skeptical in sending and receiving information on the problems caused by human pressures in the ocean*"
>
> "*that scientific skepticism has been abandoned or relaxed in many areas, which has allowed opinion, beliefs, and tenacious adherence to particular theories to play a major role in holding beliefs based on interpretations unsupported by evidence*".
>
> (Loehle, 1987)
>
> "*doom and gloom media accounts shows some—at times, severe—disconnect with actual observations*."

4. Challenging some GBR policy-science

We have examined some of the most highly cited policy-science papers (Appendix A) which have asserted damage to the GBR. The studies we have chosen cover a range of relevant topics, including simulations of riverine input of nutrients and links to management (Kroon, 2012), assessments of the changes in GBR water quality through time and links with ecology (Brodie et al., 2007; De'ath and Fabricius, 2010: Fabricius et al., 2010; Fabricius et al., 2013), changes in coral calcification through time (De'ath et al., 2009), analyses of the multi-decadal state of corals on the GBR system (De'ath et al., 2012) of the GBR system more broadly (Bellwood et al., 2004), and as part of change on geological timescales in the state of coral reef ecosystems (Pandolfi et al., 2003). Together, these papers have been cited a combined total of 5791 times (Table 1) and have formed the basis of many statements in the national and international media, by politicians and organisations of all types – political, environmental, scientific, and

Table 1
Citations for those papers reviewed in Appendix A.

Source	Citations on Google Scholar, at 01/05/2017
Bellwood et al. (2004)	2383
Brodie et al. (2007)	144
De'ath et al. (2009)	575
De'ath and Fabricius (2010)	238
De'ath et al. (2012)	663
Fabricius et al. (2013)	82
Fabricius et al. (2010)	188
Kroon (2012)	32
Pandolfi et al. (2003)	1486
Total	5791

industrial – as well as underpinning much government policy and spending (e.g. Commonwealth of Australia, 2015).

Some of these policy-science papers make very significant claims about the health and the future of the GBR system, including dire predictions of the imminent demise of the GBR "without intervention" (De'ath et al., 2012). They attribute a range of impacts to runoff of sediment and nutrient from agriculturally influenced catchments, and thus go to the heart of the practical influence of agriculture on the GBR system. 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 (Great Barrier Reef Water Science Taskforce, 2015; Great Barrier Reef Marine Park Authority and Queensland Government, 2015).

These papers make a wide suite of conclusions directly relevant to policy, including those listed below, which our analysis (Appendix A) indicates should be viewed with some doubt. These conclusions are:

(a) Halving river-borne nutrient and sediment concentrations will halve concentrations of nutrients and sediment in Great Barrier Reef waters
(b) Riverine discharge is significantly related to GBR water turbidity
(c) Nutrients from agricultural runoff are largely responsible for Crown-of-Thorns starfish plagues
(d) Minimizing pollution from agricultural runoff would reduce mean macroalgal cover on coral reefs by 39%, and would increase the mean 'richness' of hard corals and phototrophic octocorals by 16% and 33% respectively.
(e) There was a 50% reduction in coral cover in the GBR from the early 1960′s to 2000
(f) There was a 14% reduction in coral growth rates between 1990 and 2005.
(g) Coral cover will fall to 5%–10% by 2022.
(h) The outer and inner GBR are 28% and 36%, respectively, down the path to ecological extinction.

Although there are a large number of papers which claim some degree of 'stress' on the GBR system, associated with increased fluvial loads, dredging, higher temperatures, lower pHs, higher chlorophyll concentrations and other parameters, the number of papers which assert to document a measureable decline of the GBR system's coral is very small. It seems unlikely that almost all of this small number is erroneous, but in order to make reliable decisions, we must first determine what science is sound and what is not.

All the papers we discuss (Appendix A) were peer reviewed, and some were published in what are regarded as prestigious journals. However, although peer review is an important part of the process, its normal form was not rigorous enough, and did not appear to subject the original work to sufficiently robust technical review. As part of journal comment-and-reply processes, formal comments of some of these papers have been written and published (e.g. Ridd, 2007; Ridd et al., 2011, 2012, 2013; Sweatman and Sym, 2011); Boer et al., 2014), but such critiques have been largely ignored in the subsequent literature (Table 2).

Of course, it is important to remember that publication in a journal is recognition that the work is reasonable, not that it is necessarily correct, but nonetheless, some issues we have identified in these papers appear to be of a gravity to completely invalidate some of the papers' stated conclusions. There appears to be a prime facie case that further analysis is required before the conclusions could be considered ready to underpin important policy decisions regarding future management of the GBR. 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.

The issue is thus a result of the combination of at least four aspects, including that i) peer review forms the dominant QC mechanism outside the authors' institutions, ii) the journal comment-and-reply process is stymied by lack of easy access to the original data, and iii) the level of effort involved in reanalysis is high and iv) there is very weak acknowledgement (Banobi et al., 2011) of published comments in the literature. In some cases, the datasets underpinning the reviewed papers are extremely large. For the papers in Appendix A, we estimate there is at least two person years of work involved in returning to the original data and making the necessary checks to test it properly, and this is but a small selection of relevant material. Our experience indicates that this situation is probably not atypical of science in general. We are thus left greatly concerned that there appears no effective mechanism of robust technical scrutiny of policy-science regarding the GBR.

For the GBR, there are a range of perceived 'threats' and a limited financial capacity of governments and industry to address the problems. It is likely that some threats are far more important than others, and there should be carefully focussed expenditure on 'remediation'. However, the risk is that the present direction of remediation efforts could well be misdirected. There are almost certainly other areas of public policy and spending where the policy-science also needs technical scrutiny. However, without a formal mechanism, it is unlikely to ever happen, and doubts about the appropriateness of public policy and spending will persist.

It can sometimes be felt that to promote environmental policies, 'simple messages' are needed. Whilst we understand the feeling, there is a broader point to be acknowledged, that the very real, sometimes subtle and vital uncertainties in the science, risk becoming ignored and lost. We can all benefit by communicating science, but this doesn't necessitate scientific simplicity, nor, worse, should it risk causing any long-term impact on the quality of the science itself through becoming oversimplified. Improved science QC processes would clearly contribute to boosting the credibility and value of the policies developed and enacted, and therefore reducing risk to the environment.

5. How to achieve rigorous technical scrutiny for policy-science?

The above example illustrates how poor QC mechanisms for policy-science put at risk effective direction of resources regarding dealing with the GBR's environmental problems, but it is logical that a similar problem may also exist for many other environmental issues. This is not a new observation. Commenting on general matters of science credibility, Duarte et al. (2015) called for a "systematic audit" of ocean calamities, and Browman (2016) suggested the need for organised skepticism. Given that governments often use the results of environmental science to make important decisions, it is for them to commit appropriate funds to the task.

Therefore, we propose that governments should establish a new independent organisation to undertake quality reviews and audits of important scientific results which underpin government spending decisions. Here we have named it an "Institute for Policy-Science Quality Control" (IPSQC), but the name is far less important than its intended role, and the way it is structured and funded. Although the focus in this paper is on the environmental sciences, there are similar problems with policy-science in other areas where governments rely upon scientific results, such as education, health, and criminology. The IPSQC would

Table 2
Citations for published responses to papers listed in Appendix A.

Source	Citations on Google Scholar, at 05/05/2017
Boer et al. (2014)	0
Ridd (2007)	6
Ridd et al. (2012)	1
Ridd et al. (2013)	3
Sweatman and Sym (2011)	25
Total	35

thus not necessarily be restricted to environmental policy-science.

Regarding the role of a new body, we suggest it would conduct a system of guaranteed and organised technical debate, with the aim to specifically and rigorously test for any significant deficiencies in the scientific work upon which the major public expenditure is based. It would appear inevitable for some early focus to be on existing policy-science associated with policy driving current public spending, and that over time the focus would shift more towards assessing the quality of policy-science relevant to the development of new policy. There also seems a clear potential formal role supporting the process of setting environmental regulations and in performing reviews as policy options are considered. Whilst some policy-science is used in these processes, it is not routinely rigorously checked, and funds are almost never set aside to replicate important work. Again, rather than acting to form policy, the intended role is to check the veracity of the science being used by policymakers.

Clearly, any such organisation performing such a role would need significant resources to fund external scientists or to employ its own. Viewing the Australian GBR example at least, if these roles are the implicit role of any existing organisation or organisations, the evidence regarding GBR policy-science indicates to us that it is not working.

The precise mechanisms used by this new organisation could take a number of different forms. There are pros and cons to adversarial models (i.e. using a classical legal approach of prosecution and defence) and to 'truth commission' models (as used in post-apartheid South Africa). However, whatever the mechanism(s) used, there must be independence, openness and transparency in all aspects. As an example, in an adversarial model, the organisation might act like a defence attorney in a court trial, challenging the scientific evidence being used to support the government decision or intended decision. Depending upon the specific cases, this is likely to involve open questioning of scientists, commissioning attempts to replicate previous work, reanalysing data, checking experimental design, analytical methods and results, and ensuring that alternative interpretations are thoroughly considered and described.

6. Why is a new body needed?

Independent expert scientific review bodies are not novel, as they are often established to advise government on major policy issues and to prioritise management. For example, the Office of the Chief Scientist in Australia promotes quality and performs some reviews, and has recently provided high-profile advice to the Federal Government on Energy Policy. There are many examples of groups of experts which advise government about the evidence on major strategic issues, such as the "Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development" (http://www.iesc.environment.gov.au/).

Such review and advice work doesn't necessarily or specifically address QC. After gathering the available peer-reviewed science, some attempt will often be made to check the work reviewed, but it may rarely involve major re-analysis of data, and probably never attempts to replicate experiments, aspects of which may be critical in environmental policy-science, and in some other fields too. The task of these reviews is thus not primarily focused on QC. Further, the role of such review bodies is often explicitly to provide advice to government in policy development and prioritisation, and the boundaries between science and policy can become blurred.

We would see the proposed IPSQC complementing the work of such existing expert bodies by providing results of the QC work, transparently and independently assessed. In doing so, the IPSQC would also act to enhance clarity of the science-policy boundary, to the benefit of science, public discourse, policy-development and the environment. For policy-makers, they would have a resource which helps them focus policy development using the most credible and defensible science.

To re-emphasise, our view is that an IPSQC would and should not adjudicate on a particular issue, but provide independent, transparent evidence, gap analyses, technical scientific counter-arguments and other advice, to support policy-making and decision-making processes. The decisions themselves would, as now, be made by relevant parts of government and ministers elected by the public. Whatever form the IPSQC might take, it should work in a common way on all relevant policy-science. For the case of the GBR, some of the papers that assert damage to the GBR may be wrong and should be checked because they are being used to inform costly government decisions. However, there is no reason why, in the future, the situation could be reversed, and there may be scientific results which indicate that a particular perceived threat to the GBR is *not* important. Such results should be subject to the same level of scrutiny.

7. Conclusion

Given the national and international significance of the GBR system, an Australian government ought not to act to formulate policy or make spending decisions on this or any other significant conclusion without making sure the science is first subject to appropriate rigorous technical scrutiny. In the global setting, one would expect that policy and decision-making regarding preventing damage to the Amazon system, deceasing pollution in Lake Baikal, overfishing in W. European waters, and the like, would be informed by the best possible science. Compulsory, easy and open access to the data supporting published papers must be an integral part of the publishing process, as is already the case with some newer science journals, and should be a fundamental requirement of all policy-science to help promote independent re-analysis. More broadly, it would be helpful to help generate a sea-change in the culture of those (many) bodies which contribute the science, towards one where their science is judged less on number and short-term 'impact' of outputs to one judged more on long-term credibility. As well as improving the clarity of the evidence upon which government policy and spending is determined, formal rigour it will improve the quality of science and the potential of policy in the long run. The benefits of taking such an approach to help ensure the quality of policy-science far outweigh the risks of not improving matters.

Acknowledgements

These thoughts have been brewing in our heads for many years, and we thank a large range of colleagues in Australia and overseas for knowingly and unknowingly contributing to their development, and to most of these colleagues for not disowning us for expressing them. Special thanks go to Angus Morrison-Saunders and Craig Styan for their comments on an early draft. We thank the journal for encouraging submission, and the review process for delivering a number of helpful thoughts which have improved the paper.

Appendix A. Reviewed papers on 'threats' to the Great Barrier Reef

(a). Pandolfi et al. (2003): global trajectories of the long-term decline of coral reef ecosystems.

This paper found that the outer and inner GBR are 28% and 36%, respectively, down the path to ecological extinction. This conclusion was derived from a literature survey of the health of different reef organisms. Ridd (2007) found that the numerical scale used to "measure" the state of the reefs distorted the result, because the definitions had effectively hard-wired a 25% decline into the analysis. Any organism type which was not considered to be in an absolutely pristine state was defined as being 25% of the way towards ecological extinction, and this applied even to those organisms described as exhibiting no "reduction of marine resource". Thus, no reduction of marine resource was defined as being 25% of the way to ecological extinction – a patently unreasonable definition. Further, assumptions were made about the relative importance of reef species, which weighted, for example, the corals of a reef equally to its large herbivores (turtles, dugongs). Considering that corals are the central and defining ecological feature of reefs, this appears at least a questionable weighting, and the undoubted decline in the numbers of large herbivores greatly and unreasonably influenced the result.

Further, a careful review of the literature used in the paper revealed that many of the cited papers did not support the claims of the decline. As an example, Pandolfi et al. (2003) made the claim that the corals of the inner GBR are 25% of the way to ecological extinction, citing Richmond (1993) and Wollston (1995). However, Richmond's (1993) review paper regards anthropogenic impacts on corals in various regions of the world, presents no data that could be seen to indicate degradation of the inshore GBR to such an extent, nor itself makes or implies such a claim. Finally, it is unclear how Wollston's (1995) work, entitled "A Few Anecdotes from 60 years Ago in Nth. Qld." can be taken to support such a claim. Ridd (2007) outlines additional issues regarding the 25% degradation claim.

(b). Bellwood et al. (2004): confronting the coral reef crisis.

This paper concluded that there had been a 50% reduction in coral cover in the GBR from the early 1960's to 2000 (Fig. 2). From 1986 to 2003, the high quality AIMS LTMP data were used, based upon large-scale systematic surveys. However, for the period 1963 to 1985, the authors used ad-hoc and low-quality data from disparate short-term and small-scale studies from isolated areas of the reef, apparently gathered from individual studies that happened to include reports of coral cover, in some cases representing areas of only a few square metres. The older dataset was used to test whether coral cover had changed significantly before the AIMS LTMP studies commenced in 1985. The pre-1986 data had no declining trend and huge scatter, but its arithmetic mean was greater than the AIMS LTMP data (a result of the non-Gaussian distribution of coral-cover data). The result of joining these dissimilar datasets together was to indicate, erroneously, a significant decline across the whole period (see Boer et al., 2014; Sweatman and Sym, 2011). A further problem was that no literature source was cited for the pre-86 data, nor was the data available upon request (T. Hughes pers. comm.). Boer et al. (2014) attempted but failed to replicate the pre-1986 data using the literature (Fig. 3), casting further doubt on Bellwood et al.'s conclusion.

(c). Brodie et al. (2007): spatial and temporal patterns of near-surface chlorophyll *a* in the Great Barrier Reef lagoon; and Fabricius et al. (2010): three lines of evidence to link outbreaks of the Crown-of-Thorns Seastar *Acanthaster planci* to the release of larval food limitation.

These two papers make the significant claim that nutrients from agricultural runoff have caused outbreaks of coral-eating COTS, which are destroying the reef. Brodie et al. (2007) claim that Chl A concentrations are twice as high in the central region of the GBR than in other regions. In laboratory experiments, Fabricius et al. (2010) found that higher Chl A concentrations (due to phytoplankton) increased the survival rate of COTS larvae, and used Brodie et al.'s (2007) conclusion to propose that the higher Chl A concentrations in the central GBR act to trigger COTS outbreaks and thereby reduce coral cover. Fabricius et al.'s (2010) hypothesis relies on Chl A concentrations being higher in the central GBR region than the northern region.

Whilst it is certain that fluvial nutrient loads are now higher than before agricultural development, the asserted result, of doubled long-term concentrations of Chl A (a proxy for phytoplankton) in the central GBR (Brodie et al., 2007) is problematical for a number of reasons:

Firstly, GBR waters are flushed to the Coral Sea rapidly, in time periods of around 1 month (Choukroun et al., 2010). For the southern GBR, the equivalent volume of water delivered by rivers in an entire year is flushed to the Coral Sea in about 8 h. Similar flushing times also occur in the northern and central GBR regions. Simple mass-balance calculations indicate that this rapid flushing must reduce system-wide long-term nutrient enhancement to very low levels.

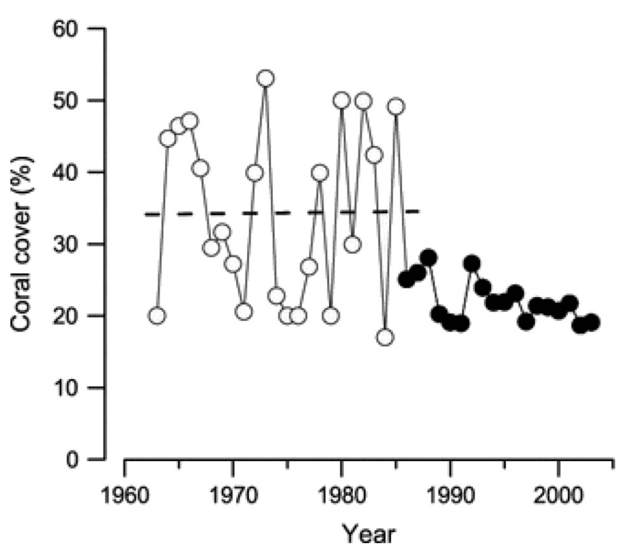

Fig. 2. Reproduction of the Bellwood et al. (2004) 'meta-analysis' of coral cover decline in the GBR from 1963 to 2003 (as redrawn by Sweatman and Sym, 2011). Each dot represents the mean coral cover for a particular year. Open circles indicate annual means based on transect and quadrant data, filled circles indicate annual means based mostly on data from manta tow surveys.

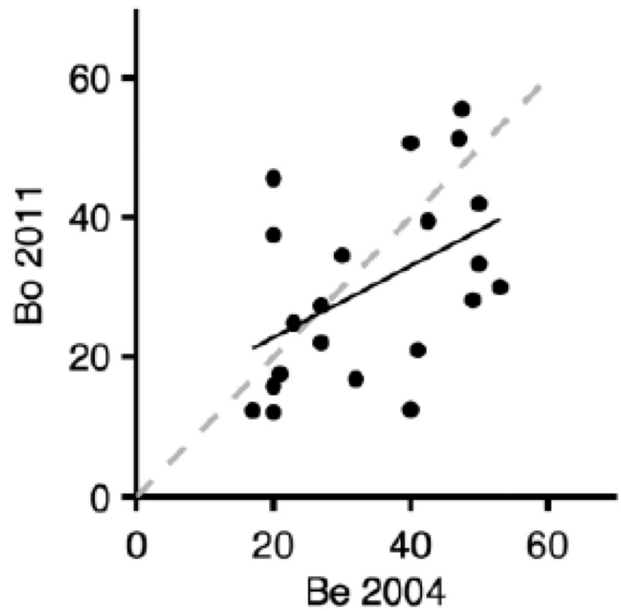

Fig. 3. GBR mean coral cover (%) for each year for pre-1986 data, comparing original compilation of Bellwood et al. (2004; Be 2004) and that of Boer et al. (2014; Bo 2011). Each dot represents the mean coral cover for a particular year. The r^2 correlation coefficient is 0.02, i.e. it was not possible to replicate the original data.

Secondly, the river discharge is only a very small component of the GBR nutrient cycle, for example, the recycling of N and P through the seabed is over 100 times the rate of delivery from rivers (Furnas et al., 1995). It is therefore difficult to identify a mechanism capable of doubling regional average Chl A concentrations solely from a minor increment in riverine nutrient input.

Assessments of regional average Chl A concentrations are influenced by the proximity of sampled sites to the open ocean. Due to shelf-ocean exchange, sites close to the Coral Sea will tend to have low Chl A concentrations (Brodie et al., 2007), and when considering shelf-wide averages, shelf width is critical because of the slower flushing times of wider shelves, and especially flushing of the inner shelf. The northern GBR shelf is narrow, down to ~20 km at one of Brodie et al.'s (2007) transects, and shows little cross-shelf concentration gradient, in marked contrast to the ~100 km wide central region, which displays a strong Chl A concentration gradient across the shelf. Brodie et al.'s (2007) simple average of the concentrations for the two regions (Fig. 4) does not take account of the shelf width. Plotted as a function of distance from the Coral Sea, Chl A concentrations appear to be identical between the two regions (Fig. 5).

Thirdly, the sampled shelf transects are dissimilar and not directly comparable. The central GBR region is characterised by the presence of a series of large muddy embayments (Maxwell, 1968; Belperio, 1983), which are known to contain higher Chl A concentrations because of the natural cycling of nutrients across the sediment-water interface (Furnas, 2003). Both Cleveland Bay and Trinity Bay were sampled, whereas the only embayment in the northern region, Princess Charlotte Bay, was not sampled. When these three factors are taken into account the data become logical and explicable, but they cannot support the assertion of fluvially driven doubling of long-term Chl A concentration in the central GBR.

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

This paper studied 328 corals on the GBR, and indicated a 14% reduction in growth rates between 1990 and 2005. It stated that the corals of the GBR are declining "at a rate unprecedented in coral records reaching back 400 years". Subsequent reanalysis of the data indicated that the apparent recent reduction in growth rate was caused by a) problems with the physical measurements of calcification, which systematically biased recent

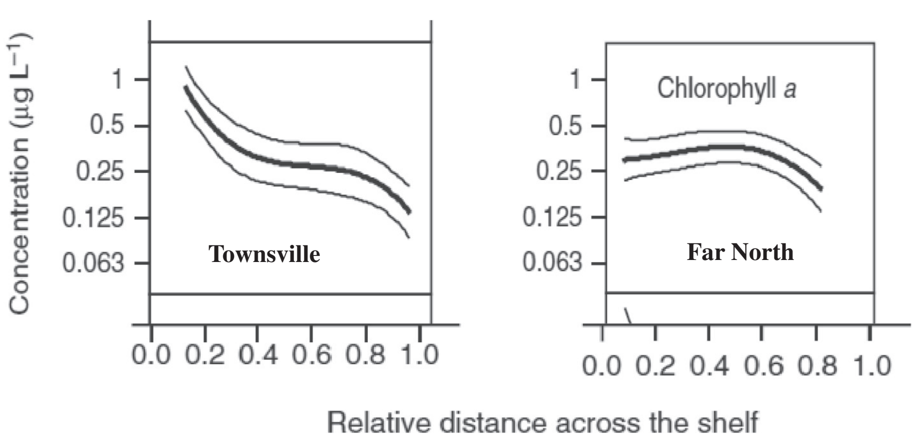

Fig. 4. Mean chlorophyll concentration (log scale, and with uncertainty limits, light lines) in the Townsville and Far Northern zones of the GBR (From Brodie et al., 2007). These plots are scaled to use the relative distance across the shelf as the horizontal coordinate, where 0 represents the coast and 1 represents the Pacific Ocean boundary of the GBR.

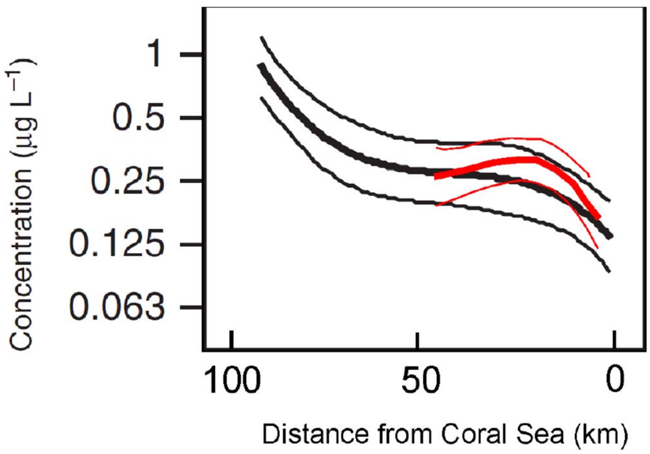

Fig. 5. As for Fig. 4, but replotted with the Townsville data (in black) overlaid upon the Far Northern data (short lines in red) using an absolute distance scale instead of the relative distance scale. The origin is at the Coral Sea boundary. It is notable that the mean Chlorophyll concentrations (thick lines) are very similar in the north and Townsville regions (ca. 0.4 mg/l) for comparable distances from the Coral Sea. Light lines represent uncertainty limits. The scale assumes that the average cross-shelf distance in the Far Northern Zone is *ca* half that of the Townsville zone. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

growth bands to give lower growth rates (D'Olivio et al., 2013; Ridd et al., 2013), and b) an unjustified assumption that coral growth rate does not change with the age of the coral (Ridd et al., 2013). With these taken into account, the dramatic fall in growth rate after 1990 is no longer evident, and a small increase in growth rates since the early 1900's appears (Fig. 6). Further, D'Olivio et al. (2013), working on a different set of GBR corals, showed an increase in coral calcification rates on middle and outer shelf reefs, which together represent 99% of GBR corals, of 10% for the period ~1950 to ~2005, but a decrease of 5% per decade between 1930 and 2008 on inner-shelf reefs, which represent only 1% of GBR corals. Therefore, it would be hard to glean from these datasets that there is a documented decline in coral 'growth' parameters, and even harder to attribute change to a particular cause.

(e). De'ath and Fabricius (2010): water quality as a regional driver of coral biodiversity and macroalgal cover on the Great Barrier Reef.

By comparing characteristics of coral reefs in the "pristine" northern GBR with the supposedly "impacted" central GBR, this paper concluded that improvements in the quality of freshwater flowing into the GBR shelf, through minimizing pollution from agricultural runoff, would reduce mean macroalgal cover on coral reefs by 39%, and would increase the mean 'richness' of hard corals and phototrophic octocorals by 16% and 33% respectively. The paper attributes all the differences between the northern and central regions to agricultural practices on the land. Unfortunately, the work relies on the questionable nutrient data of Brodie et al. (2007; see above). Further, the work ignores the critical fact that the northern and central GBR reefs have been different across all historical and geological timescales, as a result of their different geological, climatic, fluvial, estuarine, geomorphological, bathymetric, sedimentary and oceanographic characteristics (Hopley, 1982; Ridd et al., 2011). It is also well recognised that there are a variety of types of reef, described in a special issue of the journal Coral Reefs (Perry and Larcombe, 2003), and by a more recent review (Larcombe and Ridd, 2015). Therefore, by equating the reefs of the northern and central regions of the GBR system, this paper proverbially compared apples with oranges. To emphasise the nature of Dea'th & Fabricius's logic, it is akin to assuming that the vegetation around London, UK, would once have been the same, and *should* be the same, as that a thousand kilometres away around Berlin in Central Europe, and that any present differences are entirely due to human impacts.

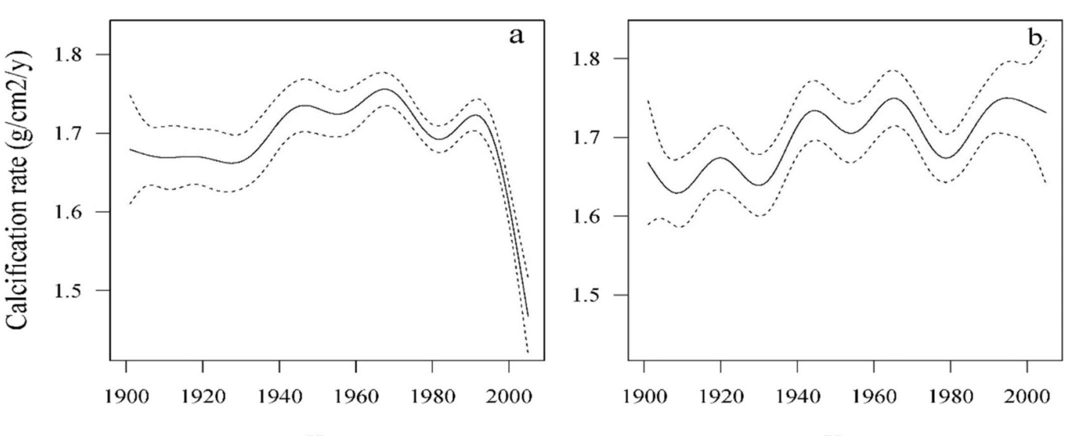

Fig. 6. Coral calcification rate on the GBR for the 20th century. (a) Calculated by De'ath et al. (2009). (b) Reanalysed to account for measurement errors and ontogenetic effects. Dotted lines represent uncertainty margin.
(From Ridd et al., 2013).

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

This paper contended that if erosion of sediment from agricultural runoff was to be reduced by 7000 k t/yr, and if Nitrogen input from fertilizers (dissolved inorganic Nitrogen, DIN) was to be reduced by 6000 t/yr, then the concentrations of suspended sediment (TSS) and Chlorophyll A (Chl A) in the Great Barrier Reef waters would be reduced by around 40%. The paper had explicitly assumed, incorrectly, that the concentration of sediment and Chl A in the GBR lagoon is solely determined, by a linear relationship, to the annual fluvial inputs of sediment and nutrients. Such linear relationships also assume, incorrectly, that there are no other sources of TSS or DIN to the water column of the GBR lagoon. Specifically, the work ignored the cycling of Nitrogen across the sediment-water interface (e.g. Furnas et al., 1995, 2011; see Ridd et al., 2012 for more detail) the magnitude of which is around 100 times the fluvial input. Additionally, the work ignored a large body of literature (e.g. Larcombe and Woolfe, 1999a, 1999b) that indicates that TSS at inner-shelf reefs is overwhelmingly controlled by the repeated resuspension of existing inner-shelf sediment, rather than by river input. The work thus ignored the dominant mechanisms controlling TSS and Chl A concentrations in the GBR shelf.

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

This paper concluded that there was a 50% reduction in GBR coral cover between 1985 and 2011, and predicted that "*without intervention*… (coral cover) … *will likely fall to 5–10% within the next 10 y*". They observed a slight decline between 1985 and 2005, mostly due to losses in the central GBR, followed by a steep decline from 2005 to 2011, due to losses in the southern GBR. They calculated that this reduction was caused 10% by bleaching, 42% by COTS and 48% by cyclones. The most important *prime facie* reasons to question the paper's conclusion is that the special environmental conditions on the GBR in 2009 and 2011 do not appear to have been appreciated.

In March 2009, a rare Category 5 system, TC Hamish, moved parallel to the outer GBR shelf, close to and over the outer-shelf, along the entire length of the central and southern shelf (Fig. 7), giving it great potential to cause damage. The Great Barrier Reef Marine Park Authority stated that "*more than 50 per cent of the coral reefs in the Great Barrier Reef Marine Park were affected by destructive or gale force winds*" (GBRMPA, 2010, 2011) and, especially given the likely waves striking the outermost outer shelf (c.f. Larcombe and Carter, 2004; their Fig. 3) it might have been one of the most destructive events of the last 100 years. Nonetheless, this significant event was not mentioned by De'ath et al. (2012), even though they presented calculations of the relative loss of corals from cyclones.

Less than two years later, in February 2011, another Category 5 system, TC Yasi, crossed the coast and destroyed much of the coastal towns of Cardwell and Tully. TC Yasi produced wind gusts up to 285 km/h, and gale force winds affected 26% (89,090 km^2) and destructive winds 13% (45,768 km^2) of the GBR Marine Park. In August that year, Perry et al. (2014) assessed some inner-shelf reefs for the effects of Yasi, finding that impacts were site specific, spatially highly heterogeneous, and related to the 'evolutionary stage' of each reef and its exposure to waves. Coral cover was greatly decreased in places, and coral recruits were common at all sites and colony re-growth evident at some. There was no observed evidence for major structural change in the reefs.

We thus contend that the large-scale loss of corals noted by De'ath et al. (2012) is largely a combined result of these cyclones. Such loss appears inevitable at times because the trajectories of episodic cyclones and extreme storms expose much of the GBR system to intense waves and currents,

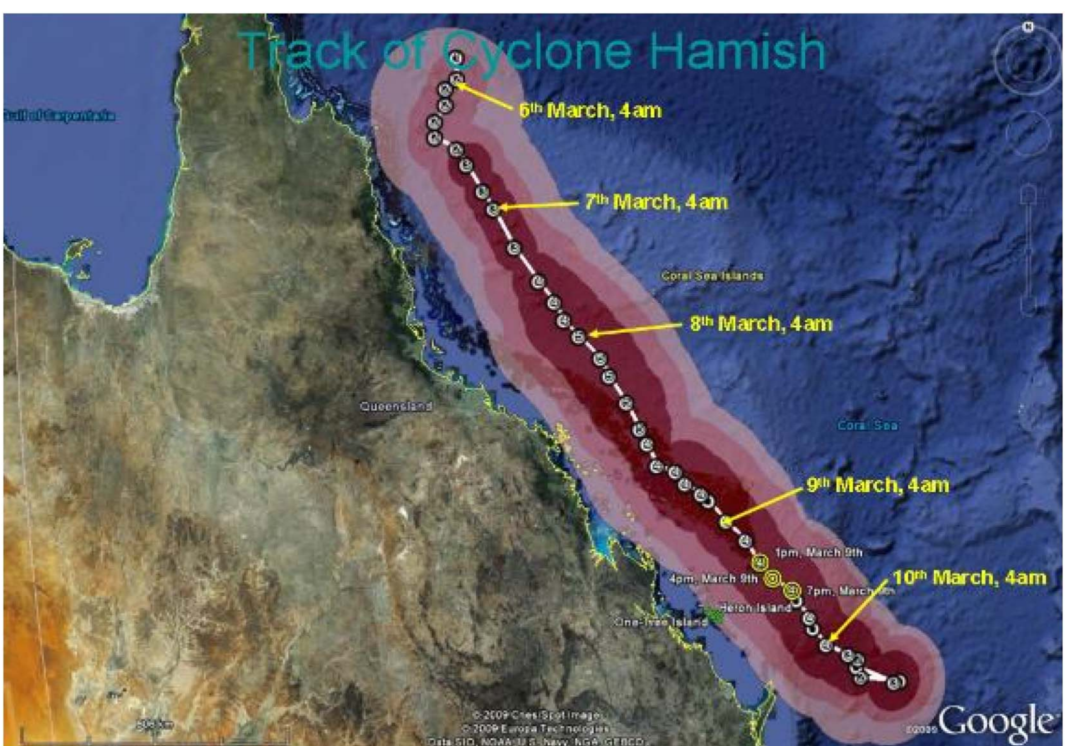

Fig. 7. Path of category 5 Tropical Cyclone Hamish 2009. Light purple represents the limit of gale force winds. Dark purple is the highly destructive core when the cyclone was category 4 or above. The cyclone was category 5 from late on 7th March to 9 March. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

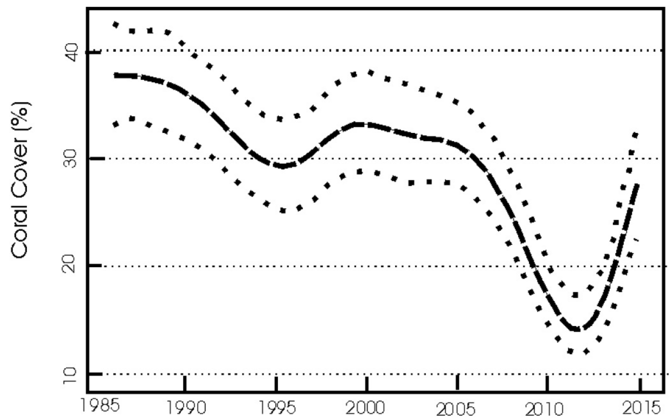

Fig. 8. Mean coral cover for the southern region of the GBR (after AIMS, 2016). Dotted lines represent 95% confidence limits.

and such events can strongly affect individual reefs and their associated seabed (Larcombe and Carter, 2004). Further, for at least the last 1000 years, there is evidence of repeated cycles between periods of relatively weak and strong cyclones on the GBR, with the cycles 1 or 2 decades long (Liu et al., 2014). However, what remains almost completely unknown is the past history of the physical extent of such events (Larcombe and Ridd, 2015), and in their absence, the predictions of De'ath et al. (2012) are unsupportable. Further, observations show that individual reefs, and large regions of the GBR, are capable of 'rebound' within ten years of their cyclonic disturbance, an example of which is present in the latest AIMS LTMP data (AIMS, 2016; Fig. 8), where rebound in coral cover in the southern region of the GBR took place.

The data used by De'ath et al. (2012) need to be placed into their correct physical context and reanalysed accordingly. For example, it would appear necessary to consider all available records of cyclone tracks, in order to place the effects of TC Hamish and Yasi into an appropriate context. It would also be vital to review the cyclone history in the decade or two before the AIMS LTMP data began in 1985, and carefully consider what this means for how the data can be interpreted, especially regarding the significance of its changes.

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

Using a three-year time series of turbidity data at fifteen fringing reefs, statistical techniques were used to identify the influence of wave climate and river flow on turbidity. It was concluded that river plumes influence the turbidity on the GBR, which led to the claim that "a reduction in the river loads of fine sediments and nutrients through improved land management should lead to measurably improved inner-shelf water clarity in the most turbid parts of the GBR".

The evidence is strong for increased erosion on agricultural land and associated increased sediment loads of the rivers (e.g. Neil et al., 2002; McCulloch et al., 2003; Bartley et al., 2014; Nichols et al., 2014) since European settlement and agricultural development, so that, at first sight, it appears plausible to suggest a concomitant increase in turbidity for GBR inner-shelf waters. However, Larcombe and Woolfe (1999a, 1999b) noted that a) the key oceanographic processes controlling turbidity do not include river plumes and b) there is regionally unlimited availability of fine sediment on the inner-shelf seabed (see also Orpin and Ridd, 2012). Many of the inner-shelf 'turbid-zone' reefs have been surrounded by fine sediment for millennia, so that any "extra" fluvial sediment over the last 200 years is immeasurable in turbidity data. Further, Perry et al. (2008) studied the turbid Paluma Shoals reef and found that the coral assemblages exhibit no measurable evidence of community shift which could be attributable to post-European water-quality changes, had they occurred (see Larcombe and Ridd, 2015 for more examples of such reefs).

Fabricius et al. (2013) has shown an influence of river plumes on the GBR inner-shelf, which should be no surprise. However, 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 and there is no evidence that it is of ecological importance. Further, the significance of any change in turbidity is unclear, and could be anywhere between an important first indication of human impact or an obvious finding regarding the natural influence of rivers upon a continental shelf. This particular policy-science paper is based upon an immense dataset, and it requires reanalysis to scrutinise it in the required detail.

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