Letters to the Editor

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Will reducing agricultural runoff drive recovery of coral biodiversity and macroalgae cover on the Great Barrier Reef?

De'ath and Fabricius (2010) (hereafter referred to as DF10) analyze data of water clarity and chlorophyll concentrations in the Great Barrier Reef (GBR) and relate these parameters to biological measures of reef status. Statistical relationships between four biotic groups (the cover of macroalgae and the taxonomic richness of hard corals and phototrophic and heterotrophic octocorals), water quality, and spatial zonation were derived from these data. The approach adopted by DF10 attributes some of the zonation visible today as a response to anthropogenic increased terrestrial runoff, and indeed suggest that "recovery" shifts in the biodiversity will result from land runoff mitigation alone. The model relationships are used by DF10 to determine potential changes in macroalgal cover and richness of hard corals and phototrophic octocorals that would occur if water quality was improved to a similar condition as found in the pristine northern sector of the GBR, which has generally high water clarity and lower chlorophyll concentration. They conclude that for 23% of GBR reefs, water quality improvement (e.g., "by minimizing agricultural runoff") will reduce macroalgal cover on average by 39%, and will increase the richness of hard corals and phototrophic octocorals on average by 16% and 33%, respectively (all else being equal). There is considerable merit in the statistical model developed by DF10 relating measured water quality and biodiversity. However, our primary criticism centers on the development of the aspirational guidelines for water quality and the unsubstantiated inference of the deterioration in water quality implicit in that approach.

DF10 do not demonstrate that the variation in water quality in the lagoon, in particular the contrast between northern and southern sectors, is natural or due to human disturbance, or that there has been a progressive reduction in water quality since before European settlement. Nonetheless, the inference made by DF10 is clear: minimizing agricultural runoff will drive reef recovery in the GBR. They state that "multiple lines of evidence strongly suggest that investment in improved land management practices that reduce inshore turbidity and chlorophyll levels will help correct multiple ecological imbalances that have arisen from poor water quality management." To provide some validity to their rationale that water quality is amenable to improved land management, DF10 cite conceptual modeling work from Haynes (2007) but acknowledge that "the direct link between increasing river loads of nutrients and sediments and changes to inshore water quality on the GBR has not been established."

The assertion that long-term water quality measurements within the lagoon, and potential ecological shifts (degradation or recovery), can be attributed to land use change and riverine inputs contradicts fundamental physical and geological data. This ambiguous proposition is manifest in DF10 as a comparison of areas which are presumed to be impacted with a pristine region, the northern GBR. This was done by setting aspirational "guideline" values of water quality against those of the relatively pristine and naturally clean northern GBR. But DF10 fail to argue if these guideline values of water quality are appropriate for other regions of the GBR. The GBR spans substantial meteorological and geographical gradients: the Northern sector (10° S to 16° S) has a river catchment area of 46 000 km^2, whereas the Central (16° S to 20° S) and Southern (20° S to 25° S) sectors are many times larger at 160 000 km^2 and 220 000 km^2, respectively. Other climatic differences include annual rainfall, leading to a twofold range in total runoff for major rivers from the Northern (16.7 km^3), Central (32.0 km^3), and Southern (34.7 km^3) sectors (Furnas 2003). In addition coastal oceanography varies dramatically along the GBR, such as the influence of the East Australia Current, North Queensland Current, and the North Vanuatu and North Caledonian jets. Similarly, shelf and reef morphology shows strong north-south variability, rendering many regional comparisons inappropriate. Although DF10 relate *biota* to this spatial zoning, the models cannot determine whether or not the water quality at a particular location has been affected by agricultural runoff. The models thus cannot be used to infer changes in biota due to agricultural runoff and is therefore of very limited use to the establishment of water quality guidelines.

Quite correctly, DF10 note that there is compelling evidence that landscape yields of erosion products from many central and southern GBR catchments have increased due to land use change (e.g., Neil et al. 2002, Brodie et al. 2003, Furnas 2003). However, in the lagoon, increased sediment yields don't necessarily translate to measurable changes in suspended sediment concentration (SSC) and water quality. The potentially limited impact of riverine supply to the GBR nutrient budget is illustrated by Monbet et al. (2007), who show that most of the phosphorus supply to the inshore GBR lagoon is derived from inputs from the Coral Sea.

Modern riverine sediment is trapped in estuarine mangroves and nearshore estuarine embayments inside the 20-m depth contour (Woolfe and Larcombe 2001, Brunskill et al. 2002). Moreover, data in Furnas et al. (1995) and Furnas and Mitchell (1996) indicate that riverine supply is a comparatively minor component of the nitrogen and phosphorus budgets of the central GBR compared with fluxes associated with resuspension of sediment, benthic release, and denitrification. As such, these dominant components and processes of the GBR nutrient cycle are largely independent of land use impacts and have likely not changed since European settlement.

The application of man-made contaminants (pesticides, herbicides, estrogens, hormones from cattle, and metal contamination from industry) has undoubtedly increased in recent times. However, even in high-yield, dry topics catchments in the central sector of the GBR most studies indicate that these river-borne contaminants are efficiently trapped in floodplain soils, estuarine mangrove sediments, and muddy coastal embayment depocenters (Walker and Brunskill 1997, Cavanagh et al. 1999, Doherty et al. 2000, Lewis et al. 2009). These contaminants are not found in the mid and outer shelf reef matrix.

One way that the conclusions of DF10 might be supported would be to demonstrate that the biodiversity of the "degraded" regions have made measurable ecological shifts in direct response to anthropogenic increases in riverine supply. However, in the absence of a thorough examination of historical data, such an analysis is beyond the scope of the dataset provided, and thus an unwarranted conclusion. In this respect DF10 have not considered a significant body of literature that indicates that some of the inshore reefs in DF10's degraded zones have always existed in conditions of low water clarity. (Woolfe and Larcombe 1998, Larcombe and Woolfe 1999*b*, Larcombe et al. 2001, Smithers et al. 2006, Perry et al. 2008, 2009, Perry and Smithers 2011). Perry et al. (2008) studied a highly turbid reef that DF10 would classify to be highly degraded, and found that the coral assemblages exhibit no measurable evidence of community shifts attributable to post-European settlement water-quality changes. A similar finding has been reported most recently found by Roche et al. (2010), who concluded that comparisons between modern and mid-Holocene coral community data from equivalent water depths did not reveal marked shifts in coral community composition and diversity, suggesting that the long-term persistence of a resilient coral assemblage over these time periods.

Pioneering studies by Johnson (1985), Johnson et al. (1986), and Johnson and Risk (1987), and more recently by Smithers et al. (2006), showed that some fringing reefs, located in highly turbid coastal water conditions, were initiated on a muddy substrate. An inner shelf shoal first studied by Larcombe and Woolfe (1999*b*) and Larcombe et al. (2001) is exposed to high suspended sediment concentrations (SSC >100 mg/L) during periods of vigorous southeast trade winds and wind-generated wave events. Here, geological evidence suggests that these reef systems have coexisted with very high water turbidity for millennia. Throughout the Quaternary life cycles of the GBR with glacio-eustatic changes in sea level, carbonate production and early reef initiation occurred during periods of high coastal water turbidity, maintained by sediment supply and oceanographic processes (e.g., Dunbar and Dickens 2003, Page et al. 2003). Over geological timescales, reef development and water quality are inextricably linked, and on that fact we are in complete agreement with DF10. But, Smithers et al. (2006) found that many reefs go through long periods (millennia) of sustained slow growth but are now covered in a veneer of well-developed coral communities. Perry and Smithers (2011) noted major changes in coral reef growth rates over the last 8500 years and cautioned that "degraded reef states cannot de facto be considered to automatically reflect increased anthropogenic stress."

Woolfe and Larcombe (1998) and Larcombe and Woolfe (1999*a*, *b*), suggest that anthropogenic increases in riverine sediment inputs have only had a minor affect on SSC close to many inshore reefs. In contrast, these earlier studies, suggest that river plumes are only a minor contributor to coastal SSC at many inshore reefs compared with sediment resuspension driven by oceanic processes. Supported by field measurements, they demonstrated that high SSC events on the inner shelf are not sediment supply limited but instead are controlled by the energetics of wave-driven resuspension of the muddy seabed. The corollary of this hypothesis is that any realistic increase ***or*** decrease to riverine sediment supply to the coastal zone is likely to be overwhelmed by resuspension as the dominant environmental driver for elevated SSC. The strong relationship between wave conditions and SSC has most recently been confirmed by Wolanski et al. (2008) and Cooper et al. (2008). The effects of wave induced sediment resuspension have been identified to be the main driver of high SSC conditions. Although the work on reef conditions over long time scales has been concentrated on a few locations, the results can be applied to most of the GBR experiencing a similar wave regime provided that sediment bottom type is known to be composed of fine and easily suspended material.

Summary

DF10's inference that minimizing agricultural runoff should reduce macroalgal cover on average by 39% and increase the species richness of hard corals and phototrophic octocorals on average by 16% and 33%, respectively (all else being equal) is unwarranted. Their argument for aspirational guidelines for water quality relies on an implicit assumption of an anthropogenically induced deterioration in water quality. At its core is an erroneous regional comparison between southern reef communities presumed to be impacted with a control area in the generally clearer waters of the northern GBR, ignoring the possibility that these "pristine" reefs have been different across geological timescales to those reefs labeled as "impacted." Furthermore, DF10 ignore a considerable body of literature describing the relationship between hydrodynamics and local sediment and nutrient dispersal, which casts significant doubt whether systematic differences in physical conditions and biodiversity at the majority of reefs can be inferred from land use changes alone.

Literature Cited

Brodie, J., L. A. McKergow, I. P. Prosser, M. Furnas, A. O. Hughes, and H. Hunter. 2003. Sources of sediment and nutrient exports to the Great Barrier Reef World Heritage Area. ACTFR Report No. 03/11. Australian Centre for Tropical Freshwater Research, James Cook University, Townsville, Australia.

Brunskill, G. J., I. Zagorskis, and J. Pfitzner. 2002. Carbon burial rates in sediments, and a carbon mass balance, of the Herbert River region of the Great Barrier Reef continental shelf, north Queensland, Australia. Estuarine, Coastal and Shelf Science 54:677–700.

Cavanagh, J. E., K. A. Burns, G. J. Brunskill, and R. J. Coventry. 1999. Organochlorine pesticide residues in soils and sediments of the Herbert and Burdekin River regions, north Queensland: implications for contamination of the Great Barrier Reef. Marine Pollution Bulletin 39:367–375.

Cooper, T. F., P. Ridd, K. E. Ulstrup, C. A. Humphrey, M. M. Slivkoff, and K. E. Fabricius. 2008. Temporal dynamics in coral bioindicators for water quality on coastal coral reefs of the Great Barrier Reef. Marine and Freshwater Research 59:703–716.

De'ath, G., and K. E. Fabricius. 2010. Water quality as regional driver of coral biodiversity and macroalgal cover on the Great Barrier Reef. Ecological Applications 20:840–850.

Doherty, G. B., G. J. Brunskill, and M. J. Ridd. 2000. Natural and enhanced concentrations of trace metals in sediments of Cleveland Bay, Great Barrier Reef Lagoon, Australia. Marine Pollution Bulletin 41:337–344.

Dunbar, G. B., and G. R. Dickens. 2003. Late Quaternary shedding of shallow-marine carbonate along a tropical mixed siliciclastic-carbonate shelf: Great Barrier Reef, Australia. Sedimentology 50:1061–1077.

Furnas, M. J. 2003. Catchments and corals: terrestrial runoff to the Great Barrier Reef. Australian Institute of Marine Science and CRC Reef Research Centre, Townsville, Australia.

Furnas, M. J., and A. W. Mitchell. 1996. Nutrient inputs into the Central Great Barrier Reef (Australia) from subsurface intrusions of Coral Sea waters: a two-dimensional displacement model. Continental Shelf Research 16:1127–1148.

Furnas, M. J., A. W. Mitchell, and M. Skuza. 1995. Nitrogen and phosphorus budgets for the central Great Barrier Reef shelf, a report to the Great Barrier Reef Marine Park Authority. Research Publication No. 36. Great Barrier Reef Marine Park Authority, Townsville, Australia.

Haynes, D., J. Brodie, J. Waterhouse, Z. Bainbridge, D. Bas, and B. Hart. 2007. Assessment of the water quality and ecosystem health of the Great Barrier Reef (Australia): conceptual models. Environmental Management 40:993–1003.

Johnson, D. P. 1985. Age structure of the Fantome Island fringing reef. Technical Memorandum no. 6. Great Barrier Reef Marine Park Authority, Townsville, Queensland, Australia.

Johnson, D. P., A. P. Belperio, and D. Hopley. 1986. A field guide to mixed terrigenous-carbonate sedimentation in the Central Great Barrier Reef Province, Australia. Australasian Sedimentologists Specialist Group, a specialist group of the Geological Society of Australia, Sydney, Australia.

Johnson, D. P., and M. J. Risk. 1987. Fringing reef growth on a terrigenous mud foundation, Fantome Island, central Great Barrier Reef, Australia. Sedimentology 34:275–287.

Larcombe, P., and A. Costen. and K. J. Woolfe, 2001. The hydrodynamic and sedimentary setting of nearshore coral reefs, central Great Barrier Reef shelf, Australia: Paluma Shoals, a case study. Sedimentology 48:811–836.

Larcombe, P., and K. J. Woolfe. 1999*a*. Terrigenous sediments as influences upon Holocene nearshore coral reefs, central Great Barrier Reef, Australia. Australian Journal of Earth Sciences 46:141–154.

Larcombe, P., and K. J. Woolfe. 1999*b*. Increased sediment supply to the Great Barrier Reef will not increase sediment accumulation at most coral reefs. Coral Reefs 18:163–169.

Lewis, S. E., J. E. Brodie, Z. T. Bainbridge, K. Rohde, A. M. Davis, B. Masters, M. Maughan, M. J. Devlin, J. Mueller, and B. Schaffelke. 2009. Herbicides: a new threat to the Great Barrier Reef. Environmental Pollution 157:2470–2484.

Monbet, P., G. J. Brunskill, I. E. Zagorskis, and J. Pfitzner. 2007. Phosphorus speciation in the sediment and mass balance for the central region of the Great Barrier Reef continental shelf (Australia). Geochimica et Cosmochimica Acta 71:2762–2779.

Neil, D. T., A. R. Orpin, P. V. Ridd, and B. Yu. 2002. Sediment yield and impacts from river catchments to the Great Barrier Reef lagoon. Marine and Freshwater Research 53:733–752.

Page, M. C., G. R. Dickens, and G. B. Dunbar. 2003. Tropical view of Quaternary sequence stratigraphy: siliciclastic accumulation on slopes east of the Great Barrier Reef since the Last Glacial Maximum. Geology 31:1013–1016.

Perry, C. T., and S. G. Smithers. 2011. Cycles of coral reef "turn-on," rapid growth and "turn-off" over the past 8500 years: a context for understanding modern ecological states and trajectories. Global Change Biology 17:76–86.

Perry, C. T., S. G. Smithers, and K. G. Johnson. 2009. Long-term coral community records from Lugger Shoal on the terrigenous inner-shelf of the central Great Barrier Reef, Australia. Coral Reefs 28:941–948.

Perry, C. T., S. G. Smithers, S. E. Palmer. P. Larcombe P, and K. G. Johnson. 2008. A 1200 year paleoecological record of coral community development from the terrigenous inner-shelf of the Great Barrier Reef. Geology 36:691–694.

Roche, R. C., C. T. Perry, K. G. Johnson, K. Sultana, S. G. Smithers, and A. A. Thompson. 2010. Mid-Holocene coral community data as baselines for understanding contemporary reef ecological states. Palaeogeography, Palaeoclimatology, Palaeoecology 299:159–167.

Smithers, S. G., D. Hopley, and K. E. Parnell. 2006. Fringing and nearshore coral reefs of the Great Barrier Reef: episodic Holocene development and future prospects. Journal of Coastal Research 22:175–187.

Walker, G. S., and G. J. Brunskill. 1997. A history of anthropogenic mercury Input into the Great Barrier Reef Lagoon, Australia. Proceedings of the 8th International Coral Reef Symposium 2:1889–1892.

Wolanski, E., K. E. Fabricius, T. F. Cooper, and C. Humphrey. 2008. Wet season fine sediment dynamics on the inner shelf of the Great Barrier Reef. Estuarine, Coastal and Shelf Science 77:755–762.

Woolfe, K. J., and P. Larcombe. 1998. Terrigenous sediment accumulation as a regional control on the distribution of reef carbonates. Special Publications of the International Association of Sedimentologists 25:295–310.

Woolfe, K. J., and P. Larcombe. 2001. Sediment dispersal along the inner shelf of the central Great Barrier Reef. Geological Society of Australia Special Publication 21:295–302.

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Evidence that water quality is an important driver of reef biota is not refuted: response to Ridd et al.

To the Editor:

We thank Ridd et al. (2011; hereafter R11) for their interest in our study (De'ath and Fabricius 2010; referred to by R11 as DF10). DF10 investigated the relationships between indicators of reef ecosystem health on the Great Barrier Reef (GBR), and water column chlorophyll and water clarity. The spatial distribution of the indicators was modeled jointly in terms of spatial predictors (relative distance across and along the GBR) and the two water quality predictors. DF10 showed strong spatial variation in the indicators, and additionally also strong relationships between the indicators and chlorophyll and water clarity.

Our comment on R11 has two components:

1. *The statistical model and its application*.—R11 concludes that our argument for water quality guidelines is based on "an erroneous regional comparison between southern reef communities presumed to be impacted with a control area in the generally clearer waters of the northern Great Barrier Reef (GBR), ignoring the possibility that these 'pristine' reefs have been different across geological timescales to those reefs labeled as 'impacted'." This is incorrect, and demonstrates a lack of understanding by R11 of the statistical models. DF10 in no way implies that the inner central GBR should have levels of water quality similar to the pristine northern sector of the GBR. DF10 attribute variation in biotic water quality indicators to broad spatial differences, and also to local values of water clarity and chlorophyll. Thus the predictions of the four indicators depend on local relationships and values of predictors, not on the comparison between southern and northern reef communities, as suggested by R11. In other words, the effects of water quality and chlorophyll on these biota are additional to the regional differences in geography described by R11; the latter being accounted for by the spatial predictors in the models.

Biodiversity naturally declines with latitude away from the equator, and there are natural (modal) differences in biodiversity across the continental shelf. Similarly, macroalgal cover increases with latitude away from the equator, and steeply declines with distance from the coast. Our models estimate these spatial effects and account for them, and also estimate differences in the biota that are solely due to water clarity and chlorophyll. These effects are estimated at all locations on the GBR shelf. The suggested guidelines of >10 m Secchi depth (water clarity) and <0.45 g/L of chlorophyll are conditions not only experienced in the pristine northern sector of the GBR, but also apply to $\sim80\%$ and $\sim70\%$ of the GBR as a whole (see Fig. 1 of DF10). R11 also asserted that DF10 fails to acknowledge that these regions span substantial meteorological and geographical gradients. Again, this is incorrect, since DF10 account for and discuss geographical (spatial) gradients in the models (see Figs. 3c, f and 5c, d, g, h, k, l, o, p of DF10). This aspect of accounting for spatial effects in order to quantify the dependencies of the four biota on water clarity and chlorophyll is of course the primary objective of the statistical analyses of DF10.

2. *Alternative explanations of the relationships*.—R11 devote much of their critique to discussing linkages between land use and changes in water quality in the GBR, or historical changes in reef accretion. This is not relevant in terms of a critique of DF10, which does not investigate these issues. DF10 demonstrate that low water clarity is linked to increased macroalgal cover and reduced taxonomic richness of hard corals (at species level) and phototrophic soft corals (at the generic level).

These properties that are not well preserved in geological samples, and the paleontological and geomorphic studies cited by R11 do not provide data on either historic stability or on change of these reef health indicators over time.

Historical water quality data from the GBR are sparse, and no complete nutrient budget exists for the GBR (the phosphorus budget of Monbet et al. 2007 covers <3% of the GBR area). Nonetheless, modeling has shown that the mean annual loads of sediments and nutrients discharged by the >30 rivers into the shallow and wide continental shelf sea have increased six- to ninefold since pre-European times, and now amount to an estimated annual average of 17 million tonnes (Mg) of suspended sediment, 80 000 tonnes of nitrogen and 16 000 tonnes of phosphorus (Kroon et al., *in press*). There are also strong relationships between inshore turbidity and (1) distance to river, (2) river flow of freshwater, (3) rainfall, and (4) days into the dry season in the coastal GBR. For any given wave and tidal conditions, inshore turbidity is 13% lower in weeks with low compared to high river flow and rainfall, and declines by 28% from the beginning to the end of the dry season, suggesting that inshore turbidity is indeed sediment supply limited (K. E. Fabricius, G. De'ath, C. Humphrey, I. Zagorskis, and B. Schaffelke, *unpublished manuscript*). Decadal changes in water clarity due to changes in anthropogenic loadings have also been documented in numerous other parts of the world (Borkman and Smayda 1998). For example, water clarity in the northern and eastern Adriatic Sea (Mediterranean) has declined since 1960 as a consequence of nutrient enrichment from river discharges (Justic et al. 1995, Baric et al. 1992), while in the Skagerrak Sea, water clarity increased by 25% between 1970 and 1993 after reduction in phosphorus and sewage discharges (Borkman and Smayda 1998).

In conclusion, the water quality guidelines proposed by DF10 are based on analyses that account for natural geographic differences between regions, and show strong dependencies of the four biotic indicators on water quality and chlorophyll. Thus DF10 demonstrate that improved water quality on the GBR will lead to reduced macroalgal cover and increased richness of hard corals and phototrophic octocorals.

Literature Cited

Baric, A., I. Marasovic, and M. Gaccic. 1992. Eutrophication phenomenon with special reference to the Kasscarontela Bay. Chemistry and Ecology 6:51–68.

Borkman, D. G., and T. J. Smayda. 1998. Long-term trends in water clarity revealed by Secchi-disk measurements in lower Narragansett Bay. ICES Journal of Marine Science 55:668–679.

De'ath, G., and K. Fabricius. 2010. Water quality as a regional driver of coral biodiversity and macroalgae on the Great Barrier Reef. Ecological Applications 20:840–850.

Justic, D., N. N. Rabalais, R. E. Turner, and Q. Dortch. 1995. Changes in nutrient structure of river-dominated coastal waters: stoichiometric nutrient balance and its consequences. Estuarine Coastal and Shelf Science 40:339–356.

Kroon, F. J. In press. River loads of suspended solids, nitrogen, phosphorus and herbicides delivered to the Great Barrier Reef lagoon. Marine Pollution Bulletin.

Monbet, P., G. J. Brunskill, I. Zagorskis, and J. Pfitzner. 2007. Phosphorus speciation in the sediment and mass balance for the central region of the Great Barrier Reef continental shelf (Australia). Geochimica et Cosmochimica Acta 71:2762–2779.

Ridd, P. V., A. R. Orpin, T. C. Stieglitz, and G. J. Brunskill. 2011. Will reducing agricultural runoff drive recovery of coral biodiversity and macroalgae cover on the Great Barrier Reef? Ecological Applications 22:3332–3335.

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