State of the Great Barrier Reef 2024

Peter Ridd

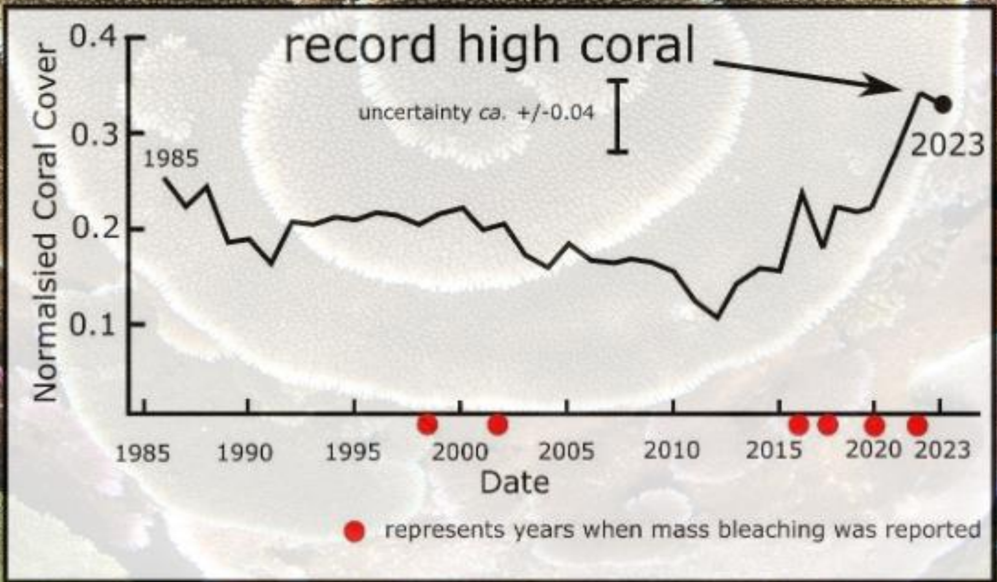

Photo by: Leonard Lim Photography

State of the Great Barrier Reef: 2024

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Note: This report describes the state of the GBR in 2024, and also describes, in a condensed and convenient form, much of the science of the GBR that the author has presented in the following

- Reef Heresy? Science Research and the Great Barrier Reef. Connor Court Publishing.
- Corals in a Warming World: Causes for Optimisms. Report No 55. Global Warming Policy Foundation
- Larcombe, P. and Ridd, P. (2015). *The Sedimentary Geoscience of the Great Barrier Reef Shelf - context for Management of Dredge Material.* Queensland Port Association.

- Reef Rebels YouTube channel

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Executive Summary

The Great Barrier Reef (GBR) is by far the world's largest coral reef system comprising 3,000 individual reefs. All reefs have excellent coral, and not a single reef or even a single species of reef life has been lost since British settlement.

According to measurements by the Australian Institute of Marine Science (AIMS), which started in 1985, the amount of coral on the GBR (coral cover) has never been higher than for 2022 and 2023, and the GBR now has twice as much coral as it had in 2012.

Measurements show that cyclones, starfish predation, and bleaching events cause huge, but temporary, fluctuations in coral cover. Recovery from the major mortality events is always very rapid indicating a healthy and robust ecosystem.

Measurements of coral growth rings by AIMS provide data go back to 1570 and there is no reduction in growth rate from 1570 to 2005. Scandalously, there is no data from 2005 to 2023 despite this being the period of most interest.

Growth rate measurements show no decline in the period when agricultural production and pesticide-use started. Concentrations of agricultural pesticides on the GBR are generally in such low concentrations that they cannot be measured even with the most sensitive scientific equipment.

Pollution to the GBR is mitigated by the enormous quantities of ocean water that flushes into and out of the GBR. In just eight hours oceanic inflow equals the entire discharge of water from all the rivers on the Queensland coast in a full year.

Sediment and nutrient runoff from farms have negligible impact on the GBR. Flood plumes rarely reach the GBR, and when they do, they only impact a small percentage of reefs, for a short period of time and, even then, with low concentrations of sediment or nutrients.

Despite the GBR experiencing four supposedly devastating bleaching events between 2016 and 2022, there has never been more coral than in 2022/23. This demonstrates that the bleaching events caused limited coral loss, and their effects were exaggerated.

The type of coral that has increased the most in this period is the Acropora species (mostly plate and staghorn types) that are *most* susceptible to bleaching.

Corals grow much faster in warmer climates and most of the coral species of the GBR also live in waters to the north of Australia where the water is at least a couple of degrees warmer, and where they grow at least 25% faster than in the warmest (northern) waters of the GBR.

The Great Barrier Reef is one of the most pristine ecosystems in Australia. It also has no feral animals (crown-of thorns starfish are native species) of invasive plants – unlike virtually any other Australian ecosystem.

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Chapter 1. What is the Great Barrier Reef?

The Great Barrier Reef (GBR) is by far the largest coral reef system on earth and contains 3,000 individual coral reefs, each roughly 1 to 10 kilometres across. Its area is comparable to Germany or Victoria and Tasmania combined, and is roughly as long as California or Italy. The present GBR is very young, by geological timescales, and has formed and been destroyed many times as the sea-level has fallen and risen with ice ages and warm interglacial periods during the last few million years.[1] It formed in times of massive upheaval and has flourished during periods of continuous change. Coral reefs have existed for hundreds of millions of years.

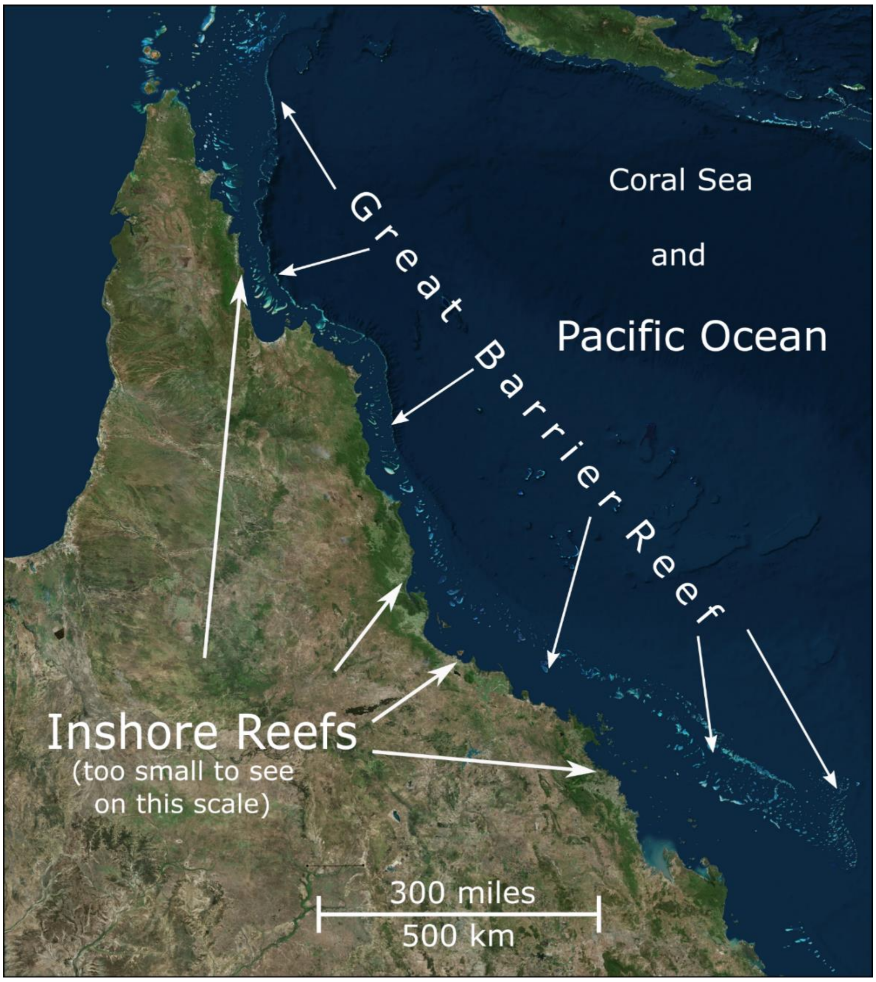

Figure 1.1: The Great Barrier Reef. *The GBR is mostly a long way from the coast – about 100 to 250 km in the south. The inshore fringing reefs are extremely small – too small to see on a picture of this scale unlike the 3,000 GBR reefs. (Image J. Vlok)*

[1] Hopley, D., Smithers, S.G. and Parnell, K. (2007). *The Geomorphology of the Great Barrier Reef: Development, Diversity and Change*. Cambridge University Press.

Each of the 3,000 reefs contains millions of corals, which are in turn composed of somewhere between hundreds to millions of individual coral polyps. The polyps are small animals that live on the outside surface of the coral skeleton in little pot-shaped cavities with walls made of calcium carbonate, which is like concrete. The polyps can vary in size but are often a few millimetres to a centimetre in size (figure 1.2). Corals grow by extending their concrete-like walls. Hard corals have an infinite variety of shapes and sizes but, very simply, can be divided into 'massive' types which are like big solid blocks, or the more intricate and fragile plate or 'staghorn' corals (figure 1.3). The coral polyp lives only at the surface of the coral; the rest of the interior is not alive. For the massive block–type corals, the inside of the coral was produced when the coral was younger, like the inside wood of a tree that was once under the growing bark. The inside of the coral provides physical strength but has little other function.

A remarkable feature of corals is that despite being animals, they are able to get energy from sunlight by nurturing inside the polyp a form of algae, called zooxanthellae, which has chlorophyl and is able to photosynthesize. The polyp and zooxanthellae live in a symbiotic relationship with the zooxanthellae getting a safe environment and the polyp getting energy. As will be explained in chapter 3, occasionally this symbiotic relationship breaks down and the polyp expels the zooxanthellae. Because the zooxanthellae give the coral its colour, when the zooxanthellae are expelled, the coral goes white. This is called 'bleaching'.

Figure 1.2: Coral polyps *Coral polyps are small animals living side by side growing on the outside of this coral colony. Left: massive type coral. Right: branching type coral. (Image Leonard Lim)*

Figure 1.3 Corals come in an infinite variety of shapes. *Left: Fragile plate and 'staghorn' coral; Right: a 'massive' coral. (images Leonard Lim)*

The life expectancy of corals varies greatly with the fragile plate and staghorn–like corals lasting a decade or two. The massive type corals by contrast can last centuries and become enormous – as big as a large car or a shipping container. When corals die, their rock–like "shell" does not rot as a forest tree. Dead coral rubble will last for millions of years under normal conditions. The dead coral eventually piles up and more coral grows on the top and sides of the pile which naturally becomes cemented together by inherent chemical processes. These dead coral substrates, with live coral and many other organisms on top, are called coral reefs. As a result of various biological and chemical processes, the individual chunks of coral will cement to each other over time to form a very hard and resilient structure able to withstand constant erosion from waves.

Importantly, from the point of view of nature conservation, most of the 3,000 reefs are far offshore – more than 100 km in the southern zone (Figure 1.1). For this reason, aside from the few hot–spots where most tourists go, most reefs will rarely see a visitor. The adjacent coast, for the whole of the 2,300 km length of the GBR, has a very low population – perhaps 700,000 people. For the northern section of the GBR, along an almost 1,000 km length of coastline, the total human population is only a few thousand. Compare this with the Caribbean Reefs which have similar extent – there are perhaps 50 million people living nearby, roughly 100 times more than the number living near the GBR. The GBR is one of the most remote, unpopulated, untouched, and unspoiled areas on earth.

The GBR in its present form is just the last in a series of many GBRs that has come and gone roughly every hundred thousand years as the climate has varied in the last few million years. When the climate is much colder than at present, which is about 90 per cent of

the time, the sea level is more than 100 metres lower and the GBR region becomes dry land. During these periods, the coastline is up to 100 km seaward of its present position. In the relatively brief periods of warmth such as the last ten thousand years, the sea level rises by 100 metres and the GBR reforms yet again. During periods of cold climate and low sea-level, the GBR becomes a long group of 3,000 thousand flat topped hills on the coastal plain, each about 50 - 100 metres high, and formed of old dead coral, possibly with fringing reefs at the edge of the continental slope.

Rebirth of the present GBR started about 18,000 years ago when the sea–level began to rise at the end of the 'ice age' (Last Glacial Maximum). By 10 000 years ago, the sea level had almost finished rising but reached its maximum only about 5,000 years ago after which it fell by about one metre until the present day.[2]

The sea–level is now lower than when the Egyptians were building pyramids and when the Earth's climate, and the GBR, was a degree or so hotter than today.[3] This slow fall in sea–level caused massive coral loss which can be seen today on many reefs in the form of dead reef–flats. These are large areas that are now exposed to the air at low tides but would once have been covered by coral when the sea level was higher (figure 1.4). The old dead reef flats are often mistaken as being areas where coral has died recently and mistakenly attributed to farmers or climate change. But this dead coral is far older.

The GBR was formed during periods of massive change, enormous erosion, and presumably high sediment loads. From the very beginning the GBR showed that it is adaptable to changing environments – it formed under conditions of massive change.

[2] Larcombe, P., Carter, R.M., Dye, J., Gagan, M.K. and Johnson, D.P. (1995). New evidence for episodic post-glacial sea-level rise, central Great Barrier Reef, Australia. *Marine Geology*, 127(1–4), pp.1–44.
[3] Roche, R.C., Perry, C.T., Smithers, S.G., Leng, M.J., Grove, C.A., Sloane, H.J. and Unsworth, C.E. (2014). Mid-Holocene sea surface conditions and riverine influence on the inshore Great Barrier Reef. *The Holocene*, 24(8), pp.885–897.

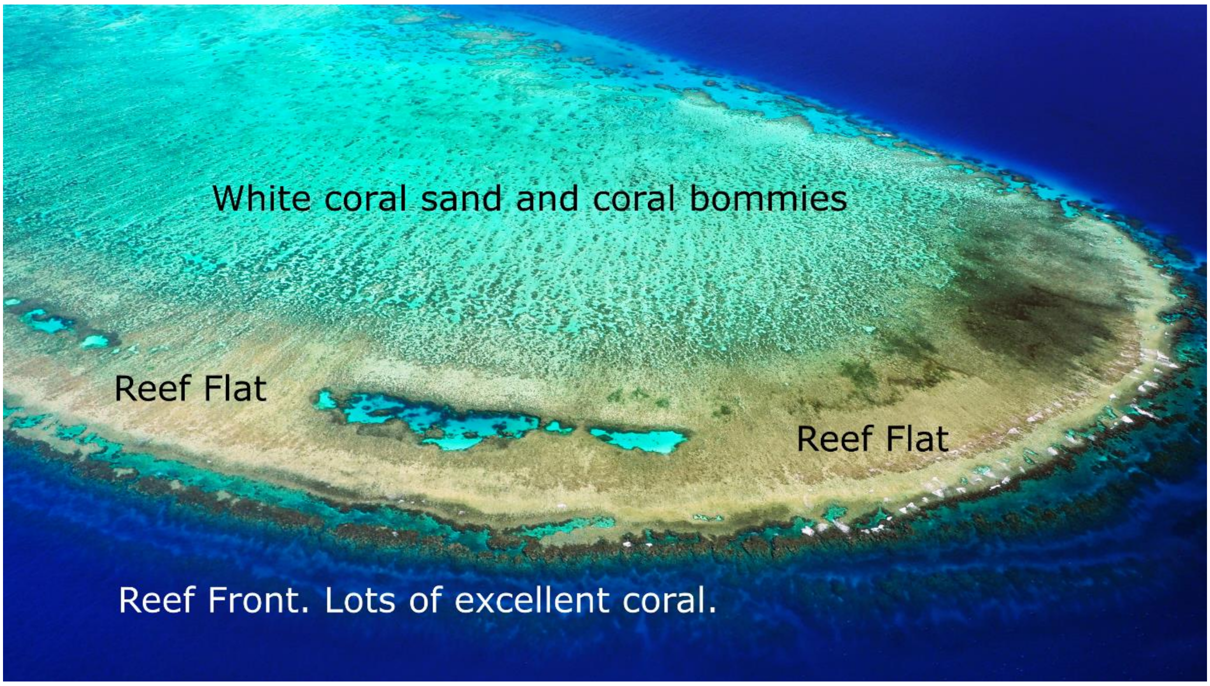

Figure 1.4 Lodestone Reef showing the white coral sand made almost entirely of broken coral and other organisms. The “reef flat” is largely dead, being killed by the slow sea–level fall that occurred over the last 5,000 years – a fact often not appreciated by marine biologists who generally have little appreciation of the geological history of the GBR. The reef flat is regularly exposed to the air at low tide so corals can no longer survive there. (Picture Shutterstock)

The GBR is an underwater chain of 3,000 flat–topped hills sitting on a wide underwater plain called the continental shelf (Figure 1.5). The continental shelf surrounding the reefs is between 50 and 100 metres deep and the sides of each reef are very steep. The shape of the reefs gives a clue to how they form. They are just a pile of dead coral with a surface layer of live coral and other organisms. The reef literally grows on the skeletons of dead ancestors, rising slowly until it reaches sea level. This may take a million years, and is not a continuous process as it can only occur in the relatively brief periods when the sea level is high, as in the last ten thousand years.

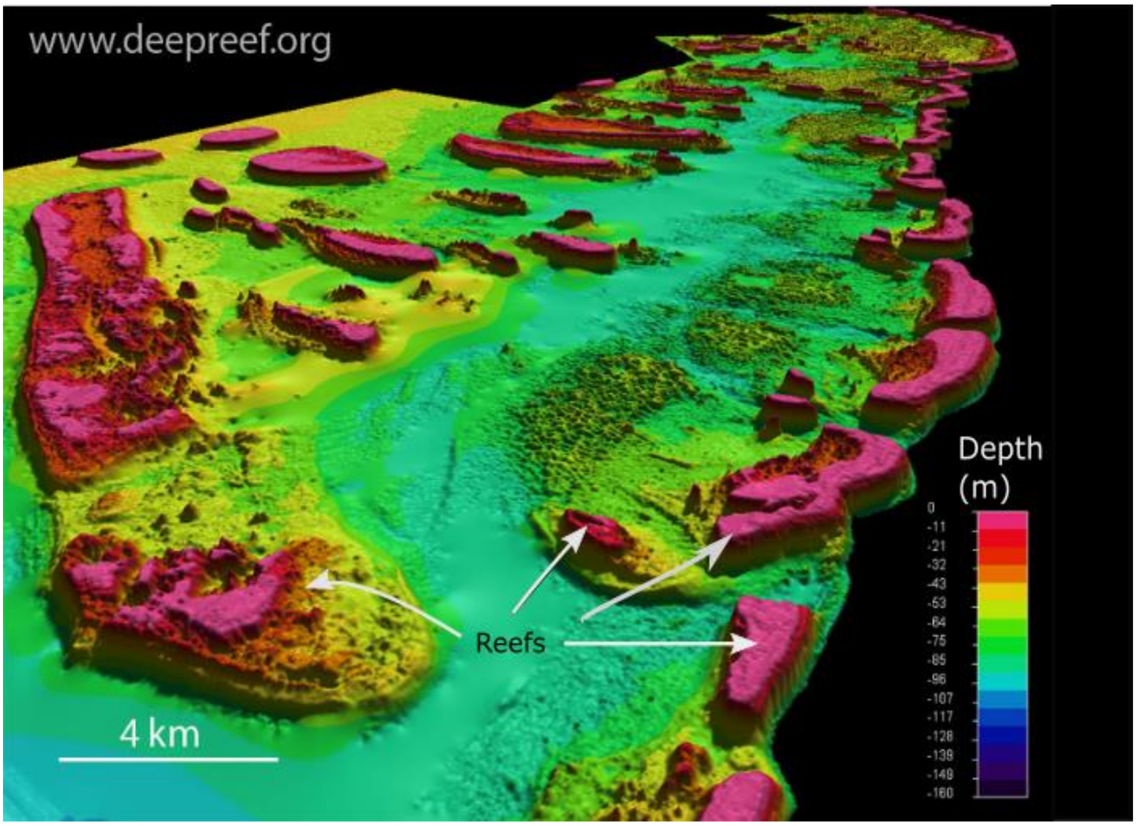

Figure 1.5 The reefs are generally flat–topped underwater hills around 50–100 metres high sitting on the plain of the continental shelf. In this image the reefs to the right are the Ribbon Reefs offshore from Cooktown. (Courtesy R. Beaman, deepreef.org)

The continental shelf upon which the reefs sit has a very steep edge on the eastern side that drops down into the deep water of the Coral Sea and Queensland Trough (Figure 1.6) where the water depth exceeds 1,000 meters. Many reefs such as the Ribbon Reefs are on the edge of this cliff.

The history and geography of the GBR are extremely important to appreciate when evaluating the frequent claims that the GBR has been seriously damaged by human activity. For example, the present gentle warming of the climate over the last decade, and century, needs to be put in context of the huge changes that have occurred over the lifetime of the GBR. In addition, the sheer scale, and distance from the coast, is crucial when considering the impact of farming. In the next chapters, the data of the GBR will be presented.

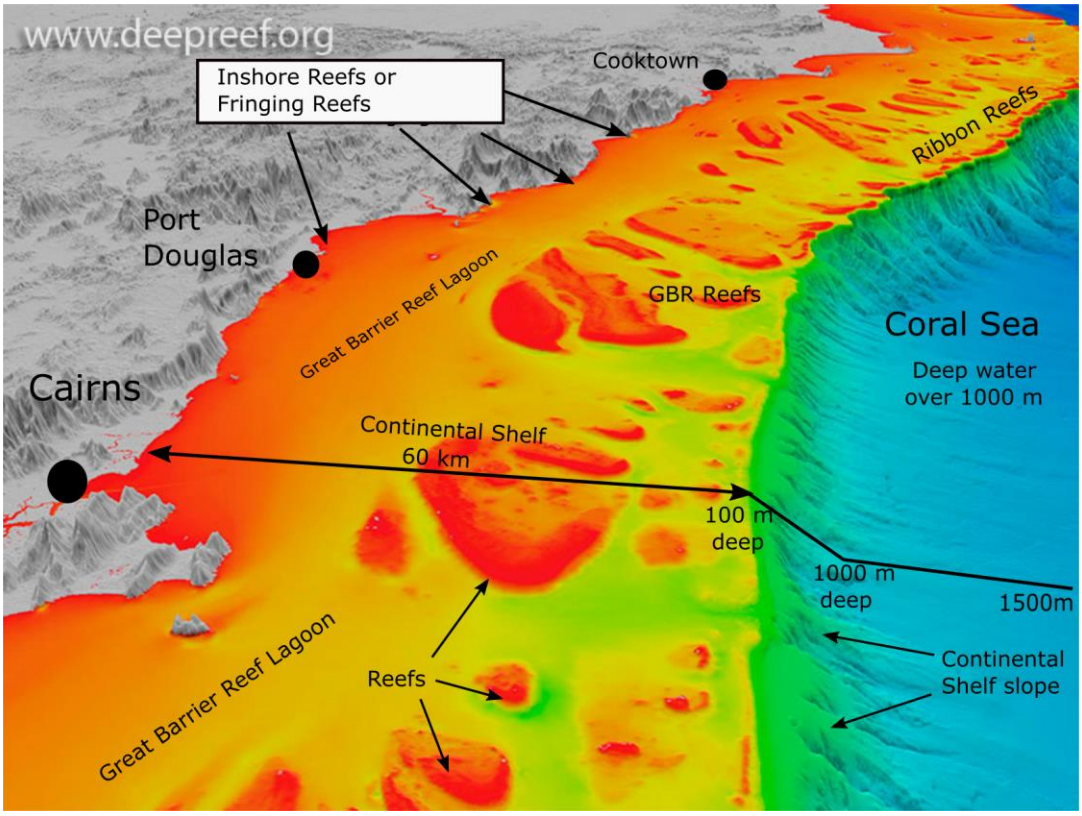

Figure 1.6 The Great Barrier Reef shelf north of Cairns. The reefs are the red patches. The seafloor drops away from around 100 metres to 1,000 metres just offshore from the edge of the barrier reefs. During periods of low sea level (18,000 years or more ago) all the red and yellow areas were dry land. (Bathymetry image: R Beaman, deepreef.org)

Chapter 2. The Great Barrier Reef and its coral: The Data.

2.1 The area and number of coral reefs on the Great Barrier Reef

Of the 3,000 individual reefs of the GBR, all still retain good coral. Not a single reef has been lost. As will be seen in the next section, the amount of coral on each reef (coral cover) can vary dramatically with time. One might question if it is possible to tell if a reef 'died' over a century ago, before good records were kept? The answer is yes – because each reef is a major platform of calcium carbonate rock that rises 50 m to 100 m above the flat seabed of the continental shelf (figure 1.5 and 1.6). If a reef had lost all its coral, the dead platform would remain for millions of years. There are no reef platforms that are bereft of coral.

It can thus be concluded that the area of coral reef is almost exactly the same as when Captain James Cook sailed up the east coast of Australia in 1770. The quality of the reef, which can be gauged from the coral cover fraction, and growth rates will be considered in the next section.

2.2 Coral Cover: the amount of coral on the Great Barrier Reef.

It is often presumed that the only organisms on the seabed of coral reefs are corals. But coral reefs are also home to many other bottom-dwelling organisms such as crustose coralline algae, soft corals, algae, sponges, and seaweed. Significant parts of the seabed on many coral reefs are covered with dead coral or by coralline sand – sand composed of the broken skeletons of corals and other organisms made of calcium carbonate. The 'coral cover' is the ratio of live hard corals to other bottom types. A coral cover value of 1 means that 100 per cent of the seabed is covered with corals. A value of 0 means that all the live hard coral has disappeared.

Because the term 'coral cover' is often misunderstood it is worthwhile comparing a coral reef with an open woodland, which also has a variety of organisms growing on it - trees, grass, and other vegetation. In this analogy, the trees might be equivalent to the corals (except remembering that corals are animals), and the grass and other vegetation would be equivalent to other types of organisms living on a coral reef. Some parts of the open woodland may have bare earth with little covering the soil. As with open woodlands, the fraction of the ground

covered with trees and grass can vary with time, and from place to place. Fires could kill many of the trees, changing the tree-cover – but the area of the forest would remain the same – it just has fewer trees.

For coral reefs, cyclones and crown of thorns starfish occasionally cause considerable coral mortality and reduce the coral cover – but the area of the coral reef does not change.

Large tracts of reefs have been surveyed each year since 1986 by the Australian Institute of Marine Science (AIMS) using 'Manta-tows' (Figure 2.1), a kind of visual census which involves a diver towed behind a small boat along a transect (a straight line that cuts through an environment), estimating the percentage cover, type, and condition of the coral over 100 metres or so. Manta-tows give a quick – broad-brush – estimate of total coral over a very large area. The diver is trained, but there is a degree of subjectivity to these estimates which are discussed in appendix 1.[4] Each reef is many kilometres long around its perimeter, so there could be roughly 50 to 100 individual estimates for each reef depending on the size of the reef. AIMS survey roughly 100 reefs each year.

Figure 2.1: A scientist from the Australian Institute of Marine Science (AIMS) surveying a reef using the manta-tow method (Image: AIMS).

[4] https://www.aims.gov.au/research-topics/monitoring-and-discovery/monitoring-greatbarrier-reef/reef-monitoring-sampling-methods. For more details see https://platogbr.com/308- 2/.

In 2022, AIMS monitoring found record high coral cover on the GBR (figure 2.2) of 0.34+/-0.04 (i.e. 34 per cent of the seabed on the coral reefs are covered with coral).[5] In 2023, the coral cover nominally dropped to 0.32 ± 0.04 although this change is smaller than the uncertainty margin. Over the last 36 years, the coral cover has varied dramatically and reached a low point in 2011 of 0.12+/-0.04. There is about twice as much live coral on the GBR in 2023 as in 2011.[6] There has been a rapid rise in coral cover since 2016 despite four bleaching events between 2016 and 2022. These bleaching events were reported to have killed a large amount of coral.[7] However the data in figure 2.2 shows that the actual impact of bleaching was very limited. It must be remembered that most corals that bleach do not necessarily die – although this point is rarely made by science institutions or the media.[8] Some corals can lose almost all living tissue, but regrow over the alga-covered dead skeleton, restoring coral cover in 12 months.[9] It should be noted that other major bleaching events on the GBR occurred in 1998 and 2002, neither of which caused major coral loss as seen from figure 2.2.[10] The low point in 2011 came after two major cyclone/hurricanes affected much of the GBR and concurrent crown of thorns starfish events.

[5] See https://platogbr.com/308-2/ for details of the analysis. Nowadays, AIMS does not calculate an average coral cover for the entire GBR, although it did until 2017. The author has therefore performed this task to create figure 2.2. AIMS does not give a reason why it stopped calculating the GBR average result even though this is the statistic of most interest to the public and management.

[6] At first glance this may appear as almost a threefold increase, but the uncertainty in the data means that the 2011 figure may be as high as 0.14, and the 2022 figure may be as low as 0.30.

[7] Great Barrier Reef Marine Park Authority (2022). Reef Snapshot: Summer 2021-22. https://elibrary.gbrmpa.gov.au/jspui/handle/11017/3916

[8] Marshall, P. and Schuttenberg, H. (2006). *A Reef Manager's Guide to Coral Bleaching.* Townsville, Australia.: Great Barrier Reef Marine Park Authority. Also https://www.aims.gov.au/research-topics/environmental-issues/coral-bleaching/coral-bleaching-events .

[9] Diaz-Pulido, G., L.J. McCook, S. Dove, R. et al., 'Doom and boom on a resilient reef: Climate change, algal overgrowth and coral recovery'. PLoS ONE, 2009. 4 (4): p. e5239.

[10] There was a slight reduction in coral after 2002 but this was not due to bleaching see De'ath, G., Fabricius, K.E., Sweatman, H. and Puotinen, M. (2012). The 27-year decline of coral cover on the Great Barrier Reef and its causes. *Proceedings of the National Academy of Sciences*, 109(44), pp.17995–17999.

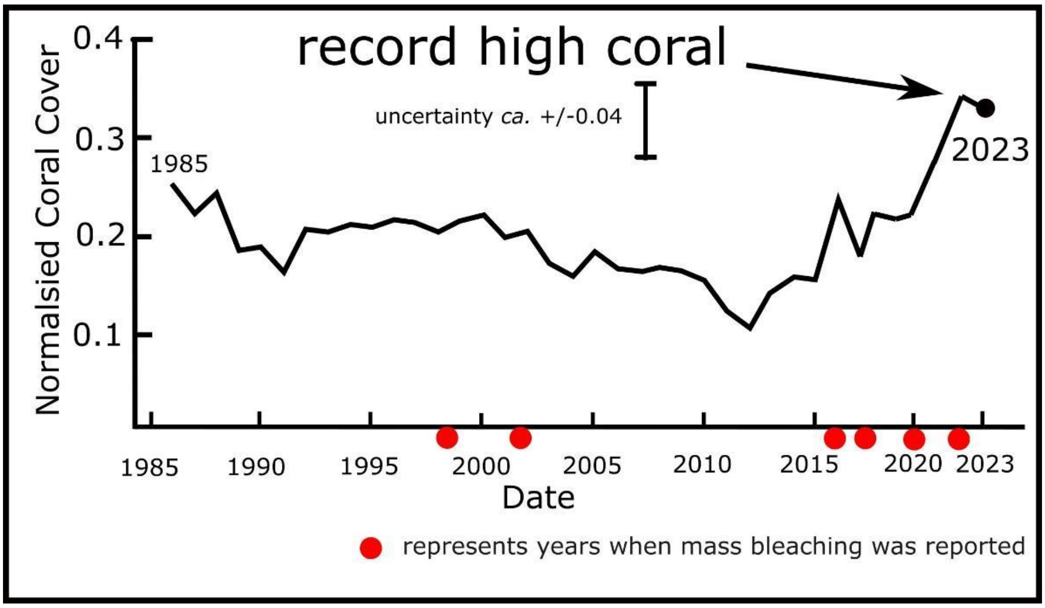

Figure 2.2: Composite of coral cover data in major regions of the Great Barrier Reef

Note: Figure 2.2 is a composite of coral cover data in three major GBR regions, as measured by the AIMS Long Term Monitoring Program and shown separately in Figure 2.3. AIMS stopped collecting the data for the three major regions in 2016-17. See https://platogbr.com/308-2/ for details of the analysis

As shown on Figure 2.2, supposedly 'devastating' bleaching events were recorded by other workers in 2016, 2017, 2020, and 2022, but the GBR has record high coral cover in 2023, and at least twice as much coral as in 2011-12. Coral is a slow growing organism, so this graph illustrates that institutions claiming major coral loss due to bleaching were grossly exaggerating.

Breaking the GBR data into its three major regions (figure 2.3) shows GBR coral cover varies greatly both temporally and spatially.

- The northern region is presently at record equalling high coral cover after experiencing a major decline around 2016 'caused by two severe cyclones, an ongoing crown-of-thorns starfish outbreak and severe coral bleaching in 2016.'[11] But this region has since completely recovered to double its 2016 value.
- The central region is also at record-equalling high coral cover, and has experienced greater degree of fluctuation.
- The southern region is at record equalling coral cover[12] and was severely affected by TC Hamish in 2009.[13] Coral cover in the Southern region is now almost three times its low point in 2011.

[11] https://www.aims.gov.au/reef-monitoring/gbr-condition-summary-2016-2017
[12] Although data for 1988 is 0.42±0.04, and 2022 is 0.35±0.04, there is overlap in the uncertainty range and therefore there is no statistically significant difference between the coral cover on those two years.
[13] There can be a significant lag between the time the coral dies, and when those reefs are surveyed.

It is interesting to note that every region is at record equalling coral cover – once uncertainty estimates (the blue bands) are taken into account. However, due to the large fluctuations of coral cover, it is unusual that coral cover is high in *all* three regions simultaneously. Thus, although none of the three regions are at record breaking high coral cover—not even the North or Central regions as has sometimes been claimed[14]—the aggregate for the entire reef for 2022/3 is at record breaking high, although only just (figure 2.2).[15]

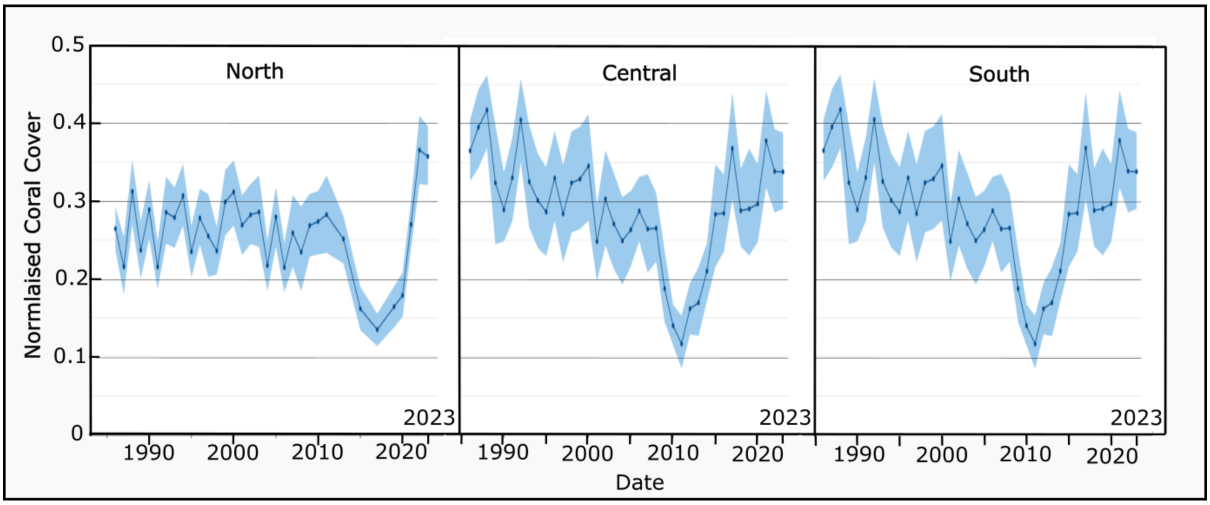

Figure 2.3: Coral cover for the Great Barrier Reef major regions as measured by the AIMS Long Term Monitoring Program.

Graphs as drawn by AIMS. Blue shading represents uncertainty band.

In order to demonstrate the large temporal variability of the coral cover it is worth considering the Capricorn-Bunkers sector, one of the eleven sectors into which the GBR is broken. In 2023/4, this sector has record equalling high coral cover of 0.56±0.06, around three times its lowest value in 2011 (0.16±0.03) (figure 2.4). This sector has been through two cycles of crash and recovery since 1985. It will crash again in the future. Viewing the data in 1993, or 2010, might have given the mistaken impression that this region was in trouble, but one of the most important results of the AIMS long term monitoring program is that we now have a much better idea of natural variability. It shows that variability of coral cover is not a recurring catastrophe – it is part of life on many coral reefs.

[14] These claims may be due to statements made to that affect by AIMS. However, this is an all-too-common misunderstanding of the uncertainty bands. If there is overlap between uncertainty bands between two years, then the two years are not statistically different.
[15] 2022 is 0.34+/-0.04, but 1986 is 0.26±0.03. https://www.aims.gov.au/reef-monitoring/gbr-condition-summary-2016-2017

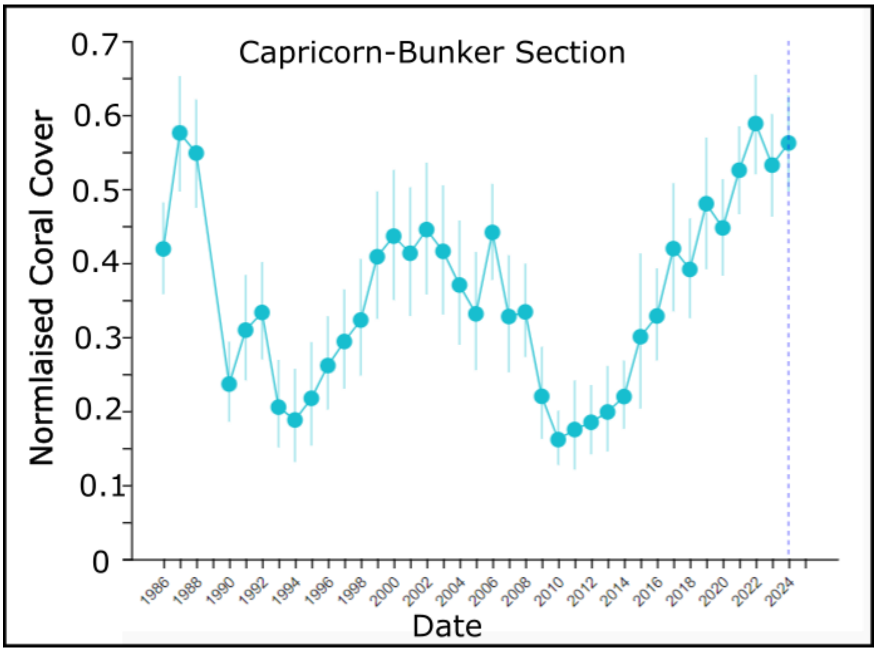

Figure 2.4: Coral cover for the Capricorn Bunkers sector of the Great Barrier Reef as measured by the AIMS Long Term Monitoring Program.

Data: as drawn by AIMS. Blue bars represent uncertainty margins.

Temporal variability gets greater as the area of coral that is sampled gets smaller. A reef with particularly large variability is Helix reef (figure 2.5). Coral cover dropped to just 0.04±0.02 in 1986 due to starfish outbreaks, recovered by 2003, increasing by almost a factor of ten to over 0.4 despite two bleaching events in 1998 and 2002. However coral cover again collapsed to 0.07 in 2012 due to the effects of starfish with a smaller influence of cyclones. It has again recovered to record equalling high levels despite four bleaching events on the GBR since 2016.[16]

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[16] The value in 2022 is not statistically different from the values in 2003. There is overlap of the uncertainty bars. So 2022 is not record breaking for Helix Reef.

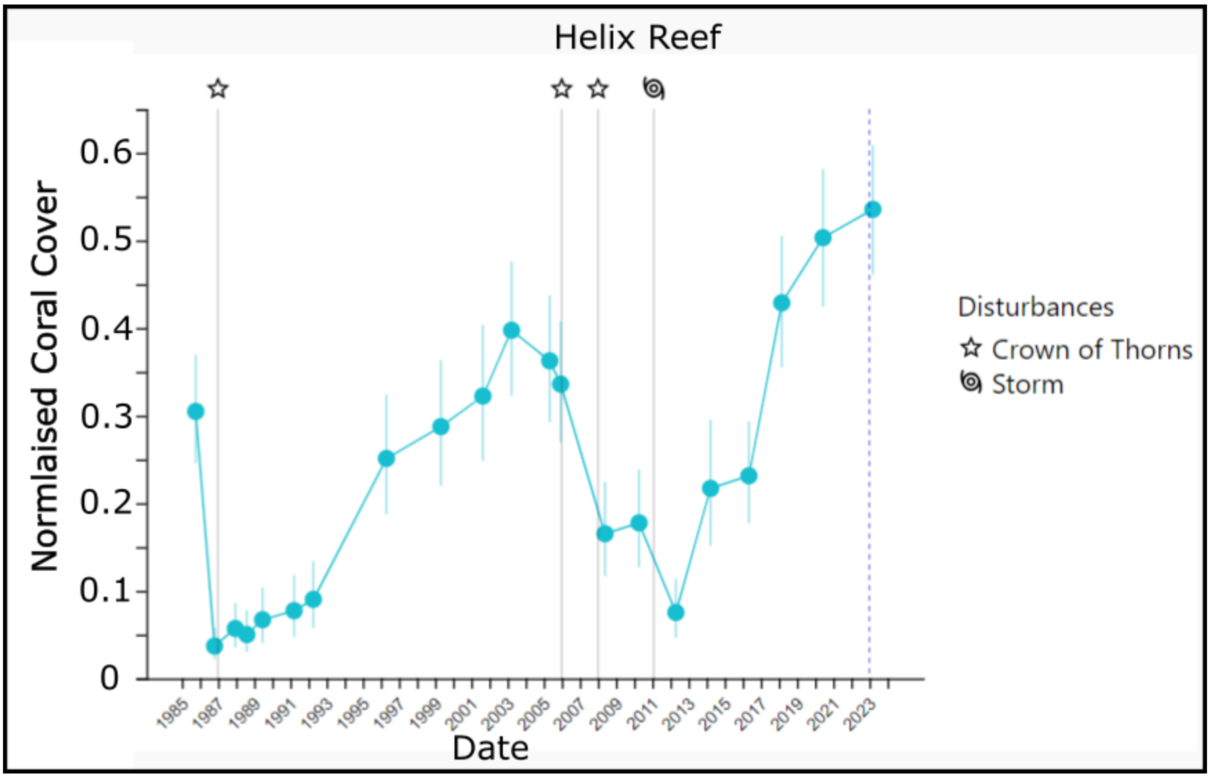

Figure 2.5: Coral cover for Helix Reef on the Great Barrier Reef as measured by the AIMS Long Term Monitoring Program. Data: as drawn by AIMS. Blue bars represent uncertainty margins. Fluctuations of coral cover are around a factor of 10 between the low and high points.

Another reef showing extreme variability is One Tree Island Reef (figure 2.6), but in this case, the variations are due to the passage of cyclones. There is a roughly factor of four change from the low points in 1994 and 2011 to the high points in 1986 and 2022. However, the variability on smaller sections of this and all reefs is even greater as shown in figure 2.7, which shows the results from three detailed short (roughly 100 metre) transects measured by AIMS. These short surveys are very detailed photographic transects which have lower uncertainty margins. For One Tree Island, the short transects show a low point in coral cover of only 0.03 in 2011 after the passage of two cyclones, down from 0.64 in 2007, and 0.78 in 2003. This is variation by a factor of 25.

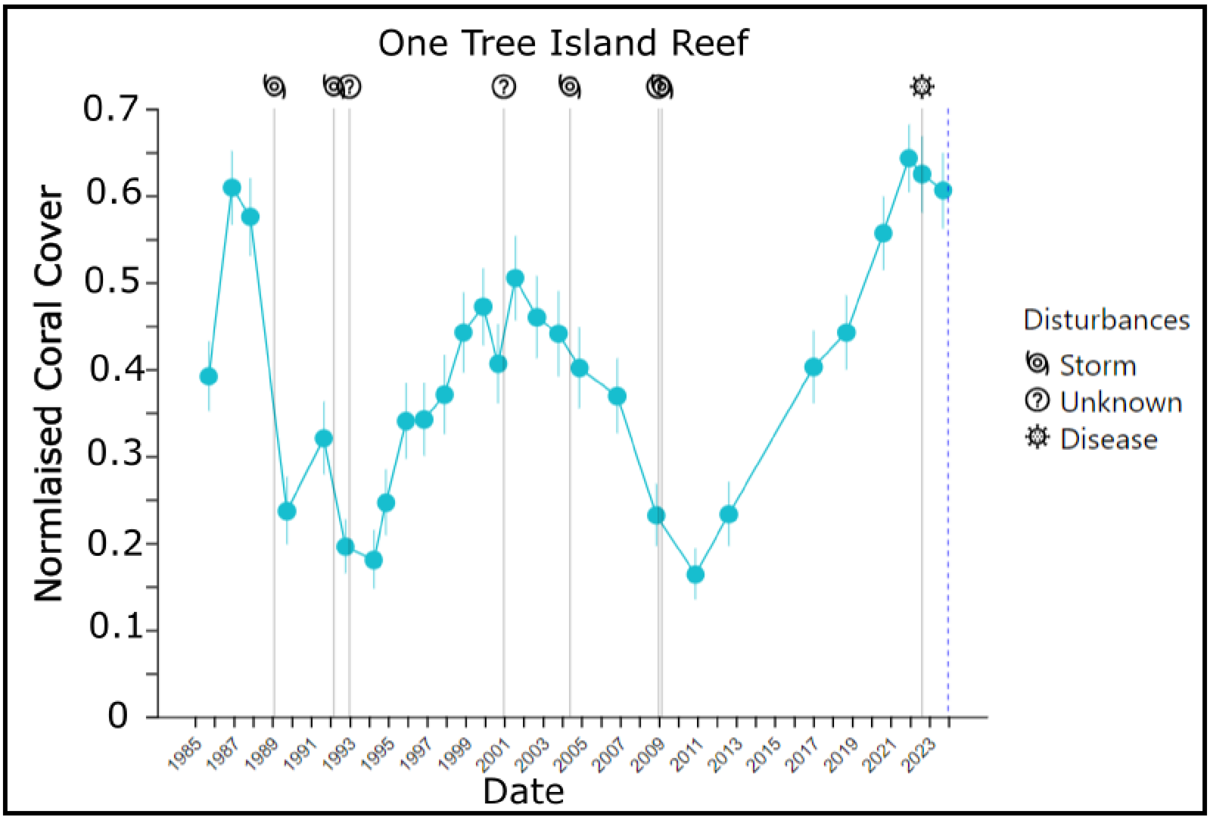

Figure 2.6: Coral cover for One Tree Island Reef as measured by the AIMS Long Term Monitoring Program. Data: as drawn by AIMS. Blue bars represent uncertainty margins.

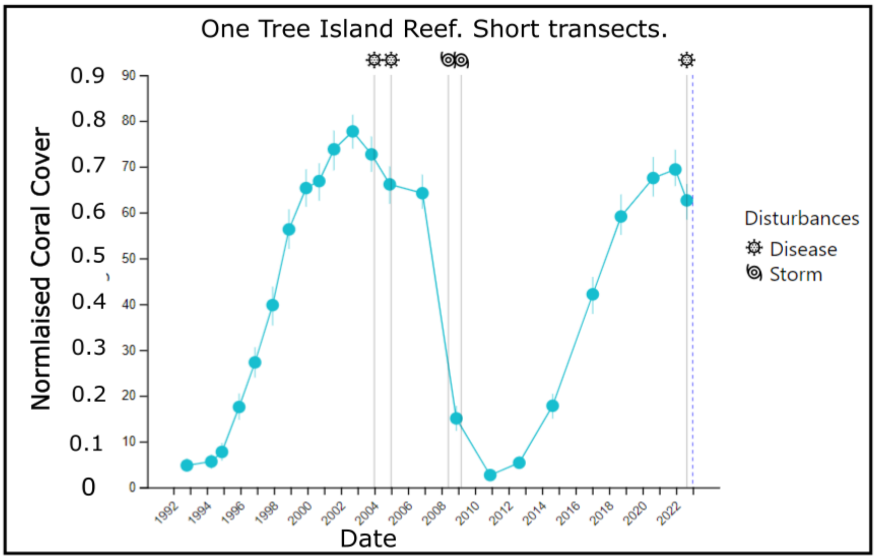

Figure 2.7: Coral cover for short transects on One Tree Island Reef as measured by the AIMS Long Term Monitoring Program (called “Benthic Community Cover” surveys on the AIMS website). Data: as drawn by AIMS. Blue bars represent uncertainty margins.

The above analysis makes it evident that coral cover varies dramatically with time. The GBR is presently in a state of record-breaking high coral, so it can be expected to fall at some stage in the future. Such falls, whilst very concerning decades ago when very little data on the reef was available, can now be put in context: These fluctuations are just a part of life of coral reefs. The falls are not 'disasters' unless there is no recovery. And for the GBR there has always been strong recovery.

2.3 Coral growth rates (calcification)

It is often claimed that climate change and pollution due to agriculture is affecting the GBR. It is evident from the data shown above that the amount of coral on the reef has not declined since records began, and that the number and area of the coral reefs has not changed. There are many commentators who have suggested that stressors, such as pollution, increased temperatures, or changing ocean pH (due to increased carbon dioxide concentrations) may have chronic impacts on corals – making the corals less healthy. One of the first signs of stress in most organisms is that they will grow more slowly. For example, plants given a low dose of herbicide, that does not kill them outright, will generally grow more slowly.

This raises the question – are corals growing more slowly nowadays than before carbon dioxide levels started to rise after the industrial revolution, and also before agriculture started on the Queensland coast about a century ago? Fortunately, large 'massive' *porites* corals (see figure 1.3) lay down a ring of coral each year, much like tree rings, and thus record their own growth rate (figure 2.8). Some extremely large corals, many meters in diameter, can be centuries old and thus record their growth rate for centuries. Smaller corals, of 30 cm or less are likely to be only a couple of decades old. Because some of these corals can live for centuries, it is possible to measure growth rates for the last 400 years by taking a core from them. By measuring the thickness of the annual ring (usually a little over one centimetre), and the density of the ring, a measure of the calcification rate (growth rate) of the coral can be determined over the lifetime of the coral.

The Australian Institute of Marine Science has been collecting coral cores since the 1980s, initially for the purpose of measuring the size of floods from the rivers flowing into the GBR lagoon. It turns out that *porites* corals trap minute quantities of chemicals emanating from rivers which can be seen under ultraviolet light to form fluorescent bands. Years when there are major floods show bright bands. Years with little rain show almost no fluorescence. This

work was specifically trying to look as far into the past as possible, so it used the largest—and thus oldest—coral that could be found. That work stopped in the roughly in 1990, but was restarted in 2003 (De'ath et al., 2009),[17] with the different aim of looking to see if coral growth rates had declined.

De'ath et al (2009), used the older set of coral cores mentioned above, but added new cores taken from many much smaller *porites* corals, and assumed that the growth rate of smaller, very young corals was the same as for very large, older, corals. De'ath et al (2009) found that coral growth rates had remained relatively stable, or even increased from 1600 to 1990, but then fell precipitously (14 per cent) from 1990 to 2005 (Figure 2.8). The fact that the fall started in 1990, precisely when the original work using large, old, coral stopped is very significant as will be discussed below. De'ath stated that the corals of the GBR are declining 'at a rate unprecedented in coral records reaching back 400 years.'

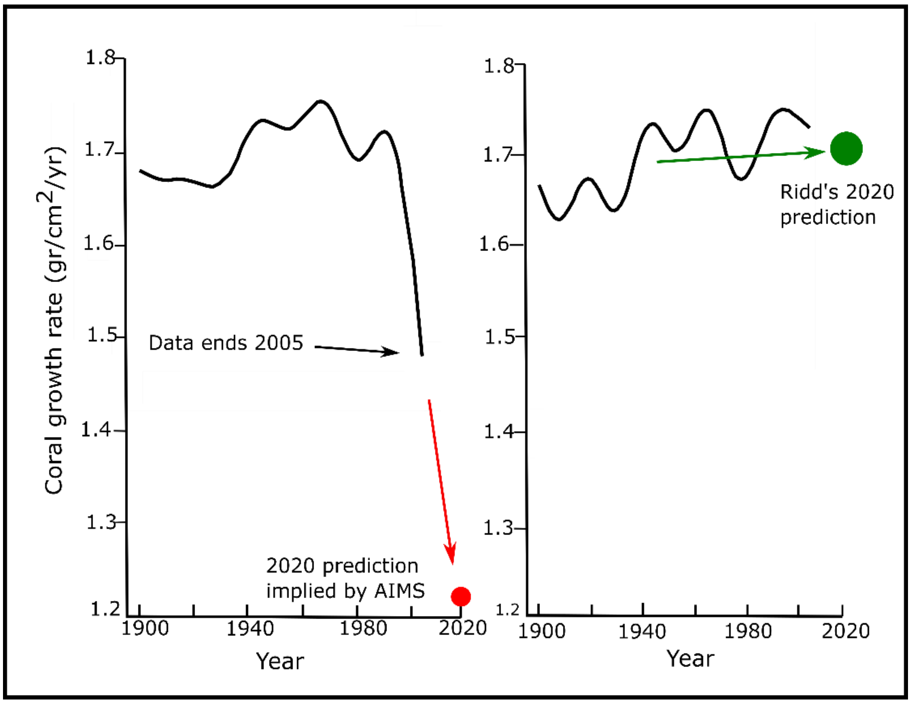

Figure 2.8: Coral growth rate (calcification rate) on the GBR for the 20th century. (Left) Calculated by De'ath et al. (2009)[18] showing drastic reduction after 1990 and prediction (red dot) for 2020 implied by the Australian Institute of Marine Science. (Right) Reanalysed to account for measurement errors and use of very small and young corals after 1990 (Ridd et al., 2013).[19] Green dot is the alternative prediction for 2020.
Note: There is no data of the GBR-average growth rate since 2005.

[17] De'ath, G., Lough, J.M. and Fabricius, K.E. (2009). Declining Coral Calcification on the Great Barrier Reef. *Science*, 323(5910), pp.116–119.
[18] See Endnote 17
[19] Ridd, P.V., Da Silva, E.T. and Stieglitz, T. (2013). Have coral calcification rates slowed in the last twenty years? *Marine Geology*, 346, pp.392–399.

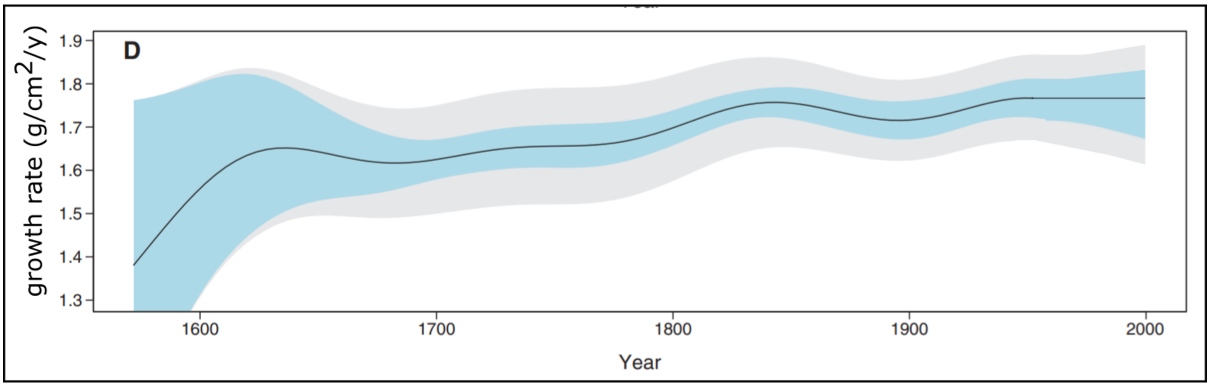

Figure 2.9: Coral growth rate derived from coral cores from 1570 to 2000 – after De'ath et al (2009). Light blue bands indicate 95% confidence intervals for comparison between years, and gray bands indicate 95% confidence intervals for the predicted value for any given year. Note: this graph uses the result from De'ath et al. (2009) from 1570 to 1990, and is estimated using the corrected data from 1990 to 2005 (see figure 2.8) which shows no significant variation after 1950. As the data is effectively smoothed to remove variations with timescales of about 80 years, this affects the data from 1950 onward. However, for this graph the period of interest is around 1900 when agriculture started. Considering the uncertainty margin, there is no change in growth rate at this time.

De'ath et al. (2009),[20] made a serious mistake in their sampling methods and analysis of the cores, which caused the apparent decline after 1990. A fundamental rule in science is that measurement methods should not be changed part way through the work. This is exactly what happened in this case. De'ath et al. (2009)[21] changed from sampling mainly very large corals for data from before 1990 to include sampling many small corals for data after 1990.[22] They thus changed the sampling method, and ignored the possibility that coral growth rate might change with the age of the coral. As a general rule in biology, younger animals and plants always grow faster than adult or mature individuals. Ridd et al. (2013)[23] corrected these mistakes, by focussing only on data from larger corals. They found that, if anything, there may have been a small increase in calcification rate over the last 100 years (Figure 2.8). The sudden drop that occurred around 1990 disappeared. Ridd et al. (2013) effectively showed that porites corals slow down growth as they get larger, and thus the change in methodology from mostly very large corals to mostly very small corals after 1990, resulted in a spurious signal indicating a reduction in growth rate.[24]

[20] See Endnote 17.
[21] See Endnote 17.
[22] See Endnote 19.
[23] See Endnote 19.
[24] This is due to the specific statistical analysis adopted by De'ath et al., as they do not plot average growth rates for all sampled coral: rather, the analysis effectively measured the *change* in growth rates for each coral from

It should be mentioned that other research (D'Olivo et al., 2013)[25] has also found an increase in growth rate of 10 percent for the period 1950 to 2005, working on a different set of GBR corals, casting further doubt on the AIMS work.

AIMS, however, disputes any errors in their work and continue to claim there was a worrying reduction in growth rate between 1990 to 2005. Influential government documents such as the 2019 Reef Outlook Report[26] still cite this disputed work. It is very unfortunate that arguably the most important data shedding light on the health of the GBR is highly questionable from 1990 to 2005.

Far more serious is that there has been no published data whatever, of the average GBR coral growth rates since 2005. Despite having a record of coral growth going back 400 years, we do not know how the coral has fared for almost two decades. The science institutions have not only failed to test their findings, they have also failed to update measurement of this fundamental parameter while claiming that the GBR is in peril.

But, ironically, this failure provides an excellent opportunity. Growth rates for the last 18 years are unknown. It would be easy to fill in the missing data and check the previous disputed results by taking more cores from the GBR. AIMS has effectively stated that coral growth is falling at 1 per cent per year. So, according to the AIMS curve (Figure 2.8), growth should now be 30 per cent lower than it was in 1990 – a disastrous fall. If Ridd et al (2013) is correct, it is more likely that growth rate has stayed the same. Either way, it is important to know what has actually happened: is the Reef really in danger or not?

The missing data since 2005 will have to be remedied sooner or later. A situation where, for one of the most important parameters about the GBR, there is no publicly available data since 2005, should not continue.

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one year to the next: as younger coral in the sample aged, the growth rate sharply declined, and as a result the curve falls after 1990 when the younger corals are included.

[25] D'Olivo, J.P., McCulloch, M.T. and Judd, K. (2013). Long-term records of coral calcification across the central Great Barrier Reef: assessing the impacts of river runoff and climate change. Coral Reefs, 32(4), pp.999–1012.

[26] Great Barrier Reef Marine Park Authority (2019). *Great Barrier Reef Outlook Report 2019*. [online] elibrary.gbrmpa.gov.au. Available at: http://hdl.handle.net/11017/3474 [Accessed 23 Oct. 2019].

Chapter 3: Hot-water ‘bleaching’ on the Great Barrier Reef

3.1: Introduction

Most reports in the media, often based upon news releases from science organisations, paint a bleak picture for coral reefs if even a very small increase in temperature occurs due to anthropogenic climate change. For example, a recent study[27] that was widely reported in the world media[28] claimed that more than 99 per cent of corals would be lost with a temperature increase of just 1.5°C over pre-industrial times. These sources predicted this temperature rise will occur by the early 2030s—only a decade away. Considering that the data in chapter 2 shows little or no coral loss in the past decades, the rate of change on coral reefs is going to have to occur very rapidly for this prediction to come true.

A 99 per cent loss from just 1.5°C effectively proposes hyper-sensitivity of corals to a very small temperature change. What other organism is deemed so sensitive? Remarkably, even corals presently living in cool water will supposedly be ‘overwhelmed’ by such a small temperature increase even though the same species may live in water far hotter, such as in the Coral Triangle located in the hottest large body of water on earth, the Indo-pacific warm pool.

The most publicised effect of rising temperatures on the GBR is ‘coral bleaching’, a phenomenon where the coral expels the symbiotic algae living inside the polyp –turning white in the process. It is often claimed, or inferred, that bleaching has been responsible for killing large amounts of coral, and will be the main cause of coral loss in the future.

3.2 Are bleaching events a new phenomenon?

This fragile-reef hypothesis[29] proposes that mass coral bleaching events only started to occur recently. For example, an eminent coral ecologist at James Cook University Coral Reef Centre of excellence in Australia, stated on Australian Broadcasting Corporation radio

[27] Dixon AM, Forster PM, Heron SF, Stoner AMK, Beger M (2022) Future loss of local-scale thermal refugia in coral reef ecosystems. PLOS Clim 1(2): e0000004. https://doi.org/10.1371/journal.pclm.0000004
[28] https://theconversation.com/safe-havens-for-coral-reefs-will-be-almost-non-existent-at-1-5-c-of-global-warming-new-study-176084
[29] A term first coined by D Mason Jones. Mason-Jones, D. (2019). *Will the Great Barrier Reef Survive? : doubting the doomed reef scenario*. Denhams Beach, NSW: www.journalist.com.au.

> a critical issue here is that these bleaching events are novel. When I was a PhD student 30 years ago regional scale bleaching events were completely unheard of. They are a human invention due to global warming.[30]

However, there are at least 26 records of coral bleaching events in the world before 1982.[31] Bleaching was observed on the first scientific expedition to the GBR, from England, in 1929.[32] Possibly the first observation of bleaching is shown in a remarkable lithograph by von Ransonnet in 1862.[33] There can be no doubt that bleaching is *not* a 'novel' phenomenon, but whether *mass* coral bleaching is a new phenomenon is in question. In other words, have major bleaching events, where large amounts of coral die over a large area, occurred before

Figure 3.1: Lithograph of bleaching of coral in the Red Sea, 1862 By von Ransonnet. See Cedhagen (Endnote 18). The white coral is clearly bleached.

[30] ABC Radio National. (2016). *Widespread coral bleaching detected on the Great Barrier Reef*. [online] Available at: https://www.abc.net.au/radionational/programs/breakfast/widespread-coral-bleaching-detected-on-the/7212760.
[31] Oliver, J.K., Berkelmans, R. and Eakin, C.M. (2018). Coral Bleaching in Space and Time. In: M.J.H. Van Oppen and J.M. Lough, eds., *Coral bleaching : patterns, processes, causes and consequences*. Springer-Verlag Berlin Heidelberg
[32] Yonge, C.M. and Nicholls, A.G. (1931). The Structure, Distribution and Physiology of the Zooxanthellæ. *Great Barrier Reef Exped 1928-29 Sci Rep*, 1, pp.135–176
[33] Cedhagen, T (2021). Coral Bleaching during the little iceage. Phuket mar. biol. Cent. Res. Bull.78: 21–28 (2021) DOI: 10.14456/pmbcrb.2021.1

the 1990s? It must be remembered that it was not until the 1960s that significant study of coral reefs began. Almost nothing was known about reefs before the 1960s. For example, on the GBR, the number of marine scientists in the 1930s was effectively zero, by 1970 there was just a handful. Today there would be easily more than a thousand scientists studying the GBR. It was not until the 1980s that large scale study of reefs began. Remarkable discoveries, such as mass coral spawning, where every coral on the GBR spawns over one or two nights, producing massive slick of eggs on the surface were not documented by scientists until the 1980s. If such a remarkable phenomenon as mass coral spawning, which is highly visible on the water surface, was not discovered by scientists until the 1980s, it is no surprise that mass coral bleaching, which is under the surface and far more difficult to observe, was not documented until the 1990s. It is certainly a remarkable coincidence that mass coral bleaching only started when scientists arrived to study it.

Given that many bleaching events occur during El Nino years, which are weather phenomenon where hot water affects areas thousands of kilometres in size, it is highly probable that some of the 26 bleaching events observed before 1982 were part of what would be termed a mass bleaching event.

In order to answer the question of whether corals are so uniquely sensitive to temperature, and have been damaged by the temperature increase of less than 1°C over the last half century, it is necessary to look at the biology of corals, and the remarkable adaptations they have to changing temperature. It will be seen that far from being the most delicate organism on earth to temperature changes, corals are among the most adaptable. In addition, coral bleaching should not be viewed solely as a death sentence – it is actually a remarkable adaptive response to deal with changing temperature.[34]

3.3: Corals and their algal friends.

Being animals, coral polyps have no chlorophyll and thus no method of getting energy from sunlight by photosynthesis. After a couple of hundred million years of evolution, however, the polyps have built a partnership with microscopic algae called zooxanthellae, that live *inside* the polyp.[35] Like plants, the zooxanthellae have chlorophyll and can get energy from

[34] See this article by Jim Steele for an excellent summary. https://wattsupwiththat.com/2016/05/18/the-coral-bleaching-debate-is-bleaching-the-legacy-of-a-marvelous-adaptation-mechanism-or-a-prelude-to-extirpation/
[35] Note: corals living in the rari-photic zone (very deep water) are excluded from consideration.

sunlight. The polyp gets energy from the zooxanthellae, and the zooxanthellae get their nutrients from the polyp. Corals also consume plankton as an additional nutrient and energy source. This symbiotic relationship with zooxanthellae is key to how corals can adapt to different temperatures as will be explained below.

Infant corals usually have no zooxanthellae, but zooxanthellae of many different types and species are floating around in the water. The coral acquires them from the water and they then grow inside the polyp. But on occasions this mutual relationship breaks down and the coral rapidly ejects the zooxanthellae. It is the zooxanthellae that give coral polyps most of their colour,[36] so ejecting the zooxanthellae leaves the coral 'bleached' white as the skeleton is now visible through the now clear polyp tissue (figure 3.1). The coral polyp however is in peril of starving if it does not take on new zooxanthellae.

Figure 3.1: Corals bleach when the symbiotic algae are expelled. They turn white as the algae give the coral most of its colour. (Picture from NOAA)

[36] and also colour to many other marine organisms in which they live, for example, sea anemones.

3.4 Bleaching is not usually lethal: it is a survival strategy

Corals eject their zooxanthellae under many different types of stress. The best known and most dramatic example is from high temperature in combination with strong sunlight. They can also bleach from cold water, from exposure to air,[37] or if too much freshwater from rivers or rainfall reduces seawater salt concentration. Thermal bleaching is not so much a death sentence as a survival strategy. Corals bleach because the zooxanthellae within them have become 'poisonous', or at least disadvantageous, to the polyp and must be expelled. Coral actively expels the zooxanthellae during bleaching.

Most corals that bleach will survive.[38] It is akin to many other survival strategies seen in nature. For example, many types of Australian trees shed their leaves during extreme droughts in order to conserve water. They regrow the leaves once the drought is over. For corals, after the stress is over, they take back or regrow their community/population of zooxanthellae, but not necessarily the same type as before they bleached.

The good news for corals is that they are highly adept at 'shuffling' or changing the zooxanthellae which come in many different strains[39]. A particular species of coral has a choice to take on many different types of zooxanthellae, and may have a few different types inside them at any one time. Some 'high octane' zooxanthellae will allow the coral to grow fast but be more susceptible to bleaching from high temperatures.[40] 'Low octane' zooxanthellae will make the coral grow slowly but be less susceptible to bleaching. Which strategy is better for a particular coral colony, at a particular location, at a particular time is like a roll of a dice and will depend on the weather.[41]

For many corals, particularly the light and delicate 'plate' or 'staghorn' corals (Figure 1.3), their life strategy is to live fast and probably die young. In ecological terms they are known as 'pioneer' species. They can certainly grow much faster than the solid blocks of the 'massive' corals because they produce a much smaller mass calcium carbonate skeleton to reach the

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[37] https://www.abc.net.au/news/2022-11-03/coral-bleached-abrolhos-islands-west-australian-coast/101608748
[38] Marshall, P. and Schuttenberg, H. (2006). *A Reef Manager's Guide to Coral Bleaching.* Townsville, Australia.: Great Barrier Reef Marine Park Authority.
[39] Baker, A.C. (2003). Flexibility and Specificity in Coral-Algal Symbiosis: Diversity, Ecology, and Biogeography of Symbiodinium. *Annual Review of Ecology, Evolution, and Systematics*, 34(1), pp.661–689.
[40] Buddemeier, R.W. and Fautin, D.G. (1993). Coral Bleaching as an Adaptive Mechanism. *BioScience*, 43(5), pp.320–326.
[41] Jones, A.M. and R. Berkelmans, *Tradeoffs to thermal acclimation: Energetics and reproduction of a reef coral with heat tolerant Symbiodinium type-D.* Journal of Marine Biology, 2011. **2011**: p. 12.

same height. And if a bleaching event does not kill the plate and staghorn coral, their delicate structure will very likely mean they will be obliterated by a cyclone/hurricane/storm within 20 years. They are also highly prone to being eaten by crown of thorns starfish. As it happens, the return incidence for bleaching events and cyclones/hurricanes is often roughly the same and it is probably no coincidence that these physically delicate and easily damaged plate and staghorn corals are the most susceptible to bleaching and have a life expectancy of a couple of decades.[42] Taking on high octane zooxanthellae and growing fast, while risking being killed by bleaching, is all part of their life strategy.

The risk in taking on low octane zooxanthellae is that the coral will be overgrown by the neighbouring coral which had used high octane zooxanthellae. It is better to grow fast when it is possible that one is to be killed by the passage of the next cyclone/hurricane, or by a starfish plague. The opposite are the massive corals that can live for centuries and become a solid block of calcium carbonate, metres across, weighing tonnes. These grow more slowly and will generally pass through a cyclone/hurricane relatively unharmed and are less affected by starfish plagues. They have a long-term strategy, and quick death by bleaching is not part of it.

But corals are very versatile – after they bleach, they can take on a different type of zooxanthellae which may make them less susceptible to high temperature bleaching.[43] Few other organisms have this type of adaptability to changing temperatures. Whereas many organisms need many generations to change their genetic make-up, corals can adapt to changing temperatures in a few weeks, simply by changing zooxanthellae during bleaching.[44]

Corals thus have a remarkable ability to deal with changing climates. Are they the ‘canary in the coal mine’, one of the toughest organisms on earth, or somewhere in between? It is certainly not realistic to consider them as one of the most susceptible organisms to climate change. Corals have survived for hundreds of millions of years, most of which have been far hotter than the present relatively cool period of the Earth’s history.

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[42] Marshall, P.A. and Baird, A.H. (2000). Bleaching of corals on the Great Barrier Reef: differential susceptibilities among taxa. *Coral Reefs*, 19(2), pp.155–163.

[43] Guest, J.R., Baird, A.H., Maynard, J.A., Muttaqin, E., Edwards, A.J., Campbell, S.J., Yewdall, K., Affendi, Y.A. and Chou, L.M. (2012). Contrasting Patterns of Coral Bleaching Susceptibility in 2010 Suggest an Adaptive Response to Thermal Stress. *PLoS ONE*, 7(3), p.e33353.

[44] It is possible that many other organisms can change their microbiome in a similar way to adapt to changing temperatures. But little is known.

3.5 Analysis of past GBR bleaching events.

Hot-water bleaching events were recorded in 1998, 2002, 2016, 2017 2020 and 2022, as marked in figure 2.2 which also shows the coral cover since records began in 1985. It is evident that the four events from 2016-2020 coincided with a period of rapidly increasing coral cover, demonstrating that the bleaching is not a major cause of coral loss. The low point in coral cover, in 2011, occurred after two major cyclones and a series of starfish plagues – it was not due to bleaching.

There was also minimal coral loss from the 1998 bleaching event despite large amounts of coral being reported bleached. According to the Great Barrier Reef Marine Park Authority, the bleaching event in 1998 caused some level of bleaching on 74 per cent of the inshore reefs, which altogether represent about one per cent of the corals of the GBR. For the offshore reefs, representing the other 99 per cent of the GBR, 21 per cent of reefs experienced some level of bleaching.[45] To understand how much coral died, it must be remembered most bleached corals fully recover. According to GBRMPA, 'most reefs recovered fully, with less than five per cent of inshore reefs suffering high coral mortality.'[46] In other words, five per cent of one percent of the GBR experienced serious coral death. Not especially serious and much less than what a decent sized cyclone would do.
Part of the reason that there is considerable confusion about mortality associated with bleaching is that bleaching disproportionately affects coral within a few meters of the water surface. Bleaching surveys are almost all done with observers in an aircraft who can only see the surface corals. Even these surface corals are not clearly visible from a fast-moving aircraft. But what about the deeper corals that go down to 100 metres depth. The deeper water is often far cooler than the water within a few meters of the surface. This is because the conditions of clear skies and low wind, which are the main reasons extreme hot water occurs in summer, have the greatest effect on heating the surface water. Low wind has a direct effect of reducing surface evaporation (cooling), and an indirect effect of reducing the size of waves. Waves are very effective at mixing water vertically, drawing cool deep water to the surface which counteracts the strong heating from sunlight.

An example of the difference between the impact of hot water bleaching between surface and deeper water can be seen from surveys conducted after the 2016/17 event. This event triggered

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[45] Australian Institute of Marine Science (2016). *Coral bleaching events*. [online] Aims.gov.au. Available at: https://www.aims.gov.au/research-topics/environmental-issues/coral-bleaching/coral-bleaching-events
[46] Ibid.

headlines around the world, with reports often implying that 95 per cent of the coral in the northern section of the GBR had been lost.[47] In the scientific literature it was claimed that the GBR lost 30 per cent of its coral (Hughes et al., 2018[48]), most of which occurred in the Northern Region where many reefs were claimed to have been devastated, with typical mortalities over 50 per cent. The fundamental problem is that the survey reported by Hughes et al. (2018) used a methodology that sampled only corals in the shallowest water – less than two metres – notwithstanding that corals live down to well over 50 metres below the surface. Hughes et al. (2018) surveyed the relatively small percentage of corals near the surface that are most at risk. The results were thus completely skewed.

With far less fanfare or world-wide publicity, the data on the deeper corals (between five and 40 metres depth) (Frade et al., 2018)[49] found mortality to be around 10 per cent for the far Northern Region where bleaching was worst and where often 50 per cent of the surface corals has purportedly died. It would be safe to assume that the mortality of deep-water corals for the Central and Southern Regions, which had very low mortality at the surface, would have been close to zero. Thus, taking the areas of these three regions into account, the total mortality for the entire GBR for the corals between five and 40 metres is around three per cent.

Surprisingly, figures are not available for the relative proportion of corals at different water depths but, if it is assumed that shallow water corals represent 20 per cent of the coral (with 30 per cent mortality) and the deeper corals representing 80 per cent of the corals (with three percent mortality), then the total mortality for the entire reef was eight percent. This should be considered as an upper estimate as it is most likely that shallow water coral is far less than the 20 per cent assumed here (Harris et al., 2013)[50].

Considering the capacity of corals to recover, a drop in cover of eight percent should not be regarded as cataclysmic. For example, the Southern region of the GBR increased coral cover by 250 per cent in just six years between 2011 and 2016 following massive coral loss after cyclones Yasi and Hamish.

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[47] McCutcheon, P. (2016). Great Barrier Reef coral bleaching at 95 per cent in northern section, aerial survey reveals. *ABC News*. [online] 28 Mar. Available at: https://www.abc.net.au/news/2016-03-28/great-barrier-reef-coral-bleaching-95-per-cent-north-section/7279338

[48] Hughes, T.P., Kerry, J.T., Baird, A.H., Connolly, S.R., Dietzel, A., Eakin, C.M., Heron, S.F., Hoey, A.S., Hoogenboom, M.O., Liu, G., McWilliam, M.J., Pears, R.J., Pratchett, M.S., Skirving, W.J., Stella, J.S. and Torda, G. (2018). Global warming transforms coral reef assemblages. *Nature*, 556(7702), pp.492–496.

[49] Frade, P.R., Bongaerts, P., Englebert, N., Rogers, A., Gonzalez-Rivero, M. and Hoegh-Guldberg, O. (2018). Deep reefs of the Great Barrier Reef offer limited thermal refuge during mass coral bleaching. *Nature Communications*, 9(1).

[50] Harris, P.T., Bridge, T.C.L., Beaman, R.J., Webster, J.M., Nichol, S.L. and Brooke, B.P. (2012). Submerged banks in the Great Barrier Reef, Australia, greatly increase available coral reef habitat. *ICES Journal of Marine Science*, 70(2), pp.284–293.

There is no doubt that coral bleaching can kill large quantities of coral, especially in shallow water, but the measurements over the last two decades indicate it is a minor cause of coral loss compared with cyclones and starfish plagues.

3.6: Excuses for Failed Bleaching Predictions

The phenomenal increase in coral cover between 2016 and 2023, should be an acute embarrassment for scientists and science institutions that claimed there was massive coral loss. It was a period when four supposedly devastating bleaching events occurred on the GBR. What is even more embarrassing is that species of coral that are known to be most susceptible to coral bleaching, the acropora (plate and staghorn corals), have exploded in number and area during this period of frequent bleaching. Despite being among the fastest growing species of coral, the acropora still take 5-10 years to regrow – to have so much acropora in 2022/3 is proof that the bleaching events caused minimal impact on the GBR.

Astonishingly, it is now often claimed that the increase in acropora is a problem for the reef – the species diversity of the reef has changed, and it is now dominated by acropora.[51] There is no doubt that the species composition of many reefs has changed dramatically over the last decade, but this is exactly what should be expected in a system where there are frequent major mortality events that affect some species more than others. Acropora, is not only the most susceptible to bleaching, it is easily destroyed by cyclonic waves and is one of the favourite foods for crown of thorns starfish. It should thus be expected that the abundance of acropora should fluctuate dramatically – and that is exactly what is seen in the data. For example, figure 3.2 shows the species composition of a transect on One Tree Island Reef, which has shown extreme variation in species composition, and coral cover. The acropora, varied from almost nothing in 1993 and 2011, to covering over 50 per cent of the reef surface today and around the turn of the century. Massive species such as *porites* and *Merulinidae*, which are very slow growing and less delicate compared to acropora, occupy a very small fraction of the sea bed.

The spectacularly high amount of acropora in 2022/3 does not only show that the four bleaching events since 2016 have caused negligible impact on the reef: it has also exposed many of the pronouncements of ‘scientific’ authorities to be entirely erroneous. For example,

[51] https://theconversation.com/record-coral-cover-doesnt-necessarily-mean-the-great-barrier-reef-is-in-good-health-despite-what-you-may-have-heard-188233

in 2012, the low coral cover was described as a disaster (De'ath et al., 2013[52]), but when it reaches record high levels it is not viewed as good news. In 2011, the main loss of coral was the delicate acropora, but when the acropora regrew strongly, it is now claimed that too much acropora is a problem.

In 2018, shortly after the well-publicised bleaching events in 2016/17, a group of sixteen highly influential scientists, representing many important reef-science institutions lamented the loss of acropora -stating

> Fast-growing staghorn and tabular corals [acropora] suffered a catastrophic die-off, transforming the three-dimensionality and ecological functioning of 29% of the 3,863 reefs comprising the world's largest coral reef system … changing it [the GBR] forever as the intensity of global warming continues to escalate.[53]

And yet in 2022/3, the reef has never had more coral, and it is dominated by the species of coral that was supposedly annihilated in 2016/7, and then again in 2020 and 2022.

[52] De'ath G, Fabricius KE, Sweatman H, Puotinen M. The 27-year decline of coral cover on the Great Barrier Reef and its causes. Proceedings of the National Academy of Sciences. 2012;109: 17995–17999.

[53] Hughes TP, Kerry JT, Baird AH, Connolly SR, Dietzel A, Eakin CM, Heron SF, Hoey AS, Hoogenboom MO, Liu G, McWilliam MJ, Pears RJ, Pratchett MS, Skirving WJ, Stella JS, Torda G. Global warming transforms coral reef assemblages. Nature. 2018 Apr;556(7702):492-496. doi: 10.1038/s41586-018-0041-2. Epub 2018 Apr 18. PMID: 29670282.

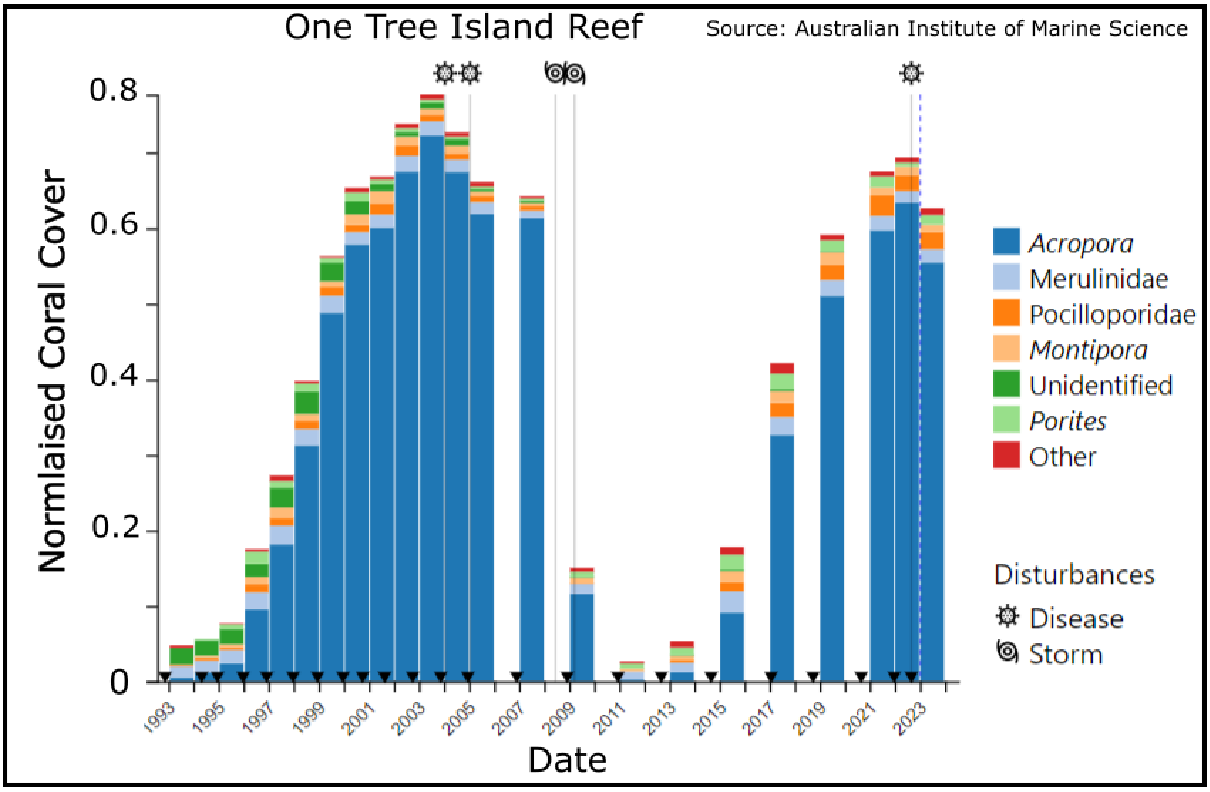

Figure 3.2 Species composition of 100 m transects on One Tree Island Reef. *Data: AIMS. Note the acropora, essentially the delicate plate and branching corals, were devastated by cyclones, but regrow over a decade. The species composition of these reefs thus also fluctuates dramatically.*

3.7 Corals Like it Hot

Although corals grow in most parts of the world's oceans, even in very cold regions such as close to Scotland or Alaska, they are far more common in tropical waters. In addition, their growth rates are far higher in hot water. Measurements on a ubiquitous type of coral called porites by the Australian Institute of Marine Science indicate that for every one degree increase in temperature, there is at least a 15 per cent increase in growth rate (figure 3.3). For the corals of the southern GBR, where the water is relatively cold, a one degree increase in temperature results in a roughly 50 per cent increase in growth rate.

The most diverse and faster growing corals grow in an area called the 'Coral Triangle', a region which includes Thailand, Malaysia, Indonesia, and Papua New Guinea. Oceanographers and meteorologists have a different name for this region: the Indo-Pacific warm pool, so-named because it is the hottest major water mass in the world's oceans. It is not

a coincidence that the Coral Triangle and the Indo-Pacific Warm Pool are the same place – it is a place with very hot water, and corals like it hot.

If the climate is to continue to gently increase in temperature, whatever the other consequences, it should be predicted that coral of the GBR will grow faster, especially in the southern regions where the growth is presently 40 per cent slower than the northern region.

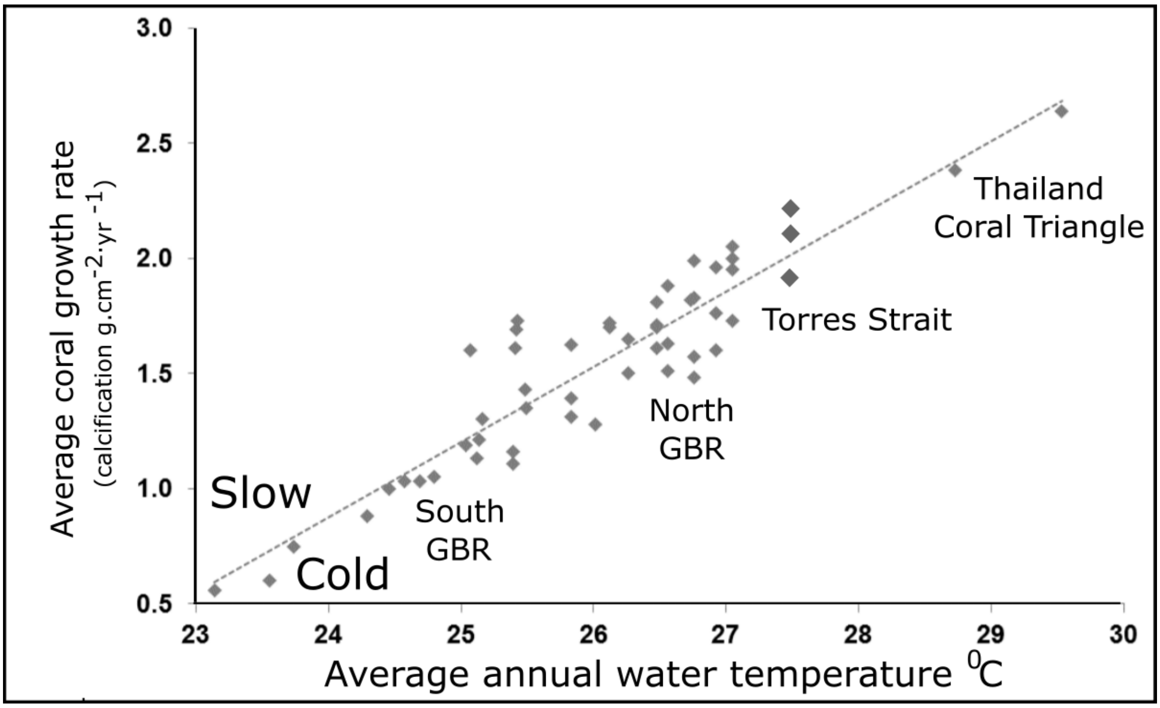

Figure 3.3 Coral growth rate (calcification rate) versus annual average water temperature for *porites* corals. Source: Australian institute of Marine Science.[54]

[54] http://nesptropical.edu.au/wp-content/uploads/2017/01/NESP-TWQ-2.2.1-INTERIM-REPORT-1.pdf

Chapter 4: Impact of agriculture on coral

4.1 Introduction

It is often claimed that the GBR is adversely affected by pollution from agriculture on the adjacent coast. Soil eroded from farms and grazing land, together with agricultural fertilizer (nutrients) and pesticides flow down rivers and are claimed to reach the GBR in quantities that threaten the GBR. There is no doubt that since agriculture started in a significant way on the GBR coastline in the late 19th century, the quantity of sediment and nutrient reaching coastal waters of the GBR has increased.[55] In addition, pesticides are a pollutant that did not exist before about the 1950s. What is in question is whether sediment, nutrient, and pesticide inputs causing a significant change in water conditions that could impact the GBR.

It is notable that the coral growth statistics do not show any reduction in growth rates in the late 19th century, when cattle grazing and sugar cane growing started (figure 4.1). In addition, there is also no change in coral growth rate when fertilizer and pesticides started to be used in large quantities in the 1950s. No reefs have been lost; even inshore reefs close to river mouths. This is a good indication that any impact on the GBR is subtle at most.

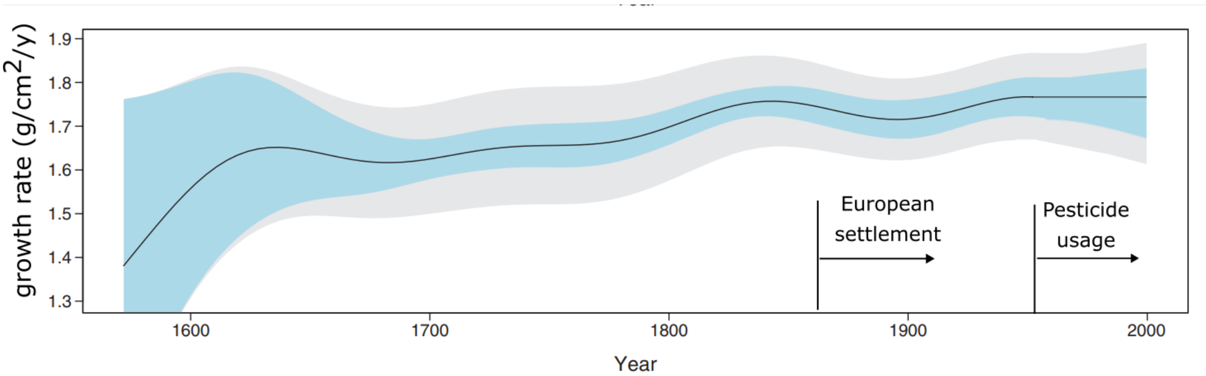

Figure 4.1 Coral growth derived from coral cores from 1570 to 2000 – after De'ath et al (2009). Uncertainty margins as per figure 2.8. European settlement started on the GBR coast around 1860 significant pesticide usage started (1950). There is no evidence of slowing growth rates since European settlement.

[55] McCloskey et al., 2021 McCloskey, G., Baheerathan, R., Dougall, C., Ellis, R., Bennett, F., Waters, D., Darr, S., Fentie, B., Hateley, L. and Askildsen, M., 2021b (In review-b). Modelled estimates of fine sediment and particulate nutrients delivered from the Great Barrier Reef catchments. Marine Pollution Bulletin 2021; McCloskey et al., 2021 McCloskey, G.L. Baheerathan, R. Dougall, C. Bennett, F. Darr, S. Fentie, B. Hateley, L.R. Askildsen, M. Waters, D. Ellis, R. 2021a (In review-a). Modelled estimates of dissolved inorganic nitrogen exported to the Great Barrier Reef. Marine Pollution Bulletin 2021.

The impact of sediment, nutrients, and pesticides will be considered separately below, but it is first useful to consider the enormous flow of water into, and out of, the GBR from large scale ocean currents which greatly mitigates any pollution emanating from the coast.

4.2 Water flushing time of the GBR.

Although flooding rivers carry huge quantities of water to the GBR lagoon, they are completely dwarfed by the flow of water from the large-scale ocean currents. Choukroun et al. (2010)[56] estimated that, in just eight hours, ocean currents push into and out of the GBR the same volume of water as comes down all rivers on the Queensland coast in an entire year. This massive exchange means that water properties of the GBR are dominated by the Pacific Ocean, not by inflows from rivers. This is a crucial fact that is never mentioned in important public policy documents such as the 2019 GBR Outlook Report.[57]

The ocean currents of the Pacific Ocean offshore from the GBR are dominated by the North Vanuatu Jet and the North Caledonian Jet. These major currents, shown in Figure 4.2, flow directly towards the GBR from the east, hitting the GBR roughly in the centre third between Townsville and Cairns. They are then deflected to the north to become the North Queensland Current, and to the south becoming the East Australia Current (EAC). A considerable fraction of these currents, however, makes its way around the reefs into the GBR lagoon. To balance this inflow, an equal amount of water leaves at a different location. It is this flushing of water with the Coral Sea, in huge quantities, that is critically important in determining the water properties. By contrast, quantities entering from rivers are relatively trivial.

In oceanography, the 'flushing time', or 'residence time', is a useful quantity to consider when assessing build-up of pollution. Flushing time is an approximate indication of how long a drop of water may remain in a particular region. For example, the flushing time for Sydney Harbour, almost entirely enclosed by land, is around 225 days.[58] For the Baltic Sea, almost completely surrounded by Sweden, Poland, Germany, and other countries, the flushing

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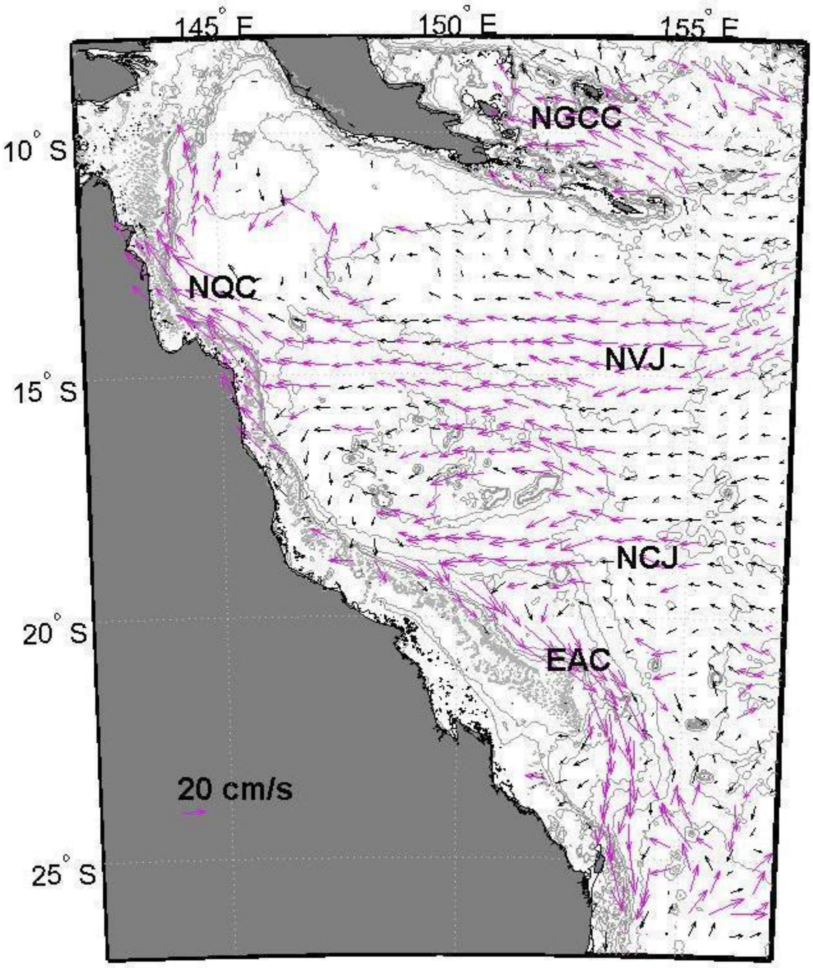
[56] Choukroun, S., Ridd, P.V., Brinkman, R. and McKinna, L.I.W. (2010). On the surface circulation in the western Coral Sea and residence times in the Great Barrier Reef. *Journal of Geophysical Research*, 115(C6).
[57] Great Barrier Reef Marine Park Authority (2019). *Great Barrier Reef Outlook Report 2019*. [online] elibrary.gbrmpa.gov.au. Available at: http://hdl.handle.net/11017/3474 [Accessed 23 Oct. 2019].
[58] Das, P., Marchesiello, P. and Middleton, J.H. (2000). Numerical modelling of tide-induced residual circulation in Sydney Harbour. *Marine and Freshwater Research*, 51(2), p.97.

time is 25 years.[59] The potential for pollution building up in a region with such long flushing times is obvious, especially when the input of pollution is large, as it is in the Baltic Sea and, to some extent, even for Sydney Harbour.

For the GBR proper, the water flushes with the Pacific Ocean over periods of around a few weeks. This has been calculated experimentally using four different methods; radionuclides; satellite tracked drifters; salinity conservation; and heat conservation. It has also been calculated using hydrodynamic computer models.[60] The results of all the four experimental methods agree with each other, and with the models.

Figure 4.2 Mean water currents of the Coral Sea.



Length of the arrows indicates the average water velocity and the direction during these periods. Pink arrows represent velocity greater than 15 cm s^{-1}. EAC-East Australia Current. NQC – North Queensland Current. NCJ – North Caledonian Jet. NVC North Van Vanuatu Jet. NGCC – New Guinea Counter Current. (From Choukroun et al., 2010)

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[59] Döös, K., Meier, H.E.M. and Döscher, R. (2004). The Baltic Haline Conveyor Belt or The Overturning Circulation and Mixing in the Baltic. *AMBIO: A Journal of the Human Environment*, 33(4), pp.261–266.
[60] Mao, Y. and Ridd, P.V. (2015). Sea surface temperature as a tracer to estimate cross-shelf turbulent diffusivity and flushing time in the Great Barrier Reef lagoon. *Journal of Geophysical Research: Oceans*, 120(6), pp.4487–4502.

To flush the water of the GBR with the Pacific in a few weeks represents a huge volume of water. The relatively tiny quantities of nutrients coming from rivers are completely incapable of polluting this massive flow of water into, and out of, the GBR except for very short periods during the peak of river floods. After the flood, the water condition reverts to its normal state dominated by the Pacific Ocean.

The relative size of the ocean currents that sweep into and out of the GBR can be gauged by comparing the flow rates of the largest river, the Burdekin, and the East Australia Current (EAC) which flows along the outside of the reef. The Burdekin has an annual discharge of about 10^{10} m^3 per year[61] and the EAC flow rate is about 10^{15} m^3 per year, about 100,000 times greater than the Burdekin flow rate. It is thus clear that only a very small fraction of the EAC or other currents need to flow into, and out of, the GBR, through the wide channels between the reefs for the water quality to be completely dominated by the ocean. The rivers have only a very small impact, for very short periods of time during floods, and for just a few of the reefs that are very close to river mouths. Additionally, the freshwater plumes from river floods are less dense and normally lie on top of the GBR lagoon water and thus affect only those corals living in the top few meters.

4.3: Nutrient 'pollution'.

It is often claimed that extra nutrients flowing into the GBR have caused an increase in algae on the reef, and may be responsible for Crown of Thorns Starfish (COTS) plagues.[62] It is hypothesized that extra phytoplankton from the extra nutrients feeds the larval stages of the COTS, though why just that one species of starfish should be preferentially favoured by an increase in phytoplankton has not been explained. Starfish, and sea urchins, of various species in numerous different places are well known for occasional population blooms and COTS booms are known from many oceanic locations and desert coasts where there is no agriculture, runoff, or pollution.[63]

Although there is no doubt that the amount of nutrients, mostly nitrogen and phosphorous, flowing into the sea has increased since European settlement, it is rarely appreciated that there are vast quantities of nutrients cycling into and out of the GBR water.

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[61] Furnas, M. (2003) Catchments and corals : terrestrial runoff to the Great Barrier Reef. Australian Institute of Marine Science. https://www.aims.gov.au/sites/default/files/catchments-and-corals.pdf
[62] Fabricius, K.E., Okaji, K. and De'ath, G. (2010). Three lines of evidence to link outbreaks of the crown-of-thorns seastar Acanthaster planci to the release of larval food limitation. *Coral Reefs*, 29(3), pp.593–605.
[63] COTS are a native Australian animal. They are not feral animals like cats or cane toads.

The contribution from rivers is relatively minor in quantity, and usually a long way from the majority of reefs of the GBR, which are farther offshore.[64]

Figure 4.3 shows the relative sizes of the nitrogen flows in the GBR compared to the river nitrogen inputs. There is roughly 100 times more cycling of nitrogen across the seabed than comes down the rivers. In addition, there is roughly 100 times more nitrogen entering the GBR, albeit in low concentrations, due to the flows from the Coral Sea. Quantities of nitrogen comparable to the river flows enters the GBR from upwelling of deep water right next to the reef – rather than the river fluxes which must travel across the shelf to reach the reefs. A huge unknown is the nitrogen input from an algae called trichodesmium which is a nitrogen fixing organism. The production of nitrogen by trichodesmium has received scant attention by research institutions even though there is a strong possibility that it could produce far more nitrogen than enters from the rivers.

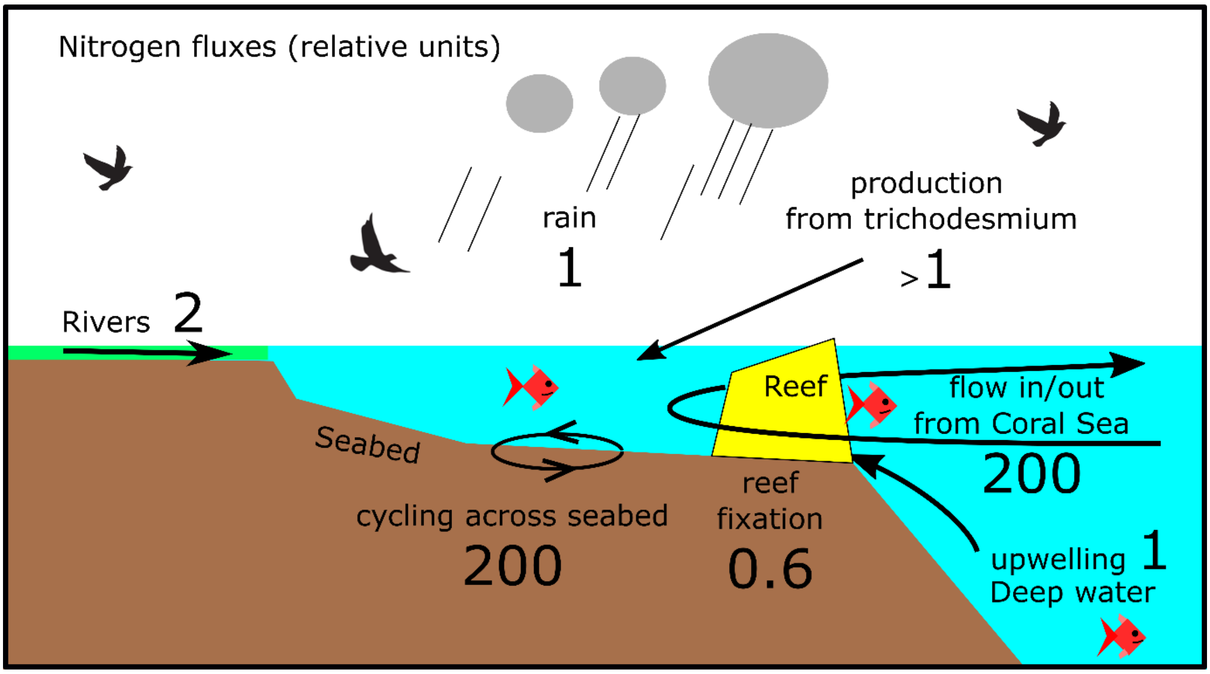

Figure 4.3 Relative fluxes of nitrogen in the GBR. Left hand side is the land with river input. Fluxes are dominated by the cycling across the seabed and the flow into and out of the reef waters from the Coral Sea. Data source Furnas et al (2011)[65]

Regarding the hypothesis that agricultural nutrients cause COTS plagues, there is very little evidence in support. It is known that COTS have been in large numbers for thousands of

[64] Furnas, M. (2003) Catchments and corals: terrestrial runoff to the Great Barrier Reef. Australian Institute of Marine Science. https://www.aims.gov.au/sites/default/files/catchments-and-corals.pdf
[65] Furnas, M., Alongi, D., McKinnon, D., Trott, L. and Skuza, M. (2011). Regional-scale nitrogen and phosphorus budgets for the northern (14°S) and central (17°S) Great Barrier Reef shelf ecosystem. *Continental Shelf Research*, 31(19–20), pp.1967–1990

years.[66] Geologists have cored reefs and found COTS skeletons buried deep in the sand and broken coral rubble structure of the reefs. With time, as the reefs grow towards the surface, their skeletons have become buried.

It should be noted that COTS are widespread throughout the coral reefs of the Indo-Pacific and outbreaks have been observed in oceanic atolls far from any continent and with no obvious agricultural pollutants.[67]

Perhaps the best evidence that COTS are not caused by agricultural nutrients is the finding that the area with the most persistent high numbers of COTS is in the area of the Swains Reefs (figure 4.4) which are the most distant from the coast, and where the impact of river discharge is completely negligible. For example, figure 4.5 shows the coral cover on Turner Cay Reef. This reef has seen two plagues of COTS reduce the coral cover by about 80 per cent with a period of recovery in between. But Turner Cay, which is over 200 km from the nearest land and 250 km from the nearest river, is right on the outer edge of the GBR next to the East Australia Current.

[66] Henderson, R.A. and Walbran, P.D. (1992). Interpretation of the fossil record of Acanthaster planci from the Great Barrier Reef: a reply to criticism. *Coral Reefs*, 11(2), pp.95–101.
[67] some refs: https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=e075e4bcbe762f79e2e5c8f90c8b34466dfb2c7f and https://www.biorxiv.org/content/10.1101/2021.09.13.460188v1.abstract

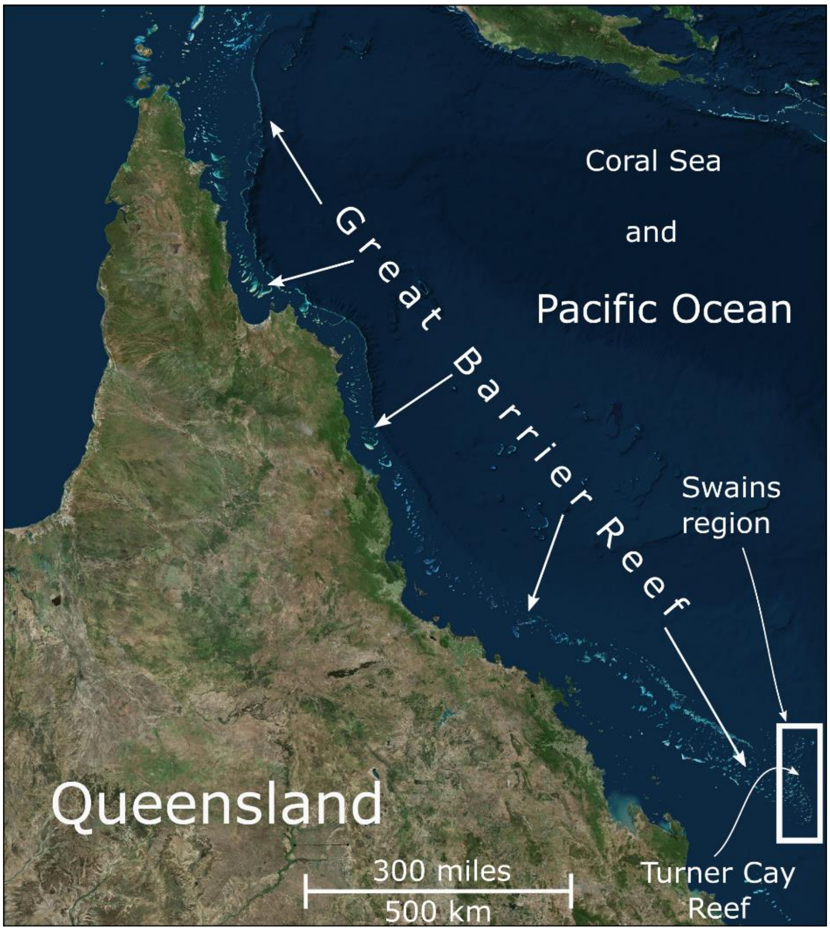

Figure 4.4: Great Barrier Reef showing Swains region and Turner Cay (Figure 4.5). These are some of the reefs most distant from the coast and unaffected by pollutants from land. However, they have experienced persistent outbreaks of crown of thorns starfish.

It should be noted that a major review of 30 years of COTs research by 18 authors (Pratchett et al 2017) stated that the question of whether 'high nutrient conditions and associated phytoplankton bloom … coincide with observed spawning period … was Largely Unresolved.'[68]

AUSTRALIAN ENVIRONMENT FOUNDATION

[68] Pratchett, M.S., Caballes, C.F., Wilmes, J.C., Matthews, S., Mellin, C., Sweatman, H.P.A., Nadler, L.E., Brodie, J., Thompson, C.A., Hoey, J., Bos, A.R., Byrne, M., Messmer, V., Fortunato, S.A.V., Chen, C.C.M., Buck, A.C.E., Babcock, R.C. and Uthicke, S. (2017). Thirty Years of Research on Crown-of-Thorns Starfish (1986–2016): Scientific Advances and Emerging Opportunities. *Diversity*, [online] 9(4), p.41. Available at: https://www.mdpi.com/1424-2818/9/4/41/htm

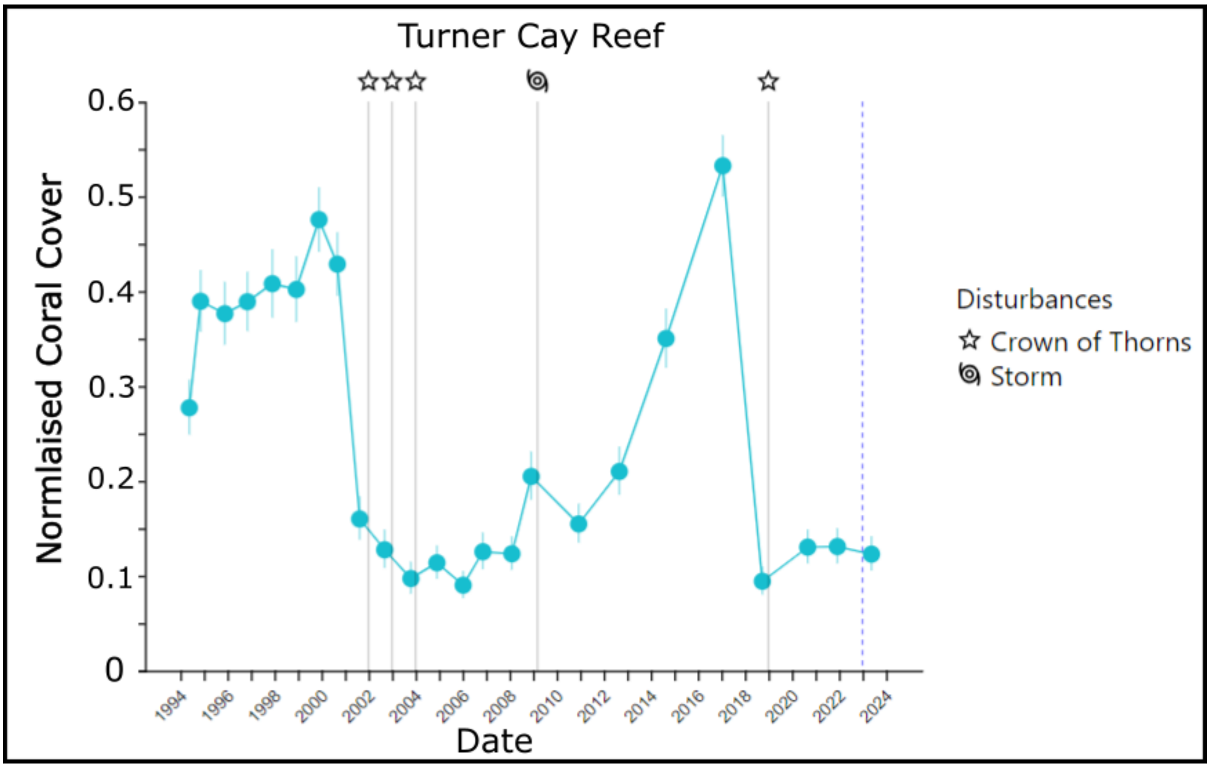

Figure 4.5 Coral cover for Turner Cay Reef as measured by the AIMS Long Term Monitoring Program. Starfish plagues at the turn of the century, and in 2018 reduced coral cover by 80%. Turner Cay is over 200 km from land, over 250 km from the nearest river, and is bathed in the waters of the East Australia current. The influence of coastally derived pollutants on this reef are negligible. Data: as drawn by AIMS. Blue bars represent uncertainty margins.

4.4 Sediment 'pollution'.

Sediment can reach the GBR by either plumes of fresh water coming from rivers during floods, or resuspension of sediment on the seabed by waves. Both these mechanisms cause negligible influence on the GBR[69] as will be shown below. There is almost no sediment on any of the 3,000 reefs of the GBR that came from rivers, although there is a huge amount of fine sand on most of the reefs. However, this sand is calcium carbonate sand with a completely different chemical composition to sediment from eroded soil that came from the land. It is thus very easy to determine the lack of influence of land-derived sediment on the reefs. Images of reefs, such as figure 4.6, always show the reefs to have no fine mud of the

[69] Larcombe, P. and Ridd, P. (2015). *The Sedimentary Geoscience of the Great Barrier Reef Shelf - context for Management of Dredge Material.* Brisbane: Queensland Port Association.

type that is very common near the coast (figure 4.7). Instead, the reefs have white sand, which often appears blue due the scattering of light from the sky.

Figure 4.6: Channel between Hook and Hardy reefs showing a scene typical of all the reefs of the GBR – sparkling clean water, white coral sand that is given a blue hue by scattering of light from the blue sky. There is no mud.

Figure 4.7: Cleveland Bay near Townsville showing a typical coastal scene during periods of strong south easterly trade winds. The waves, generated by strong winds churn the mud on the seabed, cause extreme levels of water turbidity. The mud in Cleveland Bay, and along much of the GBR coast was laid down over the last few thousand years.

River plumes largely remain attached close to the coast as seen in figure 4.8. The lefthand frame shows the exposure to plumes over a ten-year period and it is clear that most of the GBR is unaffected. The right-hand frame is an indirect measure of river plume extent and concentration as it maps the inferred nitrate concentrations from spectral satellite measurements (water colour). It is clear that the plumes are a minor influence on most of the GBR, which is far offshore.

On the rare occasions that river plumes reach the GBR, they only directly impact corals near the surface. The fresh water in river plumes makes the water less dense than seawater so they float on the surface. Most of what is seen in extensive aerial or satellite images has clear ocean water only a few metres below the surface. The plumes only affect the shallow tops of reefs which are also vulnerable to storms, floods, tidal extremes, cold fronts, heat waves, extended periods of calm (which stops wave driven mixing and currents resulting in strong surface warming), and El Niño conditions which can lower sea level by as much as a half-metre.

Most of the mud delivered by rivers deposits on the seafloor close to the river mouth within a few kilometres of the shore.[70] This is because mud particles contain a lot of clay which, when reaching saltwater, tends to stick together (flocculate) to form bigger and heavier conglomerates that settle rapidly to the seabed. Figure 4.9 shows the water turbidity measured by a drifter thrown into floodwaters from the Johnstone River. As the drifter passes out to sea, the turbidity of the water drops within a few kilometres of the mouth.[71]

Although the mud settles rapidly near the mouth of the rivers, it does not necessarily remain there for long. It will, instead, be resuspended from the seabed by wave action caused by strong winds. For the GBR, the South-Easterly trade winds cause waves that resuspend the sediment close to shore (figure 4.7), for roughly two days per fortnight. The quantity of sediment resuspended during these periods of SE trade winds has yet to be measured properly but is probably a few million tonnes and this occurs every couple of weeks (Larcombe and Ridd, 2015).

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[70] Belperio, A.P. (1983). Terrigenous sedimentation in the central Great Barrier Reef lagoon: a model from the Burdekin region. *Bureau of Mineral resources Journal of Australian Geology and Geophysics*, 8, pp.179–190.
[71] Marchant R, Reading D, Ridd J, Campbell S, Ridd P (2015) A drifter for measuring water turbidity in rivers and coastal oceans. Mar Pollut Bull 91:102–106. https://doi.org/10.1016/j.marpolbul.2014.12.021

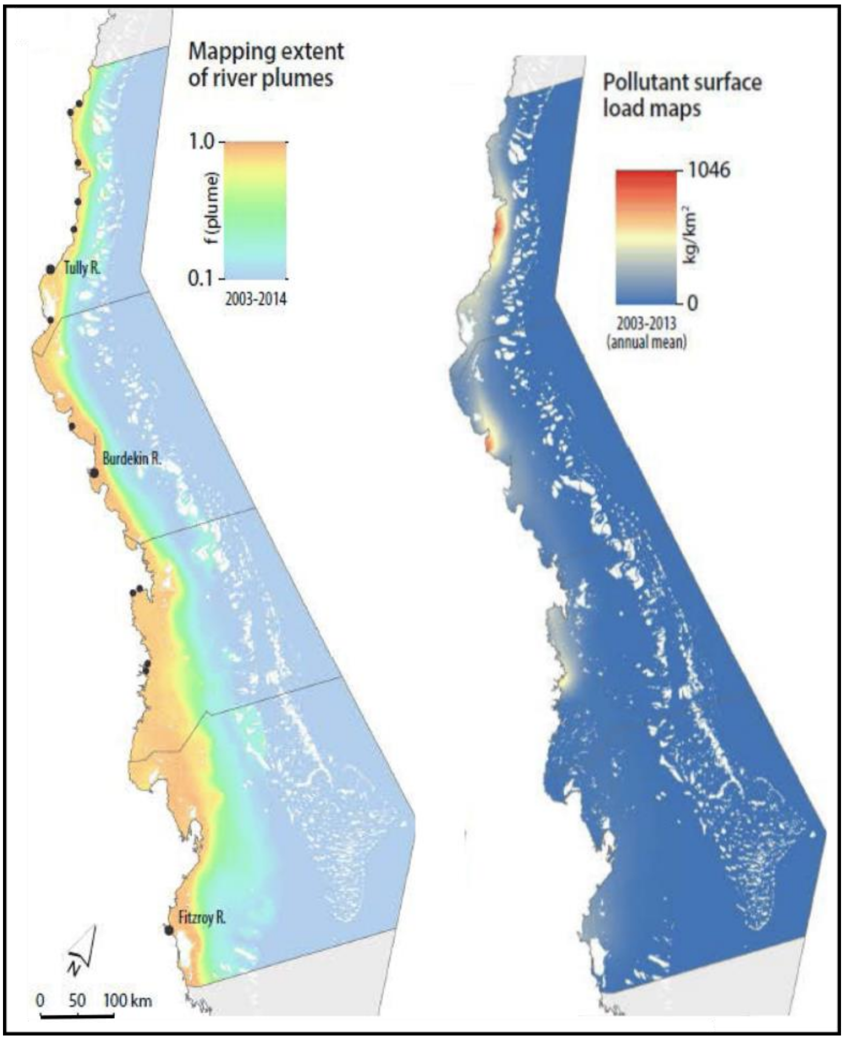

Figure 4.8: (left) the extent and frequency of river plumes along the GBR coast, 2003–2013. The frequency value is calculated as the number of weeks within the wet season (December–April, *ca*. 22 weeks) when a plume is present. (right) Depth integrated Dissolved Inorganic Nitrogen (DIN) for the wet season period December 2010–April 2011). After Develin et al, (2015)[72] Coral reefs are offshore and shaded white.

The winds creating the waves that suspend the sediment also cause a water current to flow north-westwards along the coast. The combination of the waves and the currents results in a north-westward movement of sediment. This movement stops where the sediment reaches one of the sediment traps formed by the northward facing bays such as Cleveland Bay near Townsville, or Trinity Bay near Cairns. These bays are sheltered from the waves and allow the mud to settle more or less permanently. They have a layer of mud up to ten metres deep that has been deposited over the last 10,000 years. Because these bays are full of

[72] Devlin, Michelle J., Caroline Petus, Eduardo Da Silva, Dieter Tracey, Nicholas H. Wolff, Jane Waterhouse, and Jon Brodie. 2015. "Water Quality and River Plume Monitoring in the Great Barrier Reef: An Overview of Methods Based on Ocean Colour Satellite Data" *Remote Sensing* 7, no. 10: 12909-12941. https://doi.org/10.3390/rs71012909

mud, the water is often relatively dirty especially when there are strong trade winds (Figure 4.7).

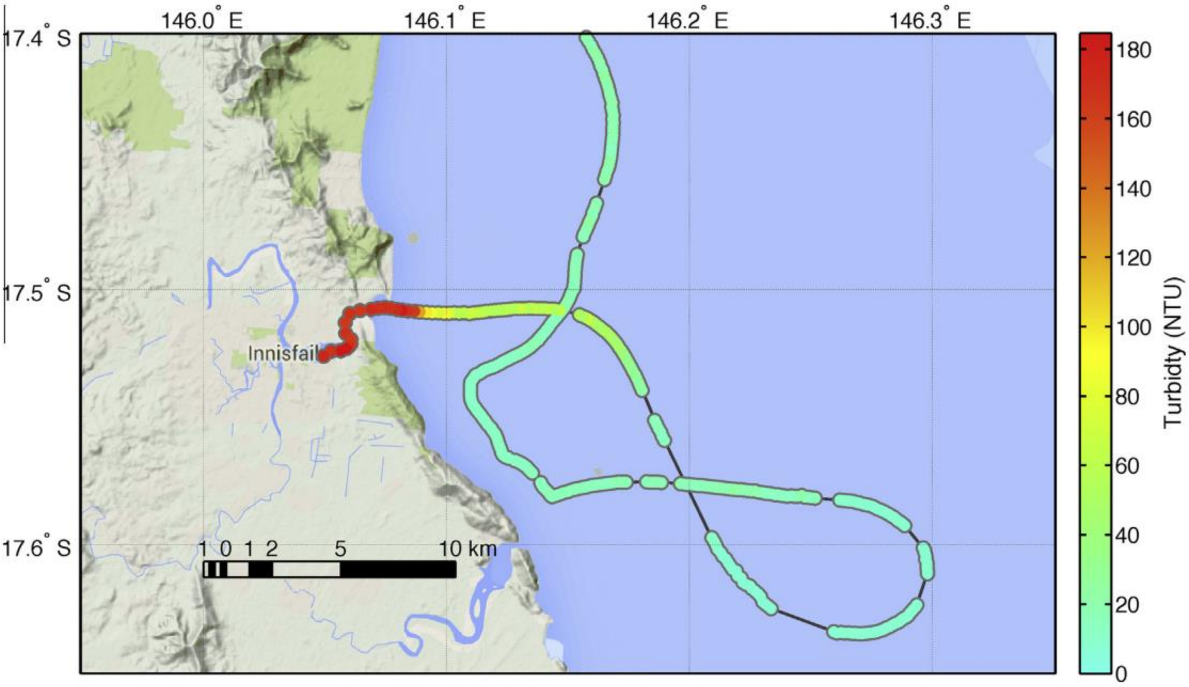

Figure 4.9: Water turbidity (cloudiness) as measured by a drifter deployed into flood water in the Johnstone River on 13 April 2014. The instrument drifted out of the river and after doing a loop moved northward with the ocean current. Most of the sediment dropped out of suspension within 2 km from the river mouth. (See footnote 70)

Very occasionally river plumes do reach the GBR, and images of these have been used to erroneously imply that the GBR is receiving significant quantities of sediment. The most recent example occurred in 2019 after a major flood of the Burdekin River, which also devastated much of Townsville. The images (figures 4.10 and 4.11) of the plume were broadcast in the media worldwide. The satellite images of the plume (figure 4.10) show it just reached the inner-most reefs of the GBR reef matrix - a distance of over 50 km from the coast. The aerial images (figure 4.11) apparently show significantly discoloured water implying large quantities of sediment. However, these images can easily give a mistaken impression of the quantity of sediment in the plume as the colour in the plume is largely due to dissolved organic molecules such as tannins, not sediment. A common household example of this is the discolouration of water in a cup of black tea which can look black but contains no suspended material. The sediment concentrations in this plume near Stanley Reef was just

a few milligrams per litre[73] (Burrows pers. comm) and if it all settled on the reef would cause a layer of only a few microns thick. Observation of the Stanley reef in 2022 found there was no sign of any sediment on the reef and it was in excellent condition.

In fact, these pictures, far from demonstrating that the reef is threatened by river plumes, actually proves the opposite. These are the worst-case conditions – a huge flood from the biggest dirtiest river flowing into the GBR coast. And this huge flood only managed to reach three of the 3,000 reefs of the GBR, with extremely low concentrations of sediment, and only for a few days – this reef will probably not see another event like this for another decade. One could take a similar picture for the next 3,650 days, and probably just see sparkling blue ocean surrounding a magnificent pristine coral reef.

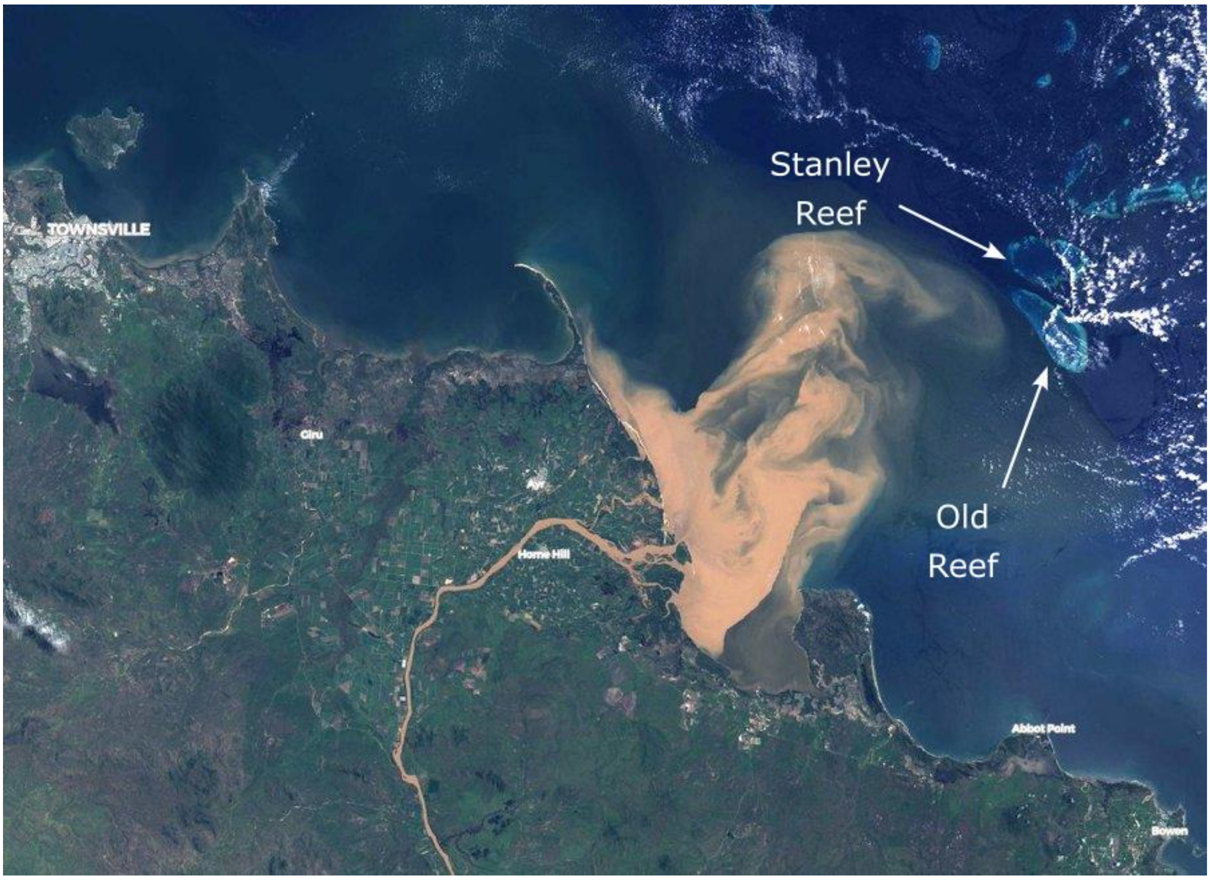

Figure 4.10: Image of Burdekin flood in February 2019 showing the plume just reaching the most inshore reefs: Stanley Reef and Old Reef. It is 55 kilometres from Old Reef to the river mouth. Image: as reported on ABC news.

[73] Correspondence from Burrows to Peter Ridd.

Figure 4.11 An aerial image of plume from Burdekin River covering Old Reef in the central Great Barrier Reef. February 2019. As reported by ABC News. (Matt Curnock/TropWATER JCU). This plume water, while looking dirty, has very low concentrations of sediment. The discolouration is largely due to organic molecules such as tannins – similar to the discolouration of water by tea. It is the worst-case scenario and only affected about three of the 3,000 reefs of the GBR, and only for a few days. This reef is likely not to see another event like this for another decade. The quantity of mud on this reef is thus negligible.

One of the most important factors controlling the sediment dynamics of the continental shelf between the GBR and coast is the impact of cyclones. The waves generated by cyclones can shift vast quantities of sediment and form sand dunes on the seabed that are kilometres long. It has been estimated that Cyclone Winifred (1986), the only cyclone where the impact of sediment was studied, moved 140 million m^3 of sediment and a layer of the seabed 15 cm thick was agitated out to 40 m water depth. This is roughly ten times more sediment than comes down rivers in flood waters on the entire Queensland coast.[74] For cyclone Yasi, the amount of sediment moved has been estimated at 500 million m^3. These are

[74] McCloskey, G.L., Baheerathan, R., Dougall, C., Ellis, R., Bennett, F.R., Waters, D., Darr, S., Fentie, B., Hateley, L.R., Askildsen, M., 2021. Modelled estimates of fine sediment and particulate nutrients delivered from the Great Barrier Reef catchments. Mar Pollut Bull 165, 112163. 751 https://doi.org/10.1016/j.marpolbul.2021.112163

truly devastating events that ‘reset’ the seabed over areas as large as a small European country. Remarkably, the impact of these events on the sediment dynamics of the GBR, or the adjacent inshore areas are ignored in major official documents concerning the GBR such as the 2017 Consensus Statement.[75]

4.5 Pesticides

Major official documents such as the 2017 GBR Scientific Consensus Statement[76] have large sections dealing with the effect of pesticides. Remarkably, while devoting chapters to what pesticides might do if in sufficiently high concentrations, there is a dearth of facts and figures about whether such high concentrations are actually found on the GBR. A little digging into the measurements of pesticides on the GBR reveals why. While pesticides have been ‘detected’, they are at levels so low that they could have no effect. That pesticides can be detected in the GBR lagoon is a tribute to the invention of exceptionally sensitive equipment. Detection of a chemicals in extremely small quantities does not mean it is having a negative effect, and biologists should not imply a greater threat than actually exists just because the mere presence of a chemical has been ‘detected’.

The 2017 Science Consensus Statement relied heavily on a major report by Gallen et al. (2014)[77] which contains results of extensive measurements of a very wide range of the most heavily used herbicides such as diuron. This report, of 100 pages, is also notable for what it did not find – pesticides in high concentrations. The researchers basically found very low levels everywhere on the inshore reefs and generally did not bother to look at the GBR because it was obvious from previous work that the concentrations on the GBR would have been too low to detect. An example of the typical concentrations found close to the coast is shown in figure 4.12 where it is seen that most of the entries are labelled n.d. - not detected. In addition, the units for the table is ng/l which is the equivalent of parts per trillion. So even those measurements where pesticides were detected are extremely low levels.

[75] See endnote 52
[76] Waterhouse, J., Schaffelke, B., Bartley, R., Eberhard, R., Brodie, J., Star, M., Thorburn, P., Rolfe, J., Ronan, M., Taylor, B. and Kroon, F. (2017). *2017 Scientific Consensus Statement: Land Use Impacts on Great Barrier Reef Water Quality and Ecosystem Condition*. [online] Brisbane: The State of Queensland. Available at: https://www.reefplan.qld.gov.au/__data/assets/pdf_file/0029/45992/2017-scientific-consensus-statement-summary.pdf.
[77] Gallen, C., Devlin, M., Thompson, K., Paxman, C. and Muller, J. (2014). *Pesticide monitoring in inshore waters of the Great Barrier Reef using both time-integrated and event monitoring techniques (2013-2014)*. Cooper Plains: The University of Queensland, The National Research Centre for Environmental Toxicology (Entox).

Sample Description	Date collected	Concentration PSII herbicides (ng/L)													% Species Affected	Concentration other herbicides/ pesticides (ng/L)												
		Ametryn	Atrazine	Diuron	Hexazinone	Tebuthiuron	Bromacil	Fluometuron	Metribuzin	Prometryn	Propazine	Simazine	Terbuthylazine	Terbutryn		DE Atrazine	DI Atrazine	Metolachlor	24 D	2,4 DB	Haloxyfop	MCPA	Fluazifop	Fluroxypyr	Imazapic	Imidacloprid	Metsulfuron-Methyl	Tebuconazole
Dunk Island north (repl)	15-Jun-17	n.d.	6.1	1.5	0.85	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	<1.1	1.00	0.57	n.d.	1.1	n.d.	n.d.	n.d.	1.0	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Dunk Island north	21-Oct-17	n.d.	8.7	7.2	2.5	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	*0.72*	n.d.	*4.9*	0.60	0.78	n.d.	1.7	2.5	n.d.	n.d.	n.d.	n.d.	n.d.	1.6	3.4	n.d.	n.d.
Dunk Island north	13-Jan-18	n.d.	0.79	1.0	*0.33*	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	*5.3*	0.00	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Dunk Island north	21-Jan-18	12	1.7	4.2	1.8	*0.07*	n.d.	n.d.	0.85	11	n.d.	n.d.	n.d.	9.7	0.30	*0.28*	*0.11*	n.d.	1.2	n.d.	n.d.	n.d.	n.d.	n.d.	0.68	0.97	n.d.	n.d.
Dunk Island north	28-Jan-18	n.d.	*0.30*	*0.43*	*0.15*	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.00	<0.09	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	*0.27*	n.d.	n.d.	n.d.
Dunk Island north (repl)	28-Jan-18	n.d.	*0.27*	*0.38*	*0.16*	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.00	<0.08	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Dunk Island north	10-Feb-18	n.d.	5.3	7.0	2.6	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	*5.7*	0.00	0.52	n.d.	n.d.	2.4	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.67	n.d.	n.d.
Dunk Island north	12-Mar-18	n.d.	7.3	22	6.3	*0.43*	*0.24*	n.d.	n.d.	n.d.	n.d.	1.7	n.d.	n.d.	0.60	2.1	1.3	0.90	20	50	0.65	n.d.	n.d.	3.8	0.78	10	n.d.	n.d.
Dunk Island north	14-Mar-18	n.d.	7.0	24	5.8	0.50	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.50	2.1	0.86	0.81	18	n.d.	n.d.	n.d.	n.d.	2.9	*0.35*	9.6	n.d.	n.d.
Dunk Island north	20-Mar-18	n.d.	3.1	4.5	1.6	0.55	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.30	1.1	n.d.	*0.29*	5.2	n.d.	n.d.	n.d.	n.d.	1.6	n.d.	1.2	n.d.	n.d.
Bedarra Island	15-Jun-17	n.d.	5.8	2.6	1.3	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	<0.63	0.70	0.83	n.d.	0.78	0.75	n.d.	n.d.	0.69	n.d.	0.81	n.d.	0.89	n.d.	n.d.
Bedarra Island (repl)	15-Jun-17	n.d.	5.7	2.6	1.4	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.70	0.81	n.d.	1.0	0.70	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.77	*0.25*	n.d.
Bedarra Island	21-Oct-17	n.d.	33	26	10	n.d.	n.d.	n.d.	4.8	n.d.	*0.34*	2.28	n.d.	n.d.	1.80	3.6	1.4	11	6.5	n.d.	*0.65*	n.d.	n.d.	n.d.	18	15	n.d.	n.d.
Bedarra Island	13-Jan-18	n.d.	2.09	0.80	*0.47*	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	*5.2*	0.00	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Bedarra Island	21-Jan-18	n.d.	7.2	30	12	n.d.	n.d.	n.d.	6.9	n.d.	n.d.	n.d.	n.d.	n.d.	0.90	1.6	0.61	0.93	6.3	n.d.	0.83	n.d.	n.d.	n.d.	7.8	9.1	n.d.	n.d.
Bedarra Island	28-Jan-18	n.d.	n.d.	<0.12	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.00	<0.06	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	*0.22*	n.d.	n.d.	n.d.
Bedarra Island	10-Feb-18	n.d.	50	78	35	n.d.	n.d.	n.d.	n.d.	n.d.	*0.33*	n.d.	n.d.	*4.5*	1.80	4.7	1.9	0.75	31	n.d.	2.1	n.d.	n.d.	n.d.	3.6	14	n.d.	n.d.
Bedarra Island	12-Mar-18	n.d.	13	61	19	0.72	0.50	n.d.	1.8	n.d.	n.d.	3.0	n.d.	n.d.	1.60	4.3	1.9	1.9	49	79	1.2	n.d.	n.d.	5.1	3.1	29	n.d.	n.d.
Bedarra Island	14-Mar-18	n.d.	8.2	31	9.3	0.72	n.d.	n.d.	n.d.	n.d.	n.d.	*0.82*	n.d.	n.d.	0.80	3.8	1.1	1.2	27	n.d.	0.85	n.d.	n.d.	4.1	1.2	22	n.d.	n.d.
Bedarra Island	20-Mar-18	n.d.	3.9	6.3	2.4	0.63	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.30	1.5	n.d.	*0.47*	6.3	n.d.	n.d.	n.d.	n.d.	2.0	n.d.	2.8	n.d.	n.d.

n.d. - not detected

Figure 4.12 A typical pesticide measurement summary for coastal waters of the GBR showing extremely low concentrations (measured in parts per trillion, ng/l) or below the detection limit of the extremely sensitive instrumentation. The pesticide concentrations on the GBR, which is generally a long way from shore (30-100 km) are far less than shown here – although scientists almost never even attempt to detect pesticides on the GBR-proper because it is pointless.

The work of Gallen et al. (2014) was followed more recently by Gallen et al. (2019)[78] who found no exceedance of 'water quality guideline values' which are set very conservatively. A new site was monitored in this more recent work, Round Top Island, which is very close to the mouth of the Pioneer River. All sites had very low pesticide levels, except Round Top Island which on one occasion had diuron concentrations about 20 times higher than any of the other fringing reef sites that were monitored. The highest concentration approached one part per billion (1µg/l) for diuron. This is still a very low concentration, but higher than had been previously found in earlier monitoring studies and approaching a level that could have minor effect on corals. Gallen stated of the Round Top Island data:

> No individual exceedances of the current marine trigger values (i.e. water quality guideline values) were detected although some of these values are undergoing a review. Assessment against the PGVs [proposed guideline values] for diuron (levels determined to protect 99% of marine species) would however result in two instances of exceedance, both from passive samplers located at Round Top Island, in the

[78] Gallen, C., Thai, P., Paxman, C., Prasad, P., Elisei, G., Reeks, T., Eagleham, G., Yeh, R., Tracey, D., Grant, S. and Mueller, J. (2019). *Marine Monitoring Program: Annual Report for inshore pesticide monitoring 2017–18. Report for the Great Barrier Reef Marine Park Authority,* Townsville: Great Barrier Reef Marine Park Authority.

> Mackay Whitsunday region: 778 and 531 compared to the proposed value of 430 ng L^{-1}.[79]

It is apparent from this statement that the scientists are in the process of reducing the ‘guideline values’; that is, the concentrations deemed to be detrimental to marine species. In essence, the implication was that by reducing the guideline values to 430 ngL^{-1}, the data from Round Top Island would have been a technical exceedance of the conservative guideline values. Given the general exaggeration and misreporting of the threat of pesticides, it is legitimate to ask if this reduction in the guideline value is based upon empirical evidence, or has been adjusted arbitrarily so that ‘exceedances’ can be documented in the future.

The key question is what diuron concentrations will damage or kill corals and other organisms on coral reefs. The main effect of these herbicides is to slow down photosynthesis which means that the plant gets less energy from sunlight. If it is slowed enough, then the plant dies. Fortunately, there is a very sensitive method, called PAM Fluorometry, that can measure slight changes in the photosynthesis at concentrations well below what might be toxic to seagrass or the algae living inside a coral polyp.

Negri et al. (2011),[80] Chakravati et al. (2019),[81] and Wilkinson et al (2017),[82] did tests on the effect of diuron and other herbicides and found that, for diuron, there was a very slight reduction in photosynthesis on seagrasses and coral symbionts at around 1 μg/l as found occasionally at Round Top Island. It would be equivalent to the coral living in slightly deeper water where there is a little less light. Nevertheless, this is an instance where there could be a tangible negative effect, albeit extremely small, at a site where corals live.

It is now necessary to put this site, Round Top Island, in perspective. The small fringing reef around the island is one of the most interesting in the entire GBR because it is arguably the most exposed to farm run-off. If there is an effect from pollution on corals, this is where it should occur. It is just a few kilometres offshore from the mouth of the Pioneer River, the catchment of which is one of the most intensively cultivated on the coast, and has about 20 per cent of the entire Queensland sugar crop including Plane Creek.

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[79] Ibid, 47.

[80] Negri, A.P., Flores, F., Röthig, T. and Uthicke, S. (2011). Herbicides increase the vulnerability of corals to rising sea surface temperature. *Limnology and Oceanography*, 56(2), pp.471–485.

[81] Chakravarti, L.J., Negri, A.P. and van Oppen, M.J.H. (2019). Thermal and Herbicide Tolerances of Chromerid Algae and Their Ability to Form a Symbiosis With Corals. *Frontiers in Microbiology*, 10:173.

[82] Wilkinson, A.D., Collier, C.J., Flores, F., Langlois, L., Ralph, P.J. and Negri, A.P. (2017). Combined effects of temperature and the herbicide diuron on Photosystem II activity of the tropical seagrass Halophila ovalis. *Scientific Reports*, 7(1).

An obvious question is, ‘what is the condition of the coral around Round Top Island?’ Data on pesticides concentrations is interesting but, in the final analysis, all that matters is the health of the corals and other organisms.

Fortunately, Round Top Island has been well studied because, in addition to being the most exposed to agricultural effects, it is also very close to the largest port adjacent to the GBR: Hay Point coal terminal. The port authorities have commissioned studies of the island to determine if dredging of the port and shipping channel has affected the fringing reefs. In fact the authors group at the James Cook University Marine Geophysical Laboratory have measured water quality at Round Top Island for roughly 15 years and, from first-hand knowledge, there is good coral there. Like all reefs, coral cover will vary dramatically with time but coral surveys[83] show about 30 per cent coral cover which is on par with what is found on the GBR which is about 100 km further offshore, and is certainly not a polluted wasteland (Figure 4.13).

Figure 4.13 Corals of Round Top Island, six kilometres from the mouth of the Pioneer River, is perhaps the fringing reef most likely to be affected by farm pollution. There is excellent coral on this fringing reef and the GBR is about 100 km further offshore. (picture courtesy North Queensland Bulk Ports).

Finally, and possibly most important, it must be remembered that Round Top Island is a fringing reef and a very long way from the GBR. In fact, none of the sites measured by Gallen et al. (2019) are on the GBR. Although it could perhaps be argued that the combination of all the pollutants are having a minor effect on corals on Round Top Island, it has certainly not destroyed the surrounding fringing reefs. The total area of coral on this reef—possibly the most polluted of the GBR coast—is about one-tenth of one square kilometre. It is tiny and because

[83] GHD (2005). Appendix E: Benthic Survey of Fringing Coral Reefs of Victor Islet, Round Top and Flat Top Islands. In: *Port of Hay Point Apron Area and Departure Path Capital Dredging: Draft Environmental Impact Statement. Prepared for Ports Corporation Queensland*. Brisbane: GHD.

there is minimal, if any, damage on Round Top Island, there is no possibility of pollutant stress, far over the horizon, 100 km away on the GBR

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Chapter 5: Stretching the GBR to the coast.

5.1 Introduction

The defining feature of the Great Barrier Reef is the 3,000 individual coral reefs which are generally 30 to 200 km from shore. They form a 'barrier' over 2,000 km long sheltering most of the Queensland coast from oceanic waves, and forming a formidable obstacle to navigation of large ships. The marine national park that contains the GBR starts at the coast, and thus contains many coastal ecosystems which are not strictly the GBR.

A notable feature of the major documents that describe the state of the GBR, such as the 2019 GBR outlook report and the 2017 Consensus statement, is that the coastal ecosystems, such a coastal wetlands, seagrass meadows, mangrove swamps, and fringing reefs are regarded as an integral part of the GBR ecosystems. Thus, much of the focus of the debate about the condition of the GBR is about these peripheral ecosystems. For example, the federal environment minister stated, when announcing a major funding initiative about the GBR, 'Mangroves, tidal marshes and seagrasses are critical in protecting the reef from run off but also provide important breeding and feeding habitats for marine life.'[84]

It is often stated in the major documents on the GBR that the ecological linkages between the coastal ecosystems and the GBR are important to the health of the GBR, and thus if the coastal ecosystems are damaged, then the GBR is also damaged. While this statement is true in the sense that all ecosystems in the world are linked to some extent, the magnitude of the linkage may be insignificant.

In this section, the condition of these peripheral ecosystems will be considered, and the extent to which they are intrinsically important to the condition of the GBR will be analysed.

5.2 Inshore Reefs

The GBR is largely 30 to 200 km, and in some areas over 250 km, from the coast. By contrast the inshore reefs (figure 5.1) are the very small reefs that occur in isolated patches along the mainland coast; they are also to be found on some of the islands. They are called 'fringing' because they are on fringes of the land. The inshore reefs have roughly 1 per cent of the coral of the GBR but, surprisingly, no quantitative study has been done to give an accurate figure.

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[84] https://minister.dcceew.gov.au/plibersek/media-releases/joint-media-release-record-budget-boost-protect-great-barrier-reef

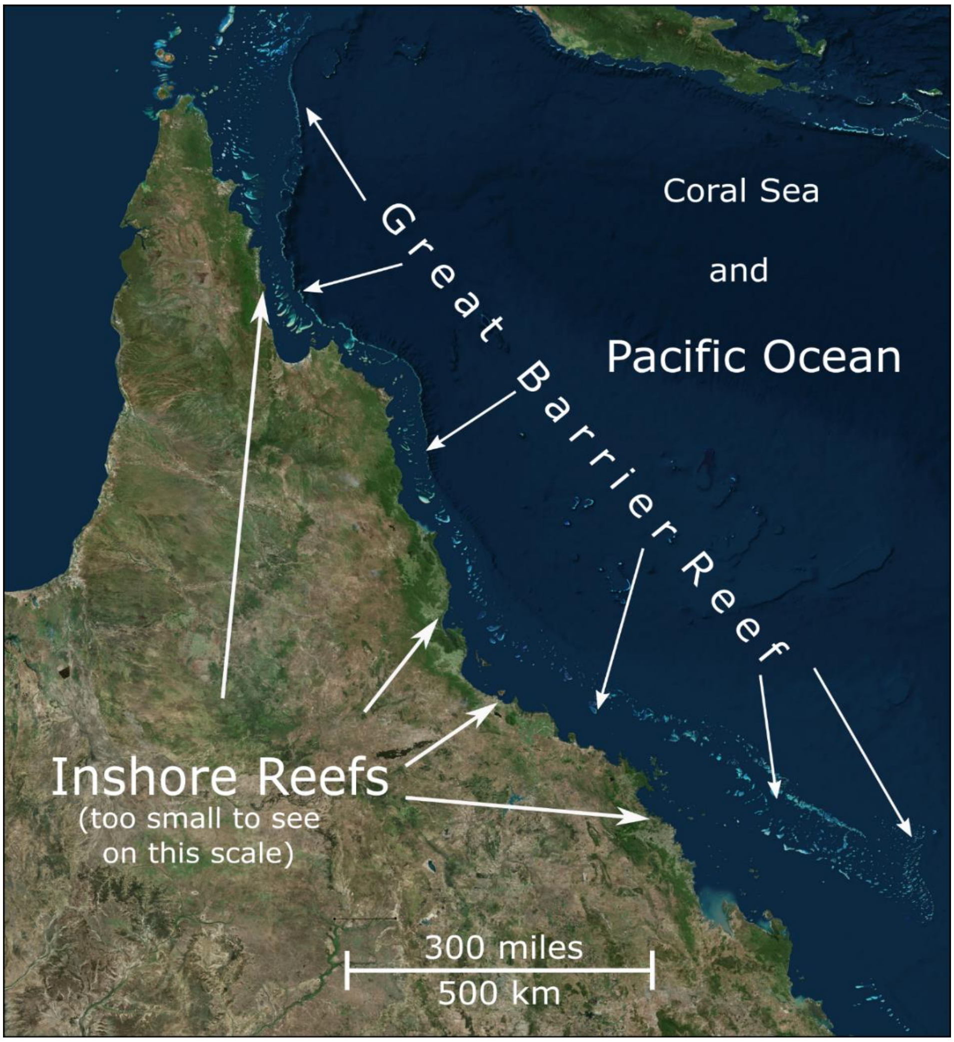


Figure 5.1: The Great Barrier Reef and the locations of inshore fringing reefs. The open water between the coast and GBR has very few coral reefs or shoals.

If there is any damage to corals caused by sediment and pesticides washing off farms, it could only occur on these inshore reefs. They are the frontline when it comes to the effects of pollution. The 'offshore' reefs of the GBR are too far away.

The inshore reefs such as Paluma Shoals shown in figure 5.2 are usually very small, often not much bigger than a few tennis courts, and tiny compared to the huge reefs of the GBR (Figure 5.1). The water is shallow and the coral rarely goes deeper than 10 metres compared to more than 50 metres for the GBR.

The corals of the inshore reefs are also often visually mediocre in comparison to the GBR,[85] and often hard to see because the water is rarely crystal clear as on the GBR, which is

[85] Perry, C.T. and Larcombe, P. (2003). Marginal and non-reef-building coral environments. *Coral Reefs*, 22(4), pp.427–432.

bathed in the deep clear waters of the Pacific. Instead, waves stir up the seabed of the shallow inshore reefs making visibility often less than a couple of meters. To contrast the inshore reefs from the GBR, the term 'mediocre fringing reef' has been coined.[86]

The coral species on the inshore reefs are often very different from those of the GBR as they have to be tolerant to lots of mud. They also must deal with hotter water in summer and colder water in winter because the shallowness of the water allows much greater swings of temperature to occur.[87] If nothing else, the inshore reefs demonstrate that corals are not like a 'canary in a coalmine'. They form robust ecosystems that can live under very adverse conditions, in many cases with very high coral cover.[88]

Figure 5.2 Paluma Shoals. A fringing reef north of Townsville. Waves stir the naturally muddy seabed. It is not a place to take tourists but it is a healthy reef and some parts have very high coral cover. Biologists often claim that reefs and shoals like this have been damaged by mud from farms and dredging, but geological evidence indicates they were always dirty reefs.[89] (Photo: Piers Larcombe)

[86] Reef Heresy? Science Research and the Great Barrier Reef. Connor Court Publishing.
[87] Mao, Y. and Ridd, P.V. (2015). Sea surface temperature as a tracer to estimate cross-shelf turbulent diffusivity and flushing time in the Great Barrier Reef lagoon. *Journal of Geophysical Research: Oceans*, 120(6), pp.4487–4502.
[88] Morgan, K.M., Perry, C.T., Johnson, J.A. and Smithers, S.G. (2017). Nearshore Turbid-Zone Corals Exhibit High Bleaching Tolerance on the Great Barrier Reef Following the 2016 Ocean Warming Event. *Frontiers in Marine Science*, 4:224.
[89] Reef Heresy? Science Research and the Great Barrier Reef. Connor Court Publishing.

Aside from some very small areas that have been reclaimed for port access (e.g., Magnetic Island) there are no examples of any fringing reefs being lost, not even in the region of the coastline closest to major agricultural regions (see section 4.5). This is good evidence that the impact of agricultural pollution is at worst, quite subtle.

Water quality on the inshore reefs is only affected by pollutants in a very minor way. Section 4.5 noted that the individual coral reef most exposed to agricultural pesticides, Round Top Island never registers levels that exceed extremely strict environmental guidelines. In addition, as will be explained below, the levels of sediment and nutrients to which the inshore reefs are exposed is only marginally above that of pre-European times. This is because the inshore areas have always had extremely high levels of sediment and nutrients, and the extra due to agriculture is relatively minor - so minor that it is difficult to measure.

The most obvious feature of the waters of the inshore reefs is that they can be extremely muddy, especially compared to the spectacularly clean water of the GBR. Figure 5.3 shows the waters of Cleveland Bay during a period of strong south-easterly trade winds which occur for many days each month. The waves from the strong wind stir up the muddy seabed. The water near the coast will routinely have concentrations of sediment 100 to 1,000 times the levels of the GBR. Most importantly, these inshore regions were always very muddy as was discovered by the pioneering work of Piers Larcombe and Ken Woolfe.[90]

[90] Larcombe, P. and Woolfe, K.J. (1999). Increased sediment supply to the Great Barrier Reef will not increase sediment accumulation at most coral reefs. *Coral Reefs*, 18(2), pp.163–169.

Figure 5.3: Cleveland Bay near Townsville. Fringing reefs are located just to the left of this picture. Waves are stirring up the muddy sea-bed. This is mud that has been deposited in the bay over thousands of years and is not caused by human activity such as soil erosion from farms or dredging. (Photo: Port of Townsville Limited**)**

To draw this conclusion Larcombe and Woolfe pointed out that drill cores into fringing reefs always contain very large quantities of mud. Fringing reefs ‘grow’ to the surface of the water at a rate of very roughly one metre every thousand years. Thus, drilling into the reefs, and dating the coral gives the conditions under which the reefs were growing thousands of years ago. And the inshore areas were always muddy. In addition, Larcombe and Woolfe pointed out that the coastal regions, especially the northward facing bays such as Cleveland Bay, contain vast quantities of mud that has been deposited over the millennia – in some cases over 10 metres depth of mud. These regions must have always been subject to extremely high sediment concentrations whenever there are strong winds. There is now more sediment coming down the rivers than in pre-European times, but this extra sediment is minor compared to what is already there.

It is almost certainly true that river plumes now contain more sediment than in pre-European times (by perhaps a factor of four),[91] and there is no doubt that the inshore reefs fall under the influence of these plumes (see figure 5.4 top). However, the inshore reefs receive a very small amount of sediment from the plumes relative to what they receive due to resuspension of sediment. For example, Figure 5.4(top) shows a Burdekin River plume over Horseshoe Bay on Magnetic Island in February 2007. On the day this picture was taken the turbidity of the water (turbidity is similar to cloudiness) was 1 NTU – quite a low reading considering that, in the satellite picture, the water looks dirtier than the blue coloured water over the GBR. The bottom picture of Figure 5.4 looks similar to the top picture with a region of dirty brown water all along the coast. This picture was taken in October 2006 during the dry season in a period of strong South-Easterly trade winds when the rivers are totally dry. Waves caused by the wind produce resuspension of sediment along the entire coast. The turbidity at Horseshoe Bay on that day was over 10 NTU – ten times what was recorded on the day the flood plume picture was taken (Orpin and Ridd, 2012).[92]

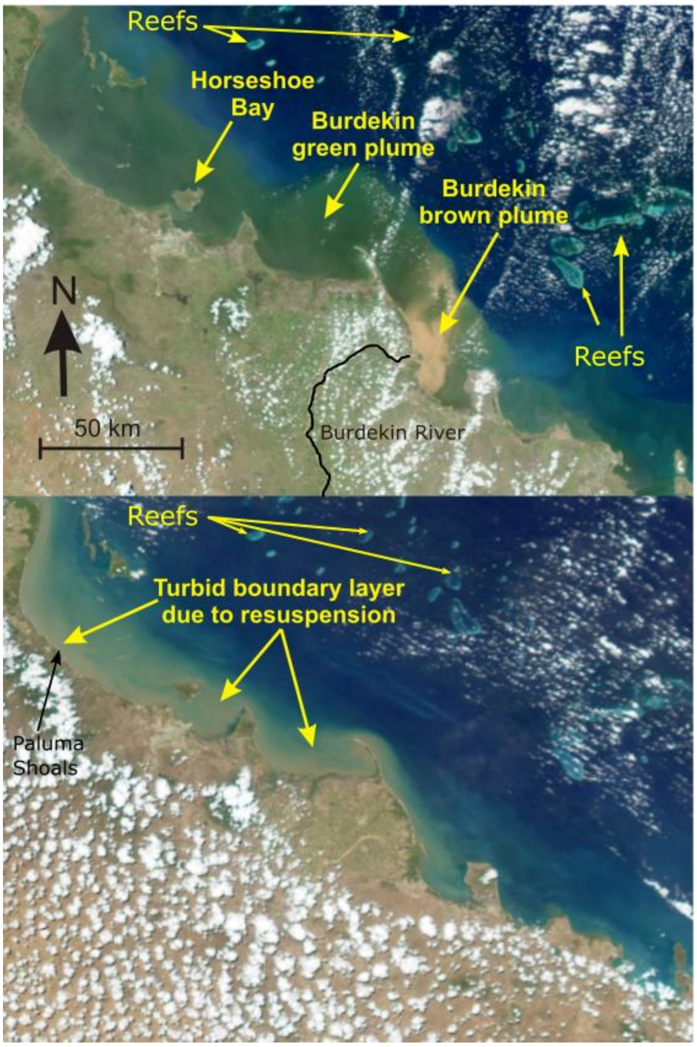
It must be remembered that river plumes occur for a few days per year, whereas resuspension events occur for a few days per month, so resuspension is about ten times more important than river plumes for about ten times the duration. Even the foregoing comment above overstates the effect of the river plumes because what has not been considered is the suspension of mud that would have occurred due to the storm that caused the flood shown in Figure 5.4 (Top). This storm caused very large waves that elevated the turbidity to over 60 NTU – 60 times higher than when there were no waves and just a flood plume (Orpin and Ridd, 2012).[93]

[91] See endnote 33 McCloskey, G.L., Baheerathan, R., Dougall, C., Ellis, R., Bennett, F.R., Waters, D., Darr, S., Fentie, B., Hateley, L.R., Askildsen, M., 2021. Modelled estimates of fine sediment and particulate nutrients delivered from the Great Barrier Reef catchments. Mar Pollut Bull 165, 112163. 751 https://doi.org/10.1016/j.marpolbul.2021.112163

[92] Orpin, A.R. and Ridd, P.V. (2012). Exposure of inshore corals to suspended sediments due to wave-resuspension and river plumes in the central Great Barrier Reef: A reappraisal. *Continental Shelf Research*, 47, pp.55–67.

[93] Ibid.

Figure 5.4



Top. Satellite image of a river plume from the Burdekin River during a flood (see Orpin and Ridd, 2012). The brown area at the river mouth is muddy water. The plume moves to the north-west, clings to the coast, and turns green as the sediment settles out and phytoplankton grows on the nutrients released from the water. The GBR reefs are further offshore, well outside the river plume, but the plume is covering a few small fringing reefs on the islands and coast. Instruments measuring sediment concentrations at Horseshoe Bay on this day showed very low concentrations (less than 1 NTU[94]). *Bottom.* Dry season turbid coastal water caused by resuspension of sediment from south-easterly trade winds. Instrument readings at Horseshoe Bay on this day were around 10 NTU.

Nutrients, like sediment, are also in very large concentrations in the inshore regions and the extra coming down the rivers is a comparatively minor addition. Sediments of the inshore region are an enormous repository of both nitrogen and phosphorous (the major nutrients for life and are also applied to crops as fertilizer), and these nutrients are constantly cycling between the sediment and seawater by chemical, physical, and biological processes. As shown in figure 4.3 the cycling of nutrients across the seabed is roughly 100 times the input of from the rivers. There are also other important fluxes of nutrients such as due to the algae trichodesmium, rainfall, and the upwelling of deep water. Finally, there is an enormous amount of nutrient that enters the GBR, albeit in small concentrations, due to the colossal in/outflow of water from the coral sea. The rivers are a very minor part of the nutrient budgets.

[94] NTU is a unit of turbidity or water cloudiness. High sediment concentrations increase turbidity. In conditions with strong waves, turbidity can easily exceed 100 NTU close inshore.

Because pesticides are in negligible quantities, and the impact of sediment and nutrients from the land is minor, though not entirely trivial, it should be no surprise that whatever changes on the inshore reefs since European settlement has been very subtle to the point of being impossible to measure with any useful confidence limits. The fact that the water condition of the inshore reefs is barely different from pre-European settlement times can give very high confidence that the GBR, which is generally far from the coast, is not directly impacted at all by pollutants from rivers.

5.3 Mangrove Swamps

Mangrove swamps are a common feature of the GBR coastline occupying an area of 1,660 km^2. Mangrove swamps have been completely protected since 1994. Before 1994 some areas of mangroves were cleared and the land reclaimed for growing sugar cane. The amount that was cleared was quite small, although the precise area is unknown.[95] Mangroves are, by definition, very low-lying areas inundated by seawater and require considerable, and expensive, earth works to make them viable for agriculture. A review of google earth images, would indicate that perhaps 2 per cent has been lost – but an accurate assessment is required.

Since 1994 there has been no evidence of any major permanent loss of mangroves. Small areas of mangroves died in the Mackay region in 2000[96] but inspection of google earth images indicates this has all recovered. Mangroves often live on geomorphologically dynamic coastlines, changing with storms, and movement of sediment banks. Sometimes the changes can be spectacular such as the large new mangrove swamp that has formed at the mouth of the Ross River since 1993 (figure 5.5). This swamp is 1.5 km long and 400 m wide. It is in part of Cleveland Bay that is prograding (shoreline moving seaward) and has seen far more spectacular changes over the last few thousand years.

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[95] Goudkamp, K. and Chin, A. June 2006, 'Mangroves and Saltmarshes' in Chin. A, (ed) The State of the Great Barrier Reef On-line, Great Barrier Reef Marine Park Authority, Townsville. Viewed on (enter date viewed), http://www.gbrmpa.gov.au/publications/sort/mangroves_saltmarshes

[96] Duke, Norman C., Bell, Alicia M., Pedersen, Dan K., Roelfsema, Chris M., Godson, Lloyd M., Zahmel, Katherin N., Mackenzie, Jock, and Bengston-Nash, Susan (2003). *Mackay mangrove dieback: Investigations in 2002 with recommendation for further research, monitoring and management: Report to Queensland Department of Primary Industries Northern Fisheries Centre, and the Community of Mackay.* Centre for Marine Studies,

Figure 5.5 A new mangrove swamp at the mouth of Ross River, Townsville. Lefthand image was taken in 1993 (source Qimagery), the righthand image 2023 (google earth). A sand bar formed offshore of the original coastline forming a sheltered area where mangroves could establish.

Although there has been an increase in mangroves at the mouth of the Ross River in recent decades, it could easily be reversed if a large cyclone passed across the region. In addition, there are other areas where mangroves swamps are presently retreating, such as at the mouth of the Johnstone River (Coquette Point) where a strip of mangroves about one kilometre long has retreated by up to 200 metres since 1964 (figure 5.6).

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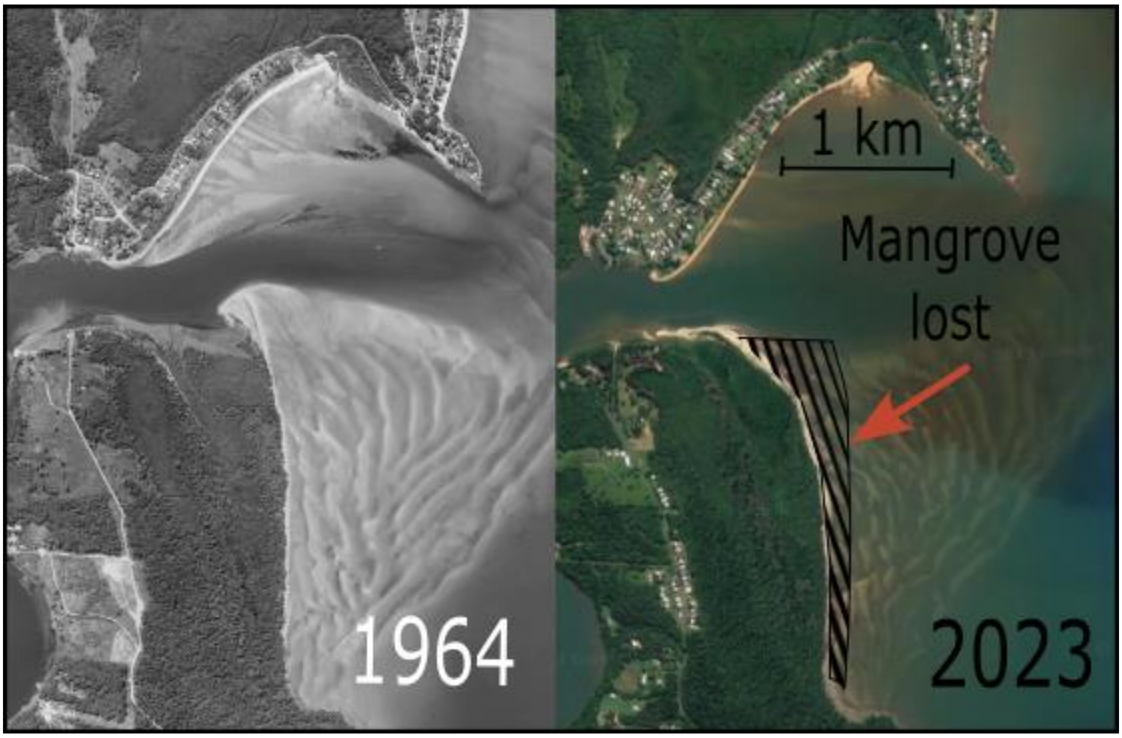

Figure 5.6: Mangrove retreat at the mouth of the Johnstone River. Lefthand image was taken in 1964 (source Qimagery), the righthand image 2023 (google earth). Shaded region is the approximate extent of mangrove swamp lost.

It should be noted that the condition of Australia's mangrove forests is far better than many other parts of the world where massive clearance and conversion to aquaculture ponds has taken place.

In summary, there is little evidence of any major loss of mangroves on the Queensland coast, certainly not in the last few decades.

5.4 Seagrass beds

Seagrass occupy roughly 10 per cent of the area of the GBR,[97] and are very common in the inshore regions, but are also common offshore. They have been regularly monitored on a large scale for almost 20 years.[98] Like corals, seagrasses are often highly variable ecosystems

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[97] Robert G. Coles, Michael A. Rasheed, Len J. McKenzie, Alana Grech, Paul H. York, Marcus Sheaves, Skye McKenna, Catherine Bryant, The Great Barrier Reef World Heritage Area seagrasses: Managing this iconic Australian ecosystem resource for the future, Estuarine, Coastal and Shelf Science, Volume 153, 2015,

[98] McKenzie, L.J., Collier, C.J, Langlois, L.A., Yoshida, R.L., Uusitalo, J. and Waycott, M. 2021, Marine Monitoring Program: Annual Report for Inshore Seagrass Monitoring 2019–20. Report for the Great Barrier Reef Marine Park Authority, Great Barrier Reef Marine Park Authority, Townsville, 169pp.

that are acutely affected by the passage of storms and floods (for nearshore seagrass beds). Seagrasses are easily uprooted by the waves from cyclones or major storms. In addition, they can also be killed by major floods due to reduction in light levels caused by turbid water, and their relative intolerance to freshwater.[99]

Inshore seagrasses often occur in dense ‘meadows’ in estuaries, in shallow coastal waters, and in intertidal regions. The two most important measurements of seagrasses are (a) the seagrass cover in the meadows, and (b) the extent of the meadows. Seagrass cover is analogous to the coral cover mentioned in section 2.2.

In the following section the results of the major seagrass surveys found in McKenzie et al (2021)[100] which have been occurring since 2005 will be presented. These surveys cover major seagrass meadows along the coast adjacent to the GBR, from Cape York to the Mary River.

Figure 5.7 shows the aggregate cover for inshore seagrass for the six major inshore regions. The most important feature of this data is the extreme variability. The seagrass cover can easily change by a factor of three. For example, the seagrasses in the Burdekin region varied from about 70 per cent in 2005 down to 20 per cent in 2011. According to McKenzie et al (2021) this occurred due to losses as a result of ‘multiple consecutive years of above-average rainfall (river discharge) and severe weather (cyclone Yasi).’ However, the system recovered very strongly by 2016. It is notable that the Burdekin is by far the most important river in terms of fine sediment loads discharging well over one third of all the riverine sediment to the GBR region (McCloskey et al 2021).[101]

With data only starting in 2005, and the extreme variability of the seagrass beds, it will take at least another two decades to resolve any long-term trend in seagrass cover.

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[99] Collier CJ, Villacorta-Rath C, van Dijk K-j, Takahashi M, Waycott M (2014) Seagrass Proliferation Precedes Mortality during Hypo-Salinity Events: A StressInduced Morphometric Response. PLoS ONE 9(4): e94014. doi:10.1371/journal.pone.0094014

[100] See endnote 70 (McKenzie 2021)

[101] McCloskey, G.L., Baheerathan, R., Dougall, C., Ellis, R., Bennett, F.R., Waters, D., Darr, S., Fentie, B., Hateley, L.R., Askildsen, M., 2021. Modelled estimates of fine sediment and particulate nutrients delivered from the Great Barrier Reef catchments. Mar Pollut Bull 165, 112163. 751 https://doi.org/10.1016/j.marpolbul.2021.112163

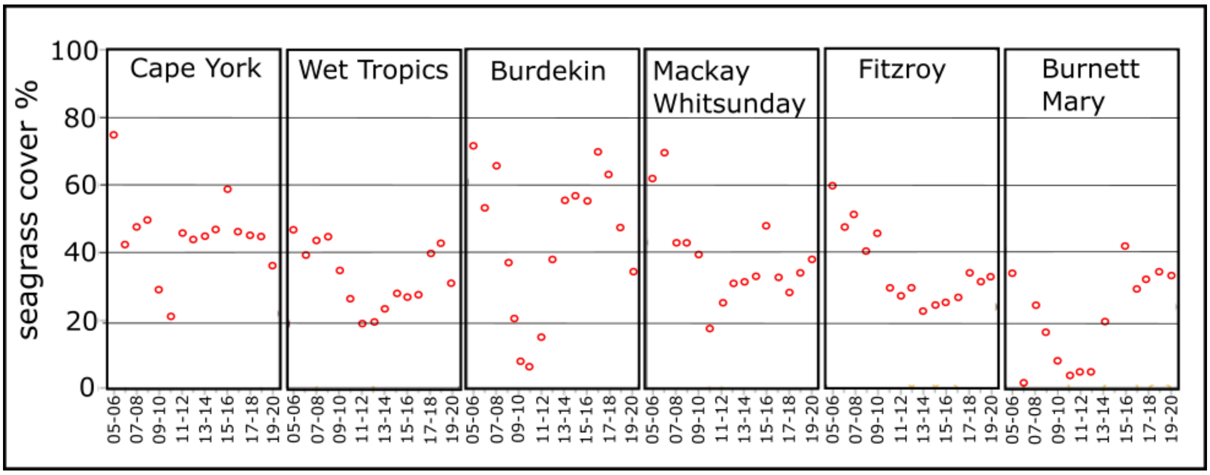


Figure 5.7 Seagrass cover from 2005 to 2020 for various regions of the inshore GBR. Data duplicated from (McKenzie et al. 2021)

In contrast to the high variability of seagrass cover, the spatial extent of the seagrass meadows shows little variability especially once the uncertainty margins are taken into account (Figure 5.8). According to McKenzie et al. (2021) the low point came ‘after the extreme weather events in 2009 to 2011…’. These included Cyclone Hamish which devastated large parts of the GBR (figure 2.3 and 2.4).

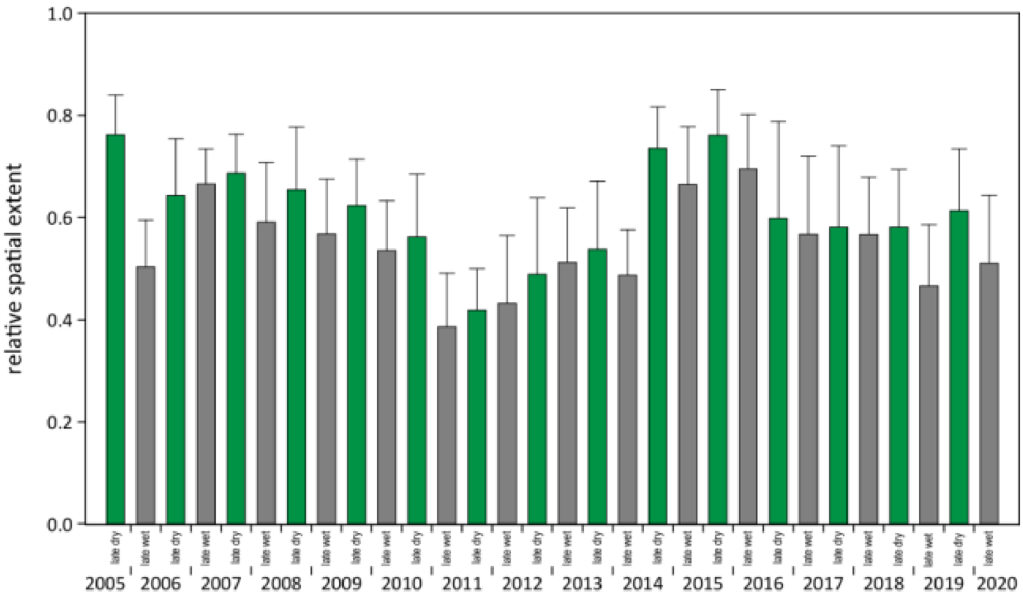


Figure 5.8 Average relative spatial extent of seagrass distribution across reef locations, habitats, and regions). Data duplicated from McKenzie et al (2021)

To demonstrate the extreme variability of some seagrass systems, it is worth considering the small seagrass beds located in the Moresby River Estuary (Mourilyan

Harbour) which have been subject to extremely fine detailed surveys since 1993.[102] These are very small seagrass meadows covering less than 10 hectares (about 0.0003 per cent of the 3.5 million hectares of seagrasses of the GBR). Being located in an estuary in the wet-tropics, the Mourilyan Harbour seagrass beds are occasionally subject to long periods of flooding. Some of the seagrass meadows include areas of intertidal mudflat where prolonged exposure to air and sunlight can influence seagrass survival. In addition, a considerable proportion the Moresby River catchment, roughly half, is under intensive agriculture (sugar cane and bananas) and thus subject to herbicide runoff.

Figure 5.9 shows the variation in seagrass meadow area. The last decade has roughly half the area of seagrasses compared to the decade between 1993 to 2003. However extreme variability is evident with almost complete loss of seagrasses occurring in 2010, 2017, and 2021. Such extreme variability means that great care must be taken when asserting anthropogenic influences regarding long term changes.

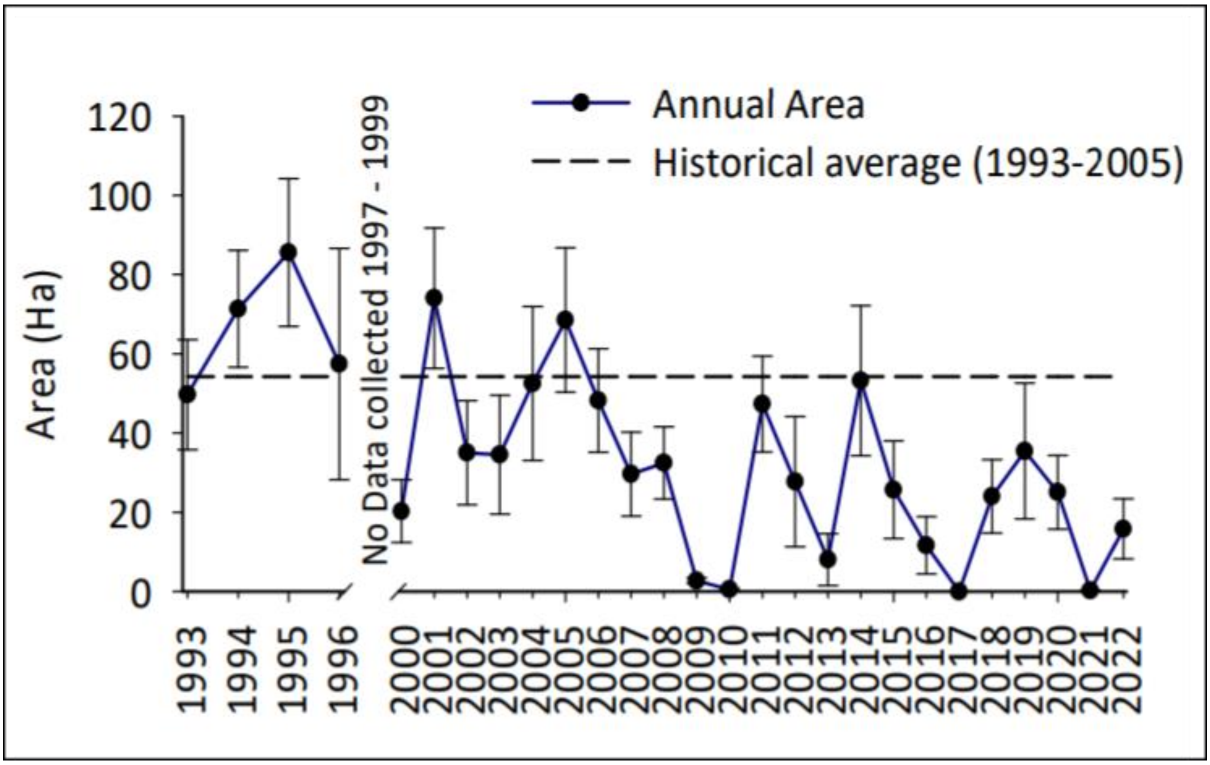


Figure 5.9 Area of seagrass meadows in Mourliyan Harbour, 1993-2022. Source: Reason et al. (2023).

102 Reason C, York PH & Rasheed M (2023) Seagrass habitat of Mourilyan Harbour: Annual Monitoring Report – 2022', Centre for Tropical Water & Aquatic Ecosystem Research, JCU Publication 23/11, Cairns, 38pp.

To further demonstrate the variability of the Mourilyan Harbour seagrass beds, figure 5.10 shows the detailed changes of the meadows from 2009 to 2022. There are no two consecutive years where the seagrass extent and biomass are similar except 2010 and 2021 when seagrass is almost completely absent.

From the data presented above, it is evident that seagrasses meadows exhibit considerable variability – perhaps even more than the reefs of the GBR. It is possible that some small systems like Mourilyan Harbour have been affected by human activity, but the variability of the system makes it very difficult to make definitive conclusions. On a broader scale, seagrasses continue to cover enormous areas of the coastal ocean and they have shown strong resilience and recovery to major events such as cyclones and floods.

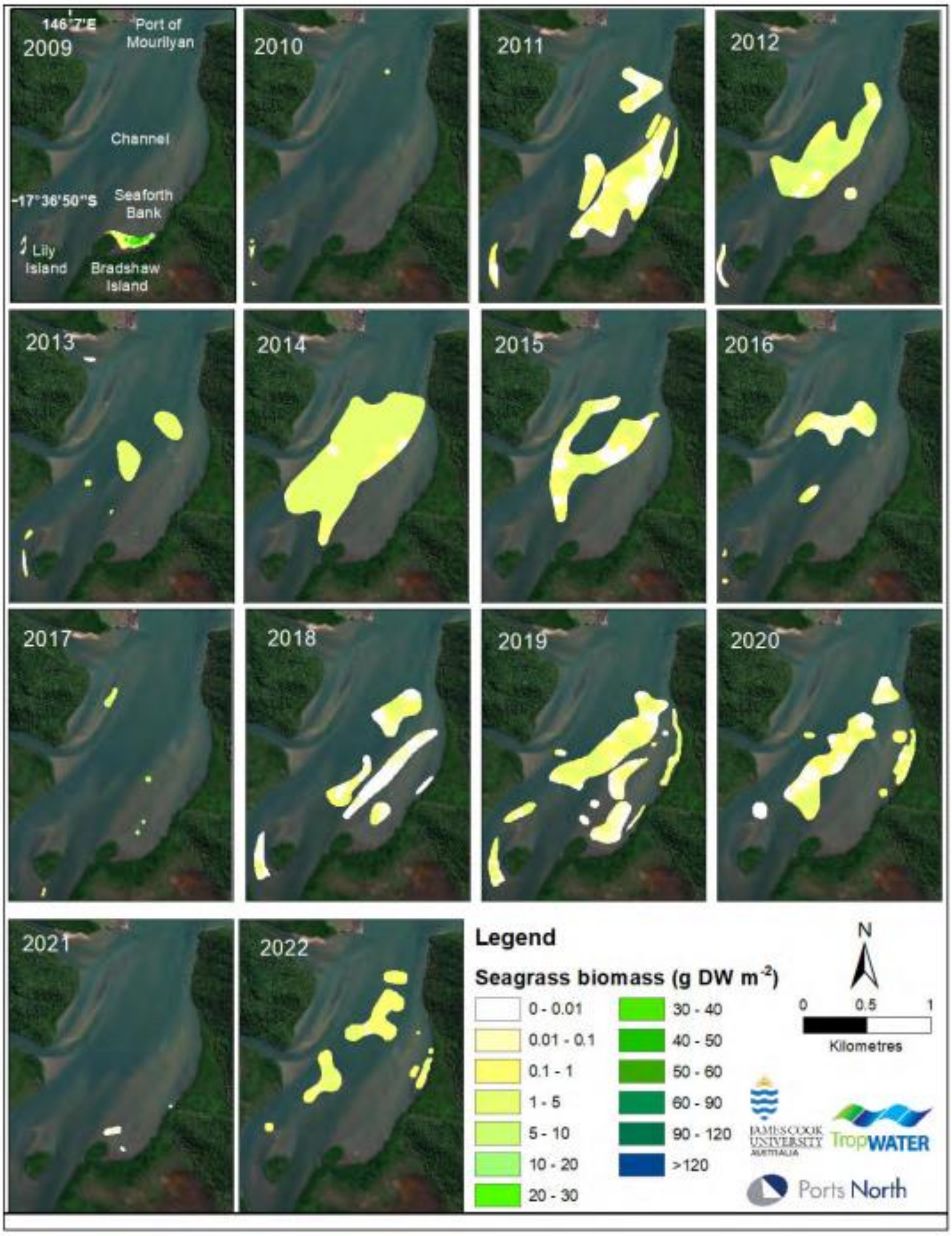


Figure 5.10: Change in seagrass distribution from 2009 to 2022. Unit: g DW m^{-2} is grams dry weight of seagrass per square meter. Data Reason et al., (2023)

5.5 Coastal Freshwater ecosystems

Coastal freshwater swamps have suffered major and irreversible loss in GBR catchments that have been developed for agriculture. The scale of this loss can be gauged by considering the

Herbert River floodplain where 80 per cent of the Melaleuca wetlands have been lost, and the freshwater wetlands in the Johnstone, Russell-Mulgrave and Moresby Rivers where over 50 per cent have been lost (Furnas, 2003).[103]

Much of this wetland area has been converted to intensive agriculture. In addition, some areas of wetland have become seriously degraded by the invasion of noxious weeds. Despite this, the entirety of Cape York, as well as numerous areas further south, seem to remain undeveloped, and those lost were not very extensive to begin with.

The loss of coastal wetlands stands in stark contrast to the almost pristine condition of the Great Barrier Reef. There is no doubt, or possible dispute, about the demise of a significant fraction of coastal freshwater wetlands.

5.6 Importance of Coastal ecosystems to the Great Barrier Reef.

The state of the coastal ecosystems adjacent to the GBR can be summarised as follows.

- Inshore coral reefs are relatively unchanged since European settlement. Their extent has not changed, and the water quality has not been greatly impacted by runoff from land.
- Mangroves have only been affected in a very minor way since European settlement, and are presently in extremely good health. Mangroves forests do not vary greatly from year to year, and are easily monitored from satellite images. There is little reason to be concerned with the health of the mangroves.
- Seagrass beds, however, are a highly fluctuating ecosystem for which there is only a limited quantity of data. Although that data does not show any major loss of seagrasses, major natural fluctuations make it difficult to gauge if there has been a significant change in the seagrass cover and extent since European settlements.
- Coastal freshwater wetlands, have suffered irreparable loss over a large fraction of their original area.

However, the defining feature of the Great Barrier Reef Marine Park is the corals of the GBR. It is the GBR that is the reason that the marine park was proclaimed in 1975. Other coastal ecosystems, such as mangroves and seagrasses, which are inside the marine park, and

[103] Furnas, 2003 Catchments and Corals- Terrestrial runoff to the Great Barrier Reef. AIMS/CRC Reef. ISBN 0 642 55041 7)

freshwater wetlands, which are slightly outside the marine park, are important ecosystems in their own right, but the focus of the world is on the GBR – that is what is special.

The question then arises, ‘to what extent are these coastal ecosystems important to the ecological functioning of the GBR’. In the major reports on the GBR,[104] far more analysis is devoted to these ecosystems than to the reef itself, and it is often stated that the linkage between the coastal ecosystems and the GBR is important. However very little data has ever been put forward to support this supposed crucial link. Certainly a few species move between the coast and reef, but no evidence has been put forward that quantifies these links, and whether the species in questions are threatened in any way.

At a more fundamental level it would be extremely surprising that the coastal ecosystems are important to the GBR, which is a long way from the coast. Many other coral reefs systems live in the Pacific Ocean, completely detached from any coastal influence, and those reefs are healthy. They do not need mangroves, coastal seagrass or turbid inshore reefs within 30 km to thrive. So why is the GBR so dependent on these inshore ecosystems? This has never been explained.

In addition, the southern parts of the GBR, in particularly the area around the Swains reefs supports some of the most remarkable assemblages of reefs on the GBR, but is up to 250 km from the coast. The linkages between coastal ecosystems must be far less important for the Swains Reefs than for the Reefs adjacent to Cape York Peninsula which are closer to the coast. And yet the Swains are doing fine.

In conclusion, although some of the coastal ecosystems have undoubtedly suffered major ecological losses, in particular the freshwater wetlands, there is no evidence that this has affected the GBR. Damage to inshore reefs, mangrove swamps, and most seagrass beds is very subtle at most. They are in a far better state than many Australian terrestrial ecosystems and there is no evidence that they are crucial to the GBR. This is not an excuse to reduce protections for these coastal ecosystems. But invoking the coastal ecosystems as being central to the health of the GBR is scientifically unjustified.

[104] See end note 50 (2017 consensus report)

Chapter 6 Summary and conclusions

The Great Barrier Reef (GBR) is by far the world's biggest coral reef system comprising 3000 individual reefs. The GBR is as big as Germany or Victoria and Tasmania combined. Of the 3,000 individual coral reefs of the GBR, all still have excellent coral. Not a single reef, or reef plant or animal, has been lost since British settlement.

According to measurements by the Australian Institute of Marine Science (AIMS), which started in 1985, the amount of coral on the GBR (coral cover) has never been higher than for 2022 and 2023.

Measurements show that cyclones, starfish predation, and bleaching events cause huge fluctuations in coral cover. For example, the GBR now has twice as much coral as in 2012, after the waves from major cyclones smashed much of the more delicate coral (e.g. acropora species). Individual reefs, can go from 60 per cent coral cover to 5 per cent due to cyclones. If a reef was a forest, this would be the equivalent of a forest losing almost all its trees in a bushfire.

Recovery from the major mortality events is always very rapid, indicating a healthy and robust ecosystem.

Measurements of coral growth rings by AIMS, which is performed on large block-type corals and are similar to tree rings, provides data going back to 1570. There is no reduction in growth rate from 1570 to 2005. There is a dispute over analysis of data covering 1990 to 2005. Scandalously, there is no data from 2005 to 2023 despite this being the period of most interest

Growth rate measurements show no decline in the period between 1860 and 1960 when agricultural production and pesticide-use started. Slowing of growth rate is a common first effect when organisms are exposed to stress or chemical poisoning. There is also no evidence that corals closer to agricultural producing areas are growing more slowly than those far away.

Concentrations of agricultural pesticides on the GBR are generally in such low concentrations that they cannot be measured even with the most sensitive scientific equipment.

Low pesticide concentrations are due to (a) relatively limited pesticide usage, (b) the GBR is a long way from the coast (generally between 30 and 100 km), and (c) there is massive

flushing of water from the Pacific Ocean. As much water flushes into and out of the GBR in eight hours as comes down all the rivers on the Qld coast in a full year. The reef is thus almost always bathed in the sparkling clear water of the Pacific Ocean.

Inshore coral reefs contain only 1 per cent as much coral as the GBR and are not part of the GBR, but are inside the GBR Marine Park. They experience very low pesticide concentrations – and are often ‘not detected’. Even the individual inshore reef that is most exposed to pesticides, Round Top Island Reef at the mouth of the Pioneer River, has extremely low pesticide concentrations.

Sediment and nutrient runoff from farms have negligible impact on the GBR. Flood plumes rarely reach the GBR, and when they do, they only impact a small percentage of reefs, for a short period of time, and with low concentrations of sediment or nutrients.

Sediment and nutrient runoff from farms have a very minor impact on inshore environments such as the inshore coral reefs. Naturally occurring sediment and nutrients, which are resuspended by waves generated from strong winds, are roughly 100 times more important than sediment and nutrients from river plumes. The resuspension of vast quantities of sediment from the seabed by waves from cyclones dwarfs other factors on the mid-shelf but is largely ignored and very poorly researched.

It is often claimed that coastal ecosystems such as mangroves, seagrass meadows and freshwater wetlands are seriously degraded and, due to ecological linkages, this negatively impacts the GBR. There is very limited evidence that these linkages are significant. In addition we should note that of these ecosystems, mangroves are in excellent condition and seagrass meadows are still widespread and generally healthy despite fluctuating greatly due to cyclones, and floods.

Climate Change ‘bleaching’.

Despite the GBR experiencing four supposedly devastating bleaching events between 2016 and 2022, there has never been more coral than in 2022/23. This demonstrates that the bleaching events caused limited coral loss.

The type of coral that has increased the most in this period are the acropora species (mostly plate and staghorn types) that are the MOST susceptible to bleaching.

Coral bleaching involves the coral expelling the symbiotic algae that grows inside the polyp, often replacing the algae with a different strain that is more suitable for a different temperature range.

Most bleached corals actually survive, and bleaching should be seen as an adaptive response mechanism that allows corals to be more resilient to climate change.

Corals grow much faster in warmer climates and most of the coral species found on the GBR already live in waters to the north of Australia where the water is at least a couple of degrees warmer and where they grow at least 25 per cent faster than in the warmest (northern) waters of the GBR.

Appendix: Usefulness of coral cover measurements.

Chapter 2 makes use of a major data set of coral cover that has been recorded by the Australian Institute of Marine Science (AIMS) since 1986. This data set is by far the most comprehensive long-term data of coral conditions on any reef system in the world. Nevertheless, it is a worthwhile exercise to question how valid and useful is the data of coral cover. It has been pointed out that the AIMS measurements rely on a subjective judgement of the coral cover and that the transects are not representative of the coral on the whole reef.[105] While accepting both these problems, the author's view is that the measurements are useful for gauging *changes* to the GBR over time.

How is the data collected?

AIMS uses the manta-tow method to survey hard coral. This involves towing a diver around the perimeter of a reef. The diver observes coral cover over a 100-200 metre distance and records the percentage estimate. This is a subjective estimate. The diver is trained to do this. Each reef has a perimeter of many kilometres/miles so there could be roughly 50 to 100 individual estimates for each reef.

The data for the GBR is broken into three regions: Northern, Central and Southern. These regions are broken into 'sectors' with 3, 5 and 3 sectors in the Northern, Central and Southern regions respectively. For each of the 11 sectors there are roughly 5-10 individual coral reefs surveyed. Data is aggregated in an objective way (averaging and weighting) to give a coral cover statistic for each reef and further aggregated to give a statistic for each sector or region.

Of the 3,000 reefs of the GBR, around 100 are surveyed each year. Divers are towed a distance of roughly 1000 km – which give an idea of the enormous size of the task, and why a rapid assessment of the coral is important

Can a subjective measurement be useful?

Yes, and there are many examples in science where subjective measures are used – usually to allow very rapid and inexpensive collection of data similar to monitoring coral. For example, for collecting data of vegetation cover in pasture, a simple subjective measure is often used.[106] Figure A1 shows examples of different plant cover percentage over the ground. It is relatively simple to train an observer to give a useful measure of plant cover. Different observers would need to be trained to minimise the uncertainty.

[105] https://jennifermarohasy.com/2022/08/latest-survey-of-coral-cover-fundamentally-unscientific/
[106] See for example Damgaard, C. (2014). Estimating mean plant cover from different types of cover data: A coherent statistical framework. Ecosphere, 5, art20. https://doi.org/10.1890/ES13-00300.1

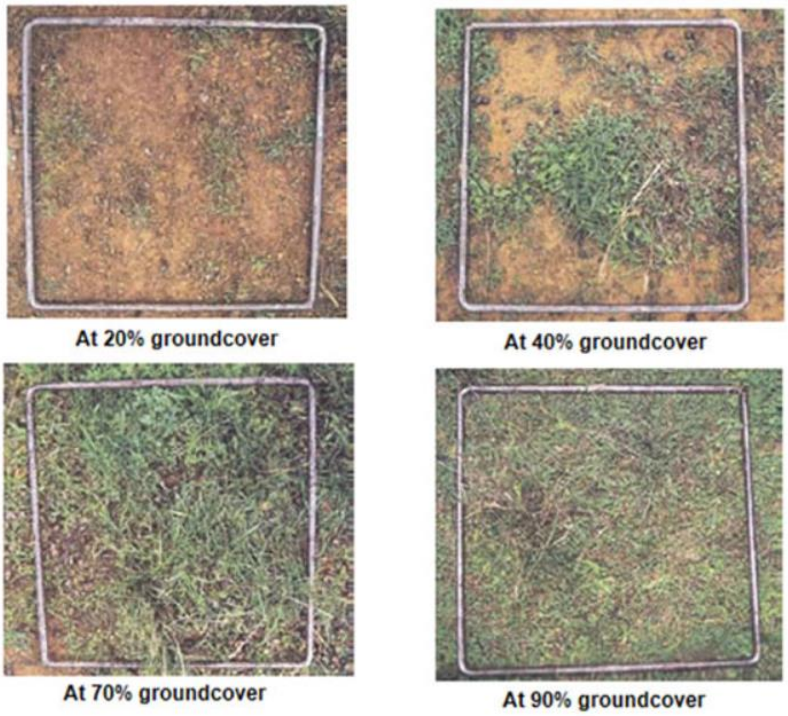


Figure A1: Estimation of ground cover in pasture. Different observers will not estimate exactly the same number, but with training the uncertainty margin can probably mean that two observers will agree within 10%. [107]

There are many other areas where humans are well able to estimate measurements without any form of instrument. For example, the height of a human ranges from about 60 cm (2 feet) for a toddler child to about 215 cm (7 feet) for an American basketball player. Almost anybody can estimate the height of another person, to within 30 cm (1 foot) and most people can do much better than that. Skilled carpenters can look at a cabinet, kitchen or wall and estimate its dimensions with remarkable accuracy – better than 10 cm for lengths less than 2m. Machinists who work on lathes can look at variations on a turned circular surface and estimate step variations to within a few thousandths of an inch. It is obviously better to do all these things with a tape measure or micrometre as this drastically reduces uncertainty. But a subjective measure can give useful data provided the size of the uncertainty can be gauged and is not too large *for the application at hand*.

Humans use subjective assessment of the size and distance to objects in many day-to-day activities. Driving a car requires an extremely good ability to judge the distance and speed of approaching cars; or judging if the size of a parking bay, or gap between two objects, is big enough for their car. Ball sports from football to snooker also require a remarkable ability to judge distances. Training and practice is the key to minimising uncertainty margins.

Subjective measures are also used in other fields such as teachers marking exam papers, essays and even answers to mathematics questions (when the answer deserves part marks). These subjective measures can then be 'added' or aggregated in some objective form to

[107] https://www.dcceew.gov.au/environment/land/landcare/my-project/monitoring-reporting/environmental-stewardship/ground-cover-percentage

produce a useful measure of the relative performance of students. Just like using an objective system to aggregate the subjective coral cover assessments.

The point has been made that technology now exists to use artificial intelligence (AI) methods to remove most of the subjectivity from the process of estimating coral cover. This is the way things should go for future surveys, as soon as possible, and it is understood that AIMS is working on this. But even with AI, the result one gets depends upon the input parameters for the AI model. The author has considerable experience with AI algorithms to detect weeds in pasture, and the way one sets up the parameters greatly affects the final results as there is a degree of subjectivity in the way the parameters are chosen. With regards to assessing coral cover, the most important thing is to make sure that whatever method is used, it is applied consistently. If there is a move to AI, the current method and new method must be used concurrently for a number of years so that there is confidence in the new method and the previous data is not wasted.

So, in conclusion, the subjective estimation method has weaknesses which could be largely avoided with modern technology, but this does not mean that the estimation method has no value. Part of the value of the coral cover data is that it goes back to 1986 and we cannot retrospectively apply the AI methods to the past. Also, surveys should be videoed as a matter of routine so that future AI technology can be retrospectively applied, and others can check the data.

The problem of only measuring coral on reef perimeter

By only measuring coral cover on the perimeter of the individual reef, the data is not representative of the average for the entire individual reef. The centre of many reefs is dominated by sand where there is also no coral. Many of the reef crests have much higher coral cover. Some of the reef flats have no coral due to air exposure at king low tides (as a result of sea level fall over the last 5000 years). However, if one is interested in *changes* of coral cover with time, measuring only the reef perimeter is not a problem provided it is safe to assume that the factors affecting coral cover (cyclones, crown-of-thorns starfish, bleaching, recruitment, and growth) do not vary too much across the different parts of the reef. Cyclones, the major factor reducing coral cover, affects virtually the entire reef with water depth less than 50 m. But even if there are some significant differences in the way coral cover changes with time between different regions of an individual coral reef, having the data for the perimeter is far better than having no data at all. The reef perimeter is a huge amount of coral and it is where most active coral reefs are growing. Because AIMS has always measured the perimeter since 1986, we can have some confidence that they can detect changes - at least for the perimeter. This is far better than no data at all.

Data Coherence and Noise

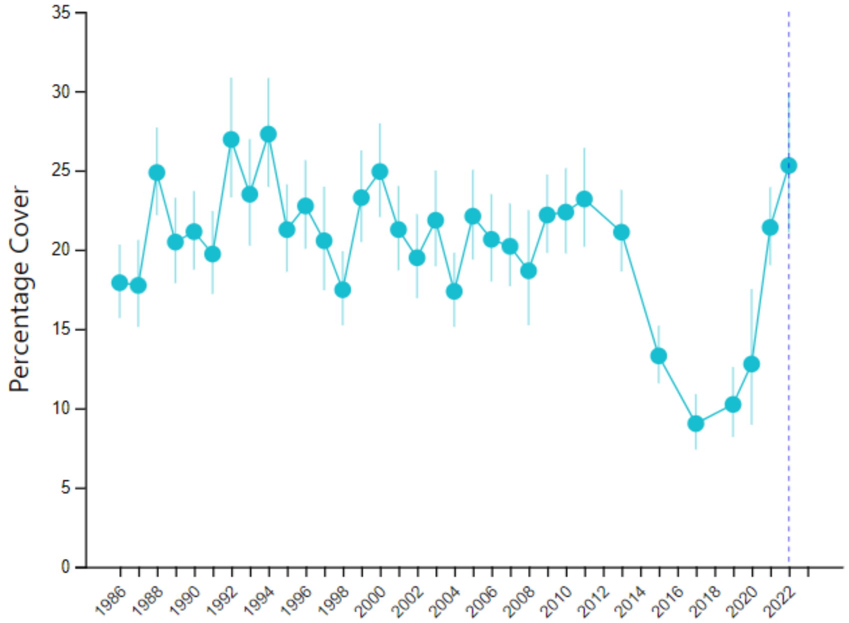
Provided one is interested only in changes in coral cover with time, one way to gauge the usefulness of the data is to look at the “noise” – fluctuations over time. If the data inexplicably and routinely bounced around from small to high numbers and back, this would be a sign of very high inaccuracy. In addition, coral cannot suddenly go from 10 per cent cover to 90 per cent cover in one year – it does not grow that fast. Useful data should see gradual changes with time as coral grows and sometimes very rapid falls due to impacts from cyclones. Also, a cyclone is a big system and will always affect many neighbouring reefs. If

the data does not show a major reduction in coral cover on *all* reefs affected by the cyclone, it would be a major red flag that there is a problem with the data inaccuracy and noise.

The AIMS data however appears to be highly consistent in these regards. After a big cyclone, the data indicated that the coral cover of many reefs does collapse. The gradual recovery is apparent. The data is not hopelessly noisy which would be the case if the subjective measurements were completely useless.

For example, the data for the Cooktown section of the reef is shown in figure A2. There is considerable fluctuation in the data, but the large collapse in 2016 and the subsequent recovery is very clear. If the data was too noisy, this fall and recovery would not have been clear. The monotonic recovery is also very evident - the coral was recovering at a very rapid rate, so even though the data has a large uncertainty margin the recovery can be distinguished. This is a good sign that the data is useful.

Figure A2: Coral cover for the Cooktown/Lizard section of the reef.

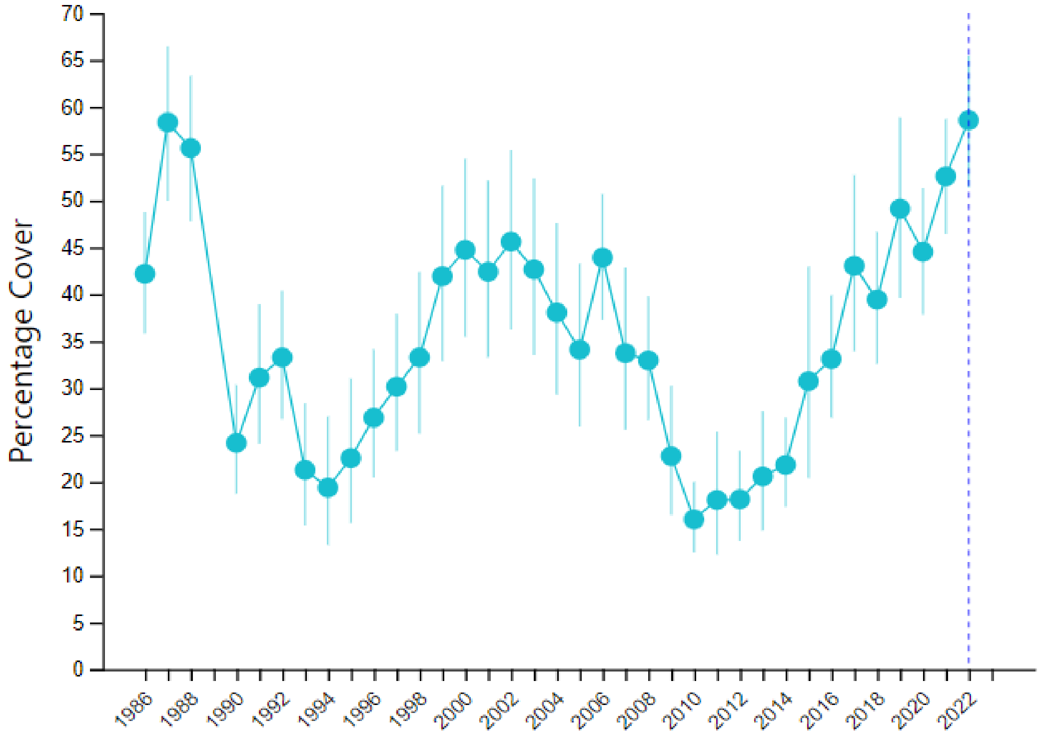


Also, the chances that the 5 years from 2017 to 2022 would have such a striking monotonic rise in value would be very small if the data was random noise caused by high observer error. It would be akin to throwing a dice five times and getting a perfect rising consecutive sequence such as 2, 3, 4, 5, 6. This is a 1 in 1,296 chance. If this happens on many reefs at the same time (that may all be recovering after a broadscale cyclonic event) the probability of getting consistent rises on coral cover by chance becomes negligible. Such coherence in the data is strongly indicative that there is a genuine ‘signal’ in the data that is not overwhelmed by the ‘noise’ from the data collection.

Such monotonic, or almost monotonic, sequences abound in the data, at reef, sector, and regional scale. For example, the data in figure A3 below shows the results for the Capricorn Bunker region of the reef. Again, there is significant noise of 10 per cent, but there is considerable coherence between different years without unreasonable rapid increases. The large mortality associated with Cyclone Hamish is clear in 2009/10 as is the very steady

increase in coral cover since then. There is no possibility that such a steady increase could occur in a purely random data series.

Figure A3: Coral Cover for Capricorn Bunkers.



A caveat

The fact that the data is based upon a subjective judgment of each 100 m section of the reefs surveyed means there is an obvious need for a high degree of quality assurance for the task. Unlike many other measurements of the reef (aerial bleaching and coral calcification data), in the author's view, AIMS has very useful QA systems for these surveys, at least in the last 25 years. However, an external audit of the surveys would be very valuable to maintain confidence in the data. It is possible that accusations could be made in the future that the divers might manipulate results in their subjective judgements to downgrade the coral result in the future. This has clearly not happened as AIMS is reporting record high coral cover. There is clearly a high degree of integrity of Mike Emslie and his team for the manta tow surveys. But a system of external audits would be very useful to maintain the integrity of the surveys in the future. For any audit to be effective, it will be essential that video be taken of the surveys. This is not a trivial task due to highly variable lighting and water turbidity, and would require extra manpower, but it would be worth doubling the funding for this coral cover work as it is such an important survey.

Summary

There is no doubt that the coral cover data has weaknesses – all data sets do. The data certainly has a large uncertainty margin which means that small changes cannot be resolved. But as a measure of large-scale *fluctuations* in coral cover, the author has no doubt that the data is very useful.

About the Author

Acknowledgements

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Peter Ridd is a physicist. He has researched the Great Barrier Reef since 1984, has published over 100 scientific publications, and invented a range of scientific instrumentation. A former head of the Marine Geophysical Laboratory and head of Physics at James Cook University, Townsville, Australia, he was fired in 2018 for pointing out quality assurance deficiencies in reef-science institutions. He presently works, without payment, on science quality assurance issues. He is an adjunct fellow of the Institute of Public Affairs, a member of the Academic Advisory Council of the Global Warming Policy Foundation, and is chairman of the Australian Environment Foundation.

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John Brewer Reef. These corals have grown in the last decade and are part of the spectacular rebound in coral cover of the Great Barrier Reef since 2012 when cyclones and starfish plagues reduced coral cover considerably. These corals were photographed during a mild bleaching event in 2022. They are of a type (acropora) that are most susceptible to hot-water bleaching events – and yet they are in record numbers on the GBR despite all the publicity about the impact of the bleaching events on the reef.

This report demonstrates that the public has been consistently misled about the state of the reef.