Table of Contents

Chapter 4 – Water Quality, Land-Use and Land-Cover

Chapter 5 - Habitats, Biodiversity and Ecosystem Function

Chapter 6 - Citizen Science

Chapter 7 – Industry and Planning

Chapter 8 – Moreton Bay Marine Park

Appendices

Maps of Moreton Bay and catchment

Holocene history of Moreton Bay reef habitats

Matthew J. Lybolt[1], John M Pandolfi[2]

Author affiliations: 1 CARDNO, Pacific Guardian Center, 737 Bishop Street, Mauka Tower, Suite 3050, Honolulu, HI 96813, USA; 2. ARC Centre of Excellence for Coral Reef Studies and School of Biological Sciences, The University of Queensland, St Lucia, Queensland 4072, Australia.

Corresponding author: mattlybolt@hotmail.com

ORCID
Matthew Lybolt: https://orcid.org/0000-0002-7175-7014
John Pandolfi: https://orcid.org/0000-0003-3047-6694

Abstract

The history of marginal coral reef development in Moreton Bay is characterized by habitats with abundant coral communities. These habitats formed during discrete intervals over the past 7,000 years and their growth is tied to relatively subtle changes in sea level and climate, along with changes in circulation patterns. Mechanisms of reef growth include both episodic reef accretion and island spit progradation. Three episodes of reef initiation and growth occurred from 7,400 to 6,800, 4,900 to 3,000, and 2,100 to 400 years before present. Modern reef growth in the Bay has been suppressed because of increased sediment and nutrient runoff from anthropogenic land-use changes, which need to be reversed if the condition of Moreton Bay reefs is to improve.

Keywords: marginal reefs, reef growth, sea level history, climate change

Moreton Bay reef habitats

The growth of reef habitats and associated reef coral communities in Moreton Bay has been intermittent during discrete episodes over the past 7,000 years or so (1). Strong environmental gradients, including sea floor composition and variables affecting water quality (e.g. turbidity, total nitrogen, temperature and dissolved oxygen) exist in Moreton Bay, from the west through the central Bay to the eastern Bay. We follow Wallace *et al.*'s (2) geographic separation of Moreton Bay into an inner region composed of the body of water partly enclosed by North and South Stradbroke, Moreton, and Bribie Islands and an outer region composed of the rocky reefs immediately outside these large islands, including Flinders Reef near Moreton Island and Flat Rock, Shark Gutter and Shag Rock off the north-east corner of North Stradbroke Island (Fig. 1). The Bay's species and habitats are well documented, including coral assemblages that are, in many ways, unique for their latitude (i.e., presence of mainland fringing reefs, absence of *Porites* species, and persistence through large temperature extremes) (2–4), and are dominated by the Faviidae, especially the genus *Favia* in most parts of the inner Bay (2). The Moreton Bay reefal habitats fit every definition of a marginal reef (5, 6) and have done so throughout the Holocene (7).

Reef structure is typical of fringing reefs in low-energy environments (8, 9). Most reefs in Moreton Bay have a reef flat from approximately 0 m to -1 m LAT (lowest astronomical tide), an upper slope from -1 to -4 m, and a somewhat gentler deep slope from -4 m to the basement

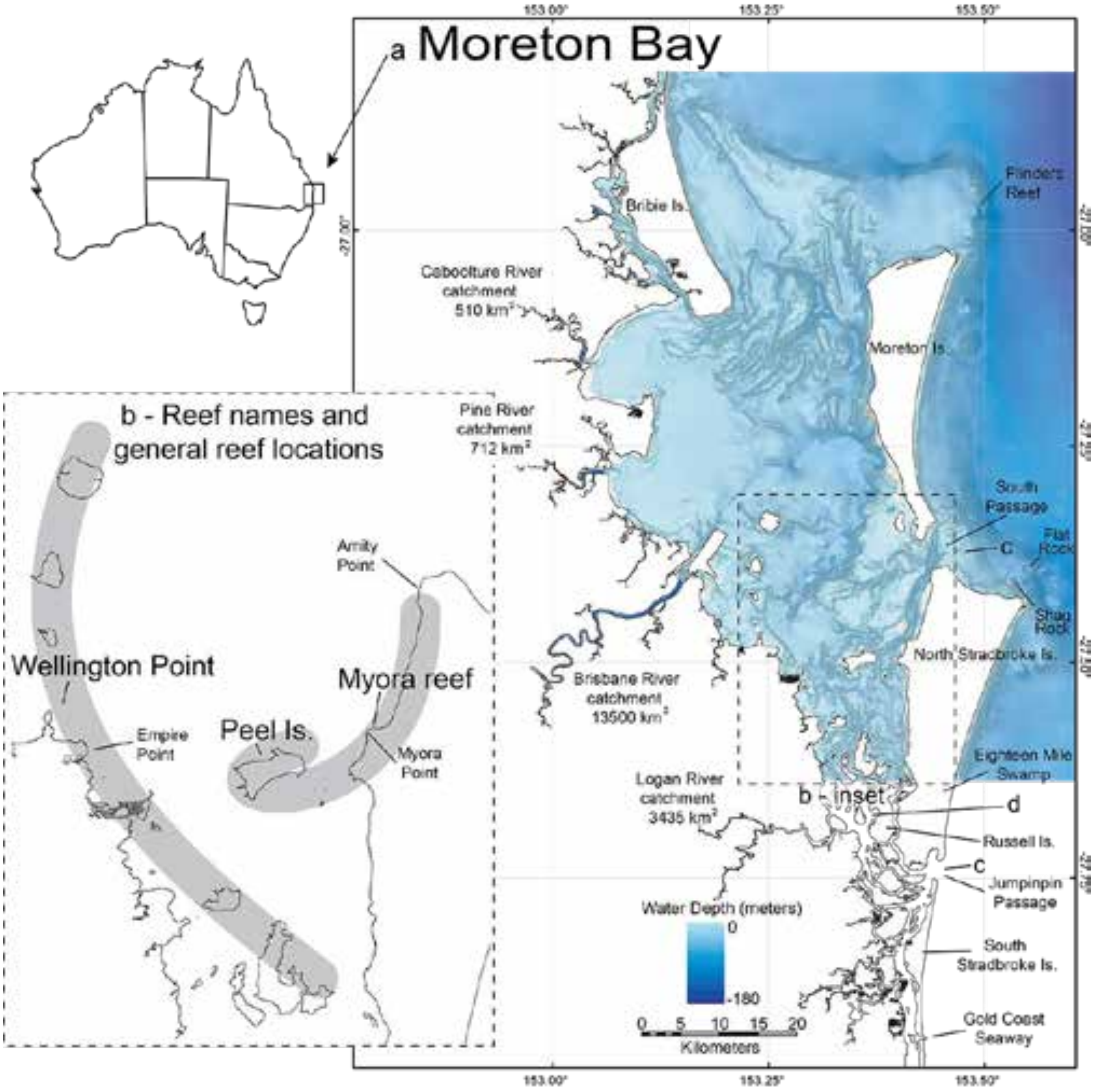

Figure 1. a - Overview of Moreton Bay with bathymetry depicting a network of tidal and river channels amidst generally shallow waters; b - Grey bands show the general areas of major Holocene reef growth; c - Historically ephemeral inlets; d - Modern tidal node.

substrate in the range of -5 to -8 m. The sediment underlying the reefs is usually composed of unconsolidated alluvial laterite sediments (clay); though also encountered is giant humus podzol (coffeerock) and kaolinite (bright white aluminium oxides). Crustose coralline algae and diagenetic cements are present on Moreton Bay's reefs, but their activity is reduced to the degree that reefs are generally unconsolidated. Reefs in inner Moreton Bay have initiated on substrate that is as deep as -8 m LAT (8, 10). There is no evidence that reefs have grown to reach sea level, either in modern or fossil reefs, though a submarine exposure at Myora Point suggests several metres of reef growth underlying living shallow water coral communities. Depth distribution of corals in Moreton Bay is restricted to approximately -0.5 to -8 m LAT, and the modern distribution of living corals is most dense in a very narrow range from -1 to -3 m LAT (11, 12). Vertical accretion does not extend into the intertidal zone as on many of the nearshore marginal reefs of the central Great Barrier Reef (GBR) (9, 13); but halts within the first metre of the subtidal zone.

Holocene Sea Level and Climate History

The Moreton Bay region was subject to changes in two major environmental factors since the mid-Holocene: (i) sea level and (ii) climatic regime, and these had primary control over reef accretion. Sea level rise following the last glacial maximum (LGM) ~18,000 years before present (ybp) began to flood proto-Moreton Bay around 9,000 ybp, and the basal elevations of the Bay's coral reefs in the range of -5 to -10 m were fully marine between 8,000 and 7,000 ybp. During the mid- Holocene, from ~ 8,000 to ~ 5,500 ybp sea level was rising to a stable level ~2 m higher than present (14, 15). This stability was followed by a drop in sea level to its present level from ~ 5,000 years ago to present (Fig. 2), which most likely occurred in a series of metre-scale oscillations (15–17). More recent data from subfossil corals in Moreton Bay show that sea level was at least 1.1 m above present from at least 6,600 ybp (18). The mid-Holocene highstand coincided with a period of climatic stability (warm and stable temperatures) and, for about 2,000 years, conditions were optimal for reefs to grow upwards to sea level. Resultant raised reefs are common features throughout much of the tropics, but are almost entirely absent from Moreton Bay. However, other features of the mid-Holocene highstand were preserved in the Bay (e.g., stranded dunes and beaches, wave-cut shorelines, and the geomorphology underlying the Eighteen Mile Swamp on North Stradbroke Island), so it is certain that sea level was approximately 2 m higher in the Bay at that time (15, 19–21). Sea level oscillations are produced by a combination of eustatic, isostatic, and climatic forcing with somewhat variable interpretations of how these drivers interact (15, 16, 18, 22, 23).

The first major climatic change following the post-glacial marine transgression was a destabilization of the mid-Holocene climatic regime. The mid-Holocene climate from 7,000 - 5,000 ybp was warmer by ~ 2°C and flooding was much less common than today despite rainfall 18-42% greater than today (24–27). Despite greater runoff, sedimentation to the nearshore reefs was an estimated 40% less than today because the enhanced vegetation cover, promoted by increased rainfall, reduced erosion (19, 28). The strength and frequency of El Niño–Southern Oscillation (ENSO) events in the early and mid-Holocene was substantially reduced relative to today (Fig. 2), and was scarcely detectable at the latitude of Moreton Bay (29). This period of stability, dubbed the "Holocene climatic optimum", ended abruptly ~ 5,500 to ~ 5,000 ybp when climatic conditions similar to today emerged. The region became about ~ 2°C cooler, precipitation declined, and cycles of extreme flood and drought associated with ENSO events became common (19, 30, 31). This climatic change caused erosion and sedimentation rates nearly double that of the Holocene climatic optimum (28).

Holocene Circulation Patterns

Dominant tidal flow and circulation in the Bay is through the northern entrance. General circulation is clockwise, tending south along Moreton Island and north along the landward margin of the Bay (4). Modern South Passage has some influence on circulation in the central and southern Bay, but modern Jumpinpin and Gold Coast Seaway have trivial influences on circulation (4, 17).

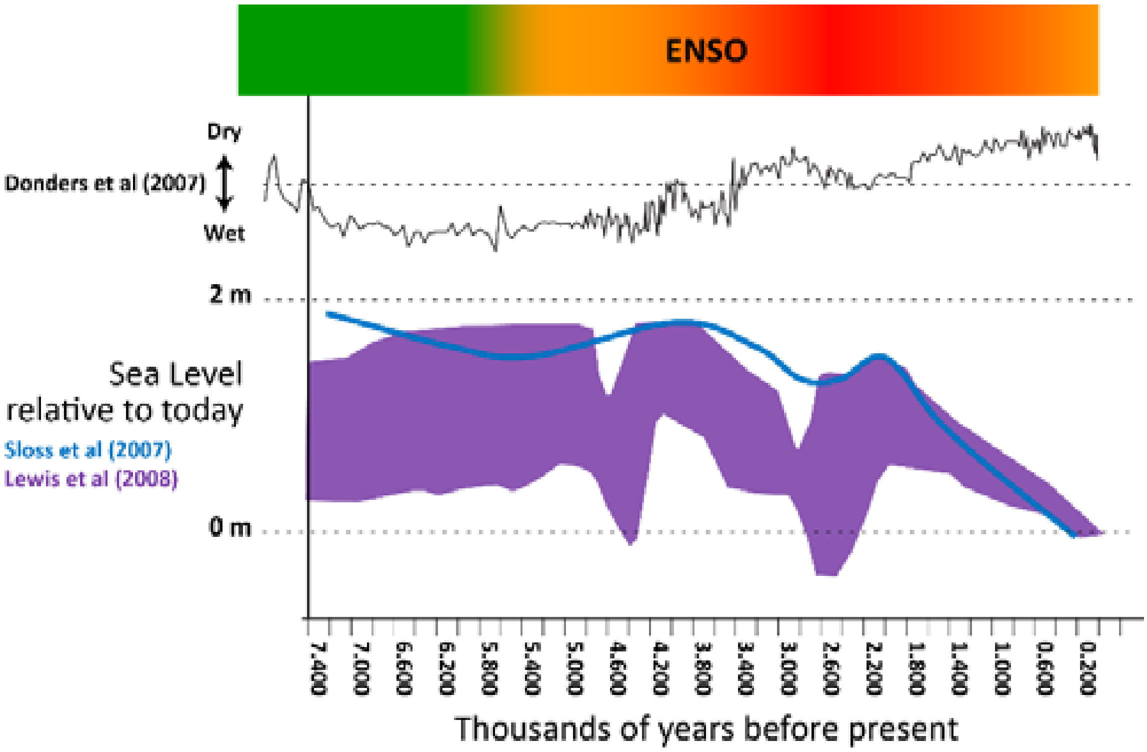

Figure 2. Composite of selected environmental data. The sea level curves of Lewis *et al.* (15) and Sloss *et al.* (14) were re-scaled to the same elevation datum. Lewis *et al.* (15) curve shows range of variability fitted between upper and lower means. Dry and wet contrasts are derived from PCA analysis of Bega Swamp (NSW, Australia) flora from peat profiles contrasting dry Asteraceae/Casuarina/Chenopodiaceae with moist Pomaderris/heath and fern taxa (27). ENSO intensity shown as a spectral colour gradient from low (green) to high (red).

Holocene changes in sea level likely had dramatic effects on circulation within the Bay in part because of changes in circulation efficiency (e.g., flushing) and in part because of the opening and restricting of tidal passages (32, 33). The modern tidal node where flushing is least efficient in Moreton Bay is near Russell Island in the southern Bay (Fig. 1) (34). At the mid-Holocene highstand, the tidal node would have been further north. Because tidal circulation was generally more efficient at higher sea levels during that time, the influence of the tidal node on water circulation was diminished relative to the present.

Shoaling of the Bay, restriction of channels, and restriction or closure of ocean passes by falling sea level reduces the efficiency of circulation, and increases the residence time of terrestrial inputs to the nearshore marine environment (19, 35). Jumpinpin passage in particular was likely much larger in the mid-Holocene as evidenced by its extensive flood tide delta (32), and South Stradbroke Island that presently blocks most of the passage is a more recent feature (19) (Fig. 1). Both South Passage and Jumpinpin are part of the dynamic beach and littoral drift system, and both should be considered ephemeral on timescales of the Holocene (17, 19, 32).

Holocene Reef Development

Two generalized representations of reef development patterns likely for Holocene reefs of Moreton Bay are episodic reef advance (Fig. 3A) and lateral progradation along island spits (Fig. 3B). Vertical accretion for Holocene reefs inside Moreton Bay approaches 8 m, and this is known primarily from reef mining practices (8, 10). Similarly, vertical accretion of the single Pleistocene reef found in Moreton Bay is approximately 6 m (36). Lateral progradation in tropical reefs throughout the Holocene can range from tens to hundreds of metres, and is dependent on the underlying substrate types, antecedent topography, and local environmental conditions (9, 37).

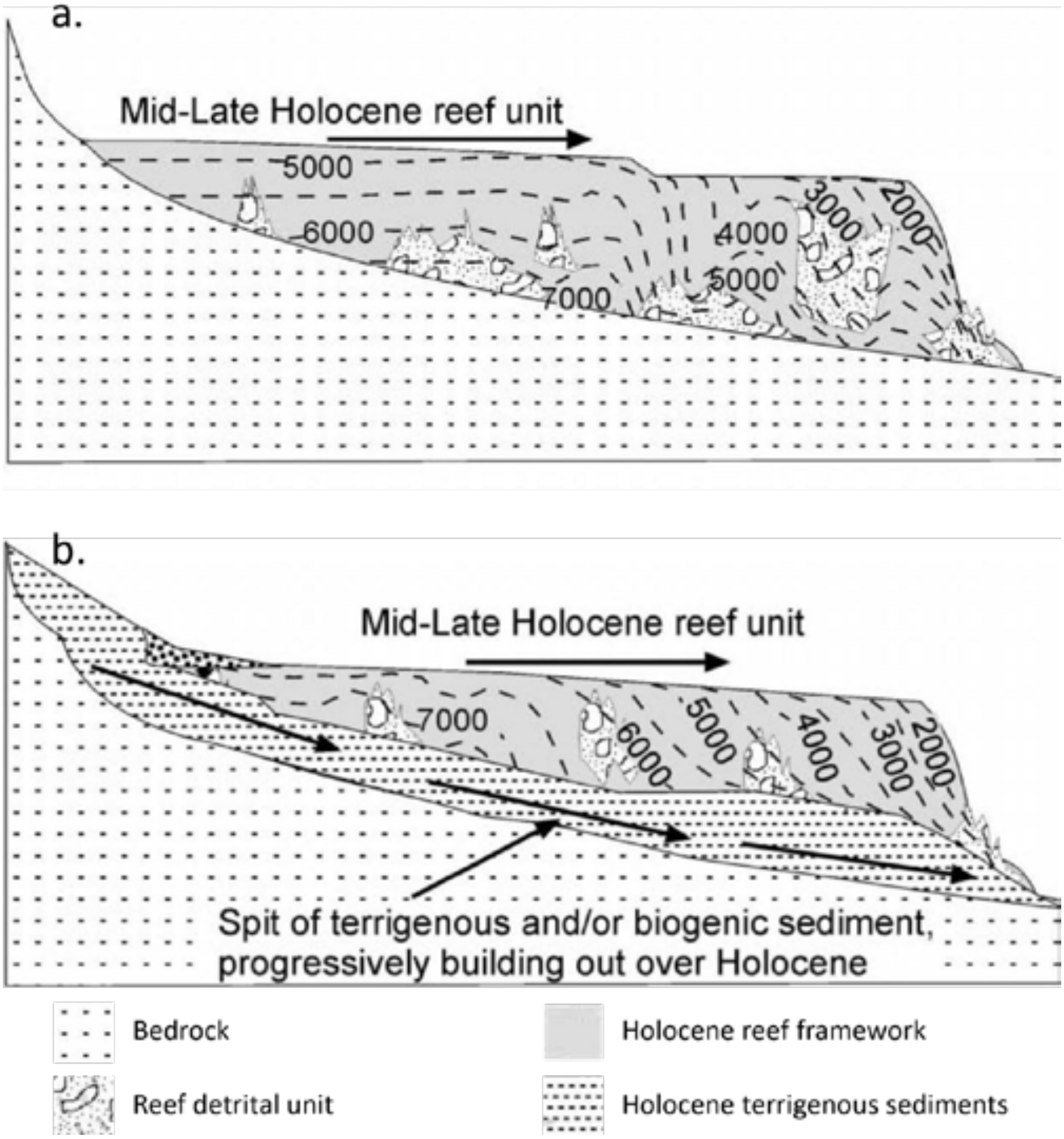

Figure 3. Conceptual schematics of nearshore reef development through the Holocene exemplifying the possible sequence of events for Moreton Bay reefs, from Smithers *et al*. (2006) (11). a) Episodic reef crest advance; b) lateral progradation along island spits.

An analysis of sediment cores from Wellington Point, Peel Island, and Myora Reef shows three clear episodes of reef development in Moreton Bay, separated by two clear episodes without coral reef growth (1). Reef initiation and growth in Moreton Bay occurred at 7,400 to 6,800, 4,900 to 3,000, and 2,100 to 400 ybp. The oldest section of Holocene reef in Moreton Bay initiated as an island spit ~ 7,400 ybp, which fits within the window of time when other marginal reefs initiated along the Queensland coast (9, 38). High-latitude marginal reefs tend to lag the tropical reef initiation window, which occurred ~ 9,000 to 7,000 ybp for the GBR (39) and as early as ~ 20,000 ybp in the central Pacific (37, 40). It is tempting to explain the older (~ 6,800 to 4,900 ybp) hiatus in Moreton Bay reef growth by a ~ 1.5 m sea level fall (14, 15, 18), combined with increased climatic instability (19, 30, 31). However, all of these factors occurred much later than the start of the hiatus, within a few centuries from ~ 5,500 to 5,000 ybp, so additional factors might also be responsible for Moreton Bay reef "turn-off" *sensu* Perry and Smithers (41).

The second episode of Bay reef growth diverges from the record of tropical nearshore GBR reefs with an intermediate reef initiation episode at 4,900 to 3,000 ybp. In the tropical nearshore GBR record this time period is a very clear hiatus in reef initiation (38) and a hiatus in reef growth for many reefs in the offshore GBR (9, 42). Either Moreton Bay was more favourable than the tropical nearshore GBR for reef initiation at this time, or this intermediate window remains undiscovered in the tropics. Regardless of the cause for this regional difference, it is clear that environmental conditions during the second episode were conducive to coral reef growth in Moreton Bay. The causes of the younger hiatus in Moreton Bay reef growth from ≈ 3,000 to 2,000 ybp is also less easily explained. There was another ~ 1.5 m sea level fall (14, 15), combined with a peak in ENSO intensity (31), but these factors cannot logically cause reef termination at ~ 3,000 ybp and also fail to prevent reef initiation at ~ 2,000 ybp.

The most recent episode of reef initiation in Moreton Bay is 2,100 to 400 ybp, which loosely fits the most recent episode defined for tropical marginal reefs of the GBR (38). Reef initiation during this recent episode is somewhat puzzling because environmental conditions do not satisfy the typical preconditions for reef growth. Environmental factors that promoted reef initiation during the Holocene climatic optimum were reversed for the youngest episode (9, 19). Sea level fell by 1 to 2 m (15), shifting the intertidal zone downward and reducing the amount of substrate available for corals. Sea level fall also shifted river mouths seaward, and the reduced volume of tidal circulation in the Bay increased the residence time of terrestrial inputs to the nearshore marine environment (35). However, a sea-level fall can also potentially allow enough light to reach the seafloor of some turbid areas, which could allow for renewed reef growth (43). The El-Niño Southern Oscillation (ENSO) reached its peak intensity at ~ 2,700 ybp, which included temperature extremes and a flooding regime more severe than today (4, 27, 31). This would have destabilized vegetation and increased sedimentation to the nearshore reefs along the tropical and sub-tropical east Australian coast. Nevertheless, reef initiation and relatively rapid reef accretion occurred in Moreton Bay and in other nearshore tropical marginal reefs as recently as ~ 900 to 300 years ago (41).

The marginal reefs of Moreton Bay exhibited robust growth in the mid-Holocene, and have grown episodically over 7,000 years with no significant change in community composition or accretion rate (7). Changes in temperature, sea level, ENSO intensity, and sedimentation led to natural reef declines sometime between 8,000 and 3,000 ybp (4), prior to major anthropogenic disturbance. However, the Bay's reefs have recently exhibited significant modern degradation due to overexploitation and water quality degradation associated with the beginning of European settlement of the Queensland coast in 1824 (4, 7, 19, 44). In the past 200 years, reefs have changed significantly, and for the first time in 7,000 years reefs of Moreton Bay persist in a degraded state caused by increased sediment and nutrient runoff from anthropogenic land-use changes (7). Branching *Acropora* corals dominated assemblages from 7,000 to 200 years ago, and since that time assemblages have been dominated by massive corals such as *Favia* (7). Reversal of this degraded state will require reduced sediment and nutrient loads onto the reefs.

References

1. Lybolt M. 2012. Dynamics of marginal coral reef ecosystems: Historical responses to climatic and anthropogenic change
2. Wallace CC, Fellegara I, Muir PR, Harrison PL. 2009. The scleractinian corals of Moreton Bay, eastern Australia: High latitude, marginal assemblages with increasing species richness. Memoirs of the Queensland Museum. 54(2):1-118
3. Davie PJ, Hooper JN. 1998. Patterns of biodiversity in marine invertebrate and fish communities of Moreton Bay. In: Tibbetts IR, Hall NJ, Dennison WC (Eds). Moreton Bay and Catchment. School of Marine Science, The University of Queensland. Brisbane, Austrlia. p.331-346
4. Johnson P, Neil DT. 1998. Susceptibility to flooding of two dominant coral taxa in Moreton Bay. In: Tibbetts IR, Hall NJ, Dennison WC. (Eds) Moreton Bay and Catchment. School of Marine Science, The University of Queensland. Brisbane, Australia. p. 597-604
5. Guinotte J, Buddemeier R, Kleypas J. 2003. Future coral reef habitat marginality: Temporal and spatial effects of climate change in the Pacific Basin. Coral Reefs. 22(4):551-558
6. Kleypas JA, McManus JW, Menez LA. 1999. Environmental limits to coral reef development: Where do we draw the line? American Zoologist. 39(1):146-159
7. Lybolt M, Neil D, Zhao J, Feng Y, Yu K-F, Pandolfi J. 2011. Instability in a marginal coral reef: The shift from natural variability to a human-dominated seascape. Frontiers in Ecology and the Environment. 9(3):154-160
8. Flood P. 1978. The significance of two contrasting sedimentary environments (the fringing coral reef and the tidal mud flat) presently in juxtaposition along the southwestern shore of Moreton Bay, Queensland. Papers, Department of Geology, University of Queensland. 8(2):44-63
9. Smithers S, Hopley D, Parnell K. 2006. Fringing and nearshore coral reefs of the Great Barrier Reef: Episodic Holocene development and future prospects. Journal of Coastal Research. 22(1):175-187
10. Allingham D, Neil D. 1996. The supratidal deposits and effects of coral dredging on Mud Island, Moreton Bay, southeast Queensland. Oceanographic Literature Review. 4(43):411
11. Lovell E. 1989. Coral assemblages of Moreton Bay, Queensland, Australia, before and after a major flood. Memoirs of the Queensland Museum. 27(2):535-550
12. Fellegara I. 2007. Ecophysiology of the marginal, high-latitude corals (Coelenterata: Scleractinia) of Moreton Bay, Qld. PhD Thesis, Centre for Marine Studies, The University of Queensland. Brisbane, Australia

13. Perry C, Smithers S, Johnson K. 2009. Long-term coral community records from Lugger Shoal on the terrigenous inner-shelf of the central Great Barrier Reef, Australia. Coral Reefs. 28(4):941. https://doi.org/10.1007/s00338-009-0528-2
14. Sloss CR, Murray-Wallace CV, Jones BG. 2007. Holocene sea-level change on the southeast coast of Australia: A review. The Holocene. 17(7):999-1014
15. Lewis SE, Wüst RA, Webster JM, Shields GA. 2008. Mid-late Holocene sea-level variability in eastern Australia. Terra Nova. 20(1):74-81
16. Baker R, Davis A, Aitchison J, Flood P, Morton BS, Haworth R. 2003. Comment on "mid-Holocene higher sea level indicators from the south China coast" by WW-S. Yim and G. Huang [Mar. Geol. 182 (2002) 225–230]: A regional perspective. Marine Geology. 196(1-2):91-98
17. Baker J. 1984. Aspects of the terrestrial and marine geology of the Jumpinpin area, southern Moreton Bay, southeast Queensland. University of Queensland
18. Leonard ND, Welsh KJ, Zhao J-x, Nothdurft LD, Webb GE, Major J, Feng Y, Price GJ. 2013. Mid-Holocene sea-level and coral reef demise: U-th dating of subfossil corals in Moreton Bay, Australia. The Holocene. 23(12):1841-1852
19. Neil DT. 1998. Moreton Bay and its catchment: Seascape and landscape, development and degradation. In: Tibbetts IR, Hall NJ, Dennison WC. (Eds). Moreton Bay and Catchment. School of Marine Science, The University of Queensland. Brisbane, Australia. p. 3-54
20. Lovell E. 1975. Evidence for a higher sea level in Moreton Bay, Queensland. Marine Geology. 18(1):M87-M94
21. Ward W, Hacker J. 2006. Brisbane airport: An alluvial landscape veiled by marine sediments. Australian Journal of Earth Sciences. 53(6):1001-1012
22. Zhao J, Yu K. 2002. Timing of Holocene sea-level highstands by mass spectrometric U-series ages of a coral reef from Leizhou Peninsula, South China Sea. Chinese Science Bulletin. 47(4):348-352
23. Thom BG, Short AD. 2006. Introduction: Australian coastal geomorphology, 1984–2004. Journal of Coastal Research. 22(1):1-10
24. Kershaw A, Nix H. 1988. Quantitative palaeoclimatic estimates from pollen data using bioclimatic profiles of extant taxa. Journal of Biogeography. 15:589-602
25. Gagan MK, Ayliffe LK, Hopley D, Cali JA, Mortimer GE, Chappell J, McCulloch MT, Head MJ. 1998. Temperature and surface-ocean water balance of the mid-Holocene tropical western Pacific. Science. 279(5353):1014-1018
26. Gagan MK, Hendy EJ, Haberle SG, Hantoro WS. 2004. Post-glacial evolution of the Indo-Pacific warm pool and El Niño-Southern Oscillation. Quaternary International. 118:127-143
27. Donders TH, Haberle SG, Hope G, Wagner F, Visscher H. 2007. Pollen evidence for the transition of the eastern Australian climate system from the post-glacial to the present-day ENSO mode. Quaternary Science Reviews. 26(11-12):1621-1637
28. Neil DT, Orpin AR, Ridd PV, Yu B. 2002. Sediment yield and impacts from river catchments to the Great Barrier Reef lagoon: A review. Marine and Freshwater Research. 53(4):733-752
29. Moy CM, Seltzer GO, Rodbell DT, Anderson DM. 2002. Variability of El Niño/Southern Oscillation activity at millennial timescales during the Holocene epoch. Nature. 420(6912):162
30. Thompson LG, Mosley-Thompson E, Brecher H, Davis M, León B, Les D, Lin P-N, Mashiotta T, Mountain K. 2006. Abrupt tropical climate change: Past and present. Proceedings of the National Academy of Sciences. 103(28):10536-10543
31. Donders TH, Wagner-Cremer F, Visscher H. 2008. Integration of proxy data and model scenarios for the mid-Holocene onset of modern ENSO variability. Quaternary Science Reviews. 27(5-6):571-579
32. Kelley R, Baker J. 1984. Geological development of North and South Stradbroke Islands and surrounds. In: RJ Coleman, J Covacevich, P Davie (Eds). Focus on Stradbroke Island: New information on North Stradbroke Island and surrounding areas, 1974-1984 Boolarong, Brisbane, Australia
33. Kelley R, Baker J. 1984. Previously unpublished notes and photographs on the Jumpinpin breakthrough, North Stradbroke Island. In: RJ Coleman, J Covacevich, P Davie (Eds). Focus

on Stradbroke: New information on North Stradbroke Island and surrounding areas, 1974-1984. Boolarong, Brisbane, Australia
34. Ulm S, Petchey F, Ross A. 2009. Marine reservoir corrections for Moreton Bay, Australia. Archaeology in Oceania. 44(3):160-166
35. Buddemeier R, Hopley D. 1988. Turn-ons and turn-offs: Causes and mechanisms of the initiation and termination of coral reef growth. In: Choat JH, Barnes D, Borowitzka M, Coll JC, Davies PJ, Flood P, Hatcher BG, Hopley D, Hutchings PA, Kinsey D, Orme GR, Pichon M, Sale PF, Sammarco P, Wallace CC, Wilkinson C, Wolanski E, Bellwood O. (Eds) Proceedings of the 6th International Coral Reef Symposium. 1: Plenary Addressess and Status review. Lawrence Livermore National Lab., CA (USA), Townsville, Australia
36. Pickett J, Thompson C, Martin H, Kelly R. 1984. Late Pleistocene fossils from beneath a high dune near Amity, North Stradbroke Island, Queensland. In: RJ Coleman, J Covacevich, P Davie (Eds). Focus on Stradbroke: New information on North Stradbroke Island and surrounding areas, 1974–1984. Boolarong Publications: Boolarong, Brisbane, Australia. pp. 167–177
37. Montaggioni LF. 2005. History of Indo-Pacific coral reef systems since the last glaciation: Development patterns and controlling factors. Earth-Science Reviews. 71(1-2):1-75
38. Perry CT, Smithers SG. 2010. Evidence for the episodic "turn on" and "turn off" of turbid-zone coral reefs during the late Holocene sea-level highstand. Geology. 38(2):119-122
39. Hopley D, Smithers SG, Parnell K. 2007. The geomorphology of the Great Barrier Reef: Development, diversity and change. Cambridge University Press. 1139463926,
40. Cabioch G. 2003. Postglacial reef development in the south-west Pacific: Case studies from New Caledonia and Vanuatu. Sedimentary Geology. 159(1-2):43-59
41. Perry CT, Smithers SG. 2011. Cycles of coral reef 'turn-on', rapid growth and 'turn-off'over the past 8500 years: A context for understanding modern ecological states and trajectories. Global Change Biology. 17(1):76-86
42. Dechnik B, Webster JM, Webb GE, Nothdurft L, Zhao J-X. 2017. Successive phases of Holocene reef flat development: Evidence from the mid-to outer Great Barrier Reef. Palaeogeography, Palaeoclimatology, Palaeoecology. 466:221-230
43. Morgan KM, Perry CT, Smithers SG, Johnson JA, Gulliver P. 2016. Transitions in coral reef accretion rates linked to intrinsic ecological shifts on turbid-zone nearshore reefs. Geology. 44(12):995-998. https://doi.org/10.1130/G38610.1
44. Pandolfi JM, Bradbury RH, Sala E, Hughes TP, Bjorndal KA, Cooke RG, McArdle D, McClenachan L, Newman MJ, Paredes G. 2003. Global trajectories of the long-term decline of coral reef ecosystems. Science. 301(5635):955-958