Status of Coral Reefs of the World: 2020

Chapter 8. Status and trends of coral reefs of the Australia region

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Chapter 8.

Status and trends of coral reefs of the Australia region

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Geographic information and context

Key numbers:

- Total area of coral reefs: 41,802 km^2
- Proportion of the world's coral reefs: 16.1%
- Number of countries with coral reefs: 1
- Number of Marine Ecosystems of the World (MEOW) ecoregions: 11

General context:

The GCRMN Australia region supports about 16% (41,802 km^2) of the world's coral reefs. Among them is the iconic Great Barrier Reef (GBR), which is the single largest reef complex on the planet, comprising almost 3000 individual reefs and extending more than 2300 km along the Queensland coast, and the world's longest fringing reef, Ningaloo Reef in Western Australia. Coral reefs occur in all of Australia's northern tropical waters and exist as far south as Lord Howe Island (31°S) off the east coast and the Houtman Abrolhos Islands (29°S) off the coast of Western Australia. Australia's coral reefs are highly diverse ecosystems, supporting more than 400 species of hard coral, and exhibiting a variety of forms including fringing reefs, particularly along the coasts of Western Australia, Queensland and offshore continental islands such as Christmas Island, Lord Howe Island and those within the GBR, mid-shelf platform reefs, offshore atolls and submerged shoals.

Coral reefs, particularly the GBR, are part of Australia's national identity, and have been central to the rich culture of Australia's coastal Aboriginal and Torres Strait Islander peoples for millennia. Australia's coral reefs are economically important. The GBR alone contributes an estimated $6.4 billion per annum to Australia's economy and supports 64,000 jobs in the reef-based tourism, fisheries, recreation and research sectors[1].

Australia is a modern, affluent country with highly developed reef management policies that are implemented in partnership among multiple tiers of government, industry, Traditional Owners,

[1] Deloitte Access Economics 2017, At What Price? The economic, social and icon value of the Great Barrier Reef, Deloitte Access Economics, Brisbane.

community groups and research organisations[2]. The prime example of this partnership approach is the development and implementation of the Reef 2050 Long-term Sustainability Plan which is the Australian and Queensland Governments' overarching framework for protecting and managing the GBR[3]. In addition, Australia has long-established regulatory authorities with both the power and resources to enforce compliance with the rules and regulations governing reef-based activities, which includes tourism, commercial and recreational fishing, recreational activities and research. Further, Australia has an enduring and sophisticated network of Commonwealth and state managed marine protected areas to promote the long-term sustainable use and conservation of critical coral reef habitats. Conservation and management of Australia's iconic coral reefs is further enhanced by inscription of the GBR, Ningaloo, Shark Bay and Lord Howe Island on the World Heritage List.

Monitoring of coral reefs in Australia was haphazard until the establishment of the Australian Institute of Marine Science Long-term Monitoring Program (AIMS LTMP)[4] in 1985, which, at the time, was primarily concerned with assessing the size and impacts of populations of crown-of-thorns starfish (CoTS) on the GBR using the manta tow method. The AIMS LTMP has since evolved to provide a rigorous assessment of the overall health of the GBR and to measure the effectiveness of management interventions particularly spatial management (zoning) arrangements on the GBR. The Western Australian Department of Biodiversity, Conservation and Attractions (DBCA) has developed and incrementally implemented long-term monitoring of coral reefs within Western Australia's marine protected areas (Shark Bay, Ningaloo, Montebello and Barrow Islands, Rowley Shoals, Lalang-gaddam, North Kimberley) since 2009, in collaboration with joint management partners (Traditional Owners) and research agencies (AIMS, CSIRO, Reef Life Survey)[5]. The longest running monitoring program in Western Australia began in 1991 and is focused on Ningaloo Reef[5]. Monitoring at Scott Reef and Rowley Shoals commenced in 1994/95 and around the Cocos-Keeling and Christmas Islands began in 1998 and 2005 respectively[5]. Monitoring in the inshore Pilbara and Dampier Archipelago is still relatively opportunistic and is based on sporadic research opportunities[5].

The GCRMN Australia region includes 11 Marine Ecoregions of the World (MEOW) ecoregions[6] (Tab. 8.1, Fig. 8.1). Data collected from each ecoregion except Lord Howe Island are reported here.

[2] Great Barrier Reef Marine Park Authority 2019, Great Barrier Reef Outlook Report 2019, GBRMPA, Townsville.

[3] Australian Government and Queensland Government 2018, Reef 2050 Long-Term Sustainability Plan, Commonwealth of Australia, Canberra.

[4] https://www.aims.gov.au/docs/research/monitoring/reef/reef-monitoring.html

[5] Gilmour, J.P., Cook, K.L., Ryan, N.M., Puotinen, M.I, Green, R.H., Shedrawi, G., Hobbs, J.A., Thomson, D.P., Babcock, R.C., Buckee, J., Foster, T., Richards, Z.T., Wilson, S.K., Barines, P.B., Coutts, T.B., Radford, B.T., Piggott, C.H., Depczynski, M., Evans, S.N., Schoepf, V., Evans, R.D., Halford, A.R., Nutt, C.D., Bancroft, K.P., Heyward, A.J. and Oades, D. (2019). The state of Western Australia's coral reefs. Coral Reefs 38: 651–667. https://doi.org/10.1007/s00338-019-01795-8

[6] Spalding, M. D., E. H. F., Allen, G. R., Davidson, N., Ferdaña, Z. A., Finlayson, M., Halpern, B. S., Jorge, M. A., Lombana, A., Lourie, S. A., Martin, K. D., McManus, E., Molnar, J., Recchia, C. A., & Robertson, J. (2007). Marine Ecoregions of the World: A Bioregionalization of Coastal and Shelf Areas, BioScience, Volume 57, Issue 7, Pages 573–583, https://doi.org/10.1641/B570707

Table 8.1. The subregions comprising the Australia region, the area of reef they support, and the constituent Marine Ecoregions of the World (MEOW)[6].

Sub-region	Reef Area (km²)*	Proportion of total reef area within the Australia region	Constituent Marine Ecoregions of the World
1	35,487	85.0	142: Torres Strait Northern Great Barrier Reef 143: Central and Southern Great Barrier Reef 202: Tweed-Moreton
2	5,989	14.3	140: Arnhem Coast to Gulf of Carpentaria 141: Bonaparte Coast 144: Exmouth to Broome 145: Ningaloo 210: Shark Bay 211: Houtman
3	180	0.4	120: Cocos-Keeling/Christmas Island
4	146	0.3	151: Lord Howe and Norfolk Islands

*World Resources Institute. Tropical Coral Reefs of the World (500-m resolution grid), 2011. Global Coral Reefs composite dataset compiled from multiple sources for use in the Reefs at Risk Revisited project incorporating products from the Millennium Coral Reef Mapping Project prepared by IMaRS/USF and IRD. https://datasets.wri.org/dataset/tropical-coral-reefs-of-the-world-500-m-resolution-grid

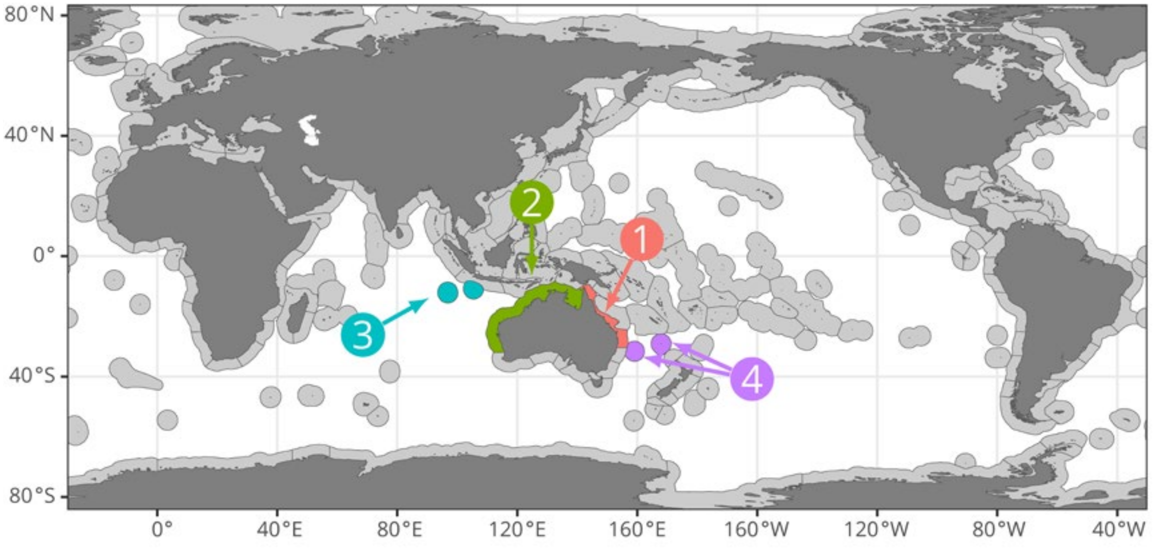

Figure 8.1. Map of each subregion comprising the Australia region. The number ascribed to each subregion corresponds with that in Table 8.1.

2. Summary of data contributed to this report

Key numbers:

- Number of countries from which monitoring data were obtained: 1 (of 1)
- Number of sites: 372
- Number of observations: 97,316
- Longest time series: 24 years

General features:

While regular monitoring of reefs within the GBR began in 1985 using manta-tows to assess the extent of CoTS outbreaks, the description of the status and trends of Australia's coral reefs presented below is based on more than 97,000 observations collected from 372 sites since 1994 (Tab. 8.2). These data were collected almost entirely using photo quadrats (Fig. 8.4) and comprise 10% of the global dataset that underpins this GCRMN *Status of Coral Reefs of the World: 2020* report. The vast majority of coral reef monitoring within Australia has been conducted on the GBR, and to a smaller extent on the west coast of Australia.

Long-term monitoring (>15 years between the first survey and the most recent survey) has occurred at 157 sites within the Australia region, with the longest time series at any one site being 24 years (Tab. 8.2, Figs. 8.2, 8.3A). The vast majority (141) of long-term monitoring sites occurred within the GBR (Tab. 8.2) and were part of the AIMS LTMP, which is supported by the Australian Government. Almost 80% of the data contributed from Australian coral reefs were collected from fixed sites that were surveyed repeatedly over periods very often exceeding a decade. Few sites (~20%) were surveyed only once (Figs. 8.2, 8.3A).

The distribution of monitoring effort over time has been reasonably constant (Fig. 8.3B), reflecting Australia's ongoing commitment to supporting long-term monitoring of coral reefs. While some increases in the number of surveys were evident in response to disturbance events, particularly the back-to-back mass coral bleaching events in 2016 and 2017, a consistent level of monitoring effort has been maintained since programs were established (Fig. 8.3B).

Table 8.2. Summary statistics describing data contributed from the Australia region. An observation is a single record within the global dataset (i.e. one row). A site is a unique GPS position where data were recorded. A site was considered a long-term monitoring site if the time between the first survey and the most recent survey was greater than 15 years. Such sites may have been surveyed multiple times during the intervening period.

Australia subregions	Observations		Sites		Long term monitoring sites	
	Total Number	Proportion of global dataset	Total Number	Proportion of global dataset	Total Number	Proportion of global dataset
All	97,316	10.04	372	3.06	157	22.62
1	83,717	8.63	300	2.47	141	20.32
2	13,599	1.4	72	0.59	16	2.31
3	0	0	0	0	0	0
4	0	0	0	0	0	0

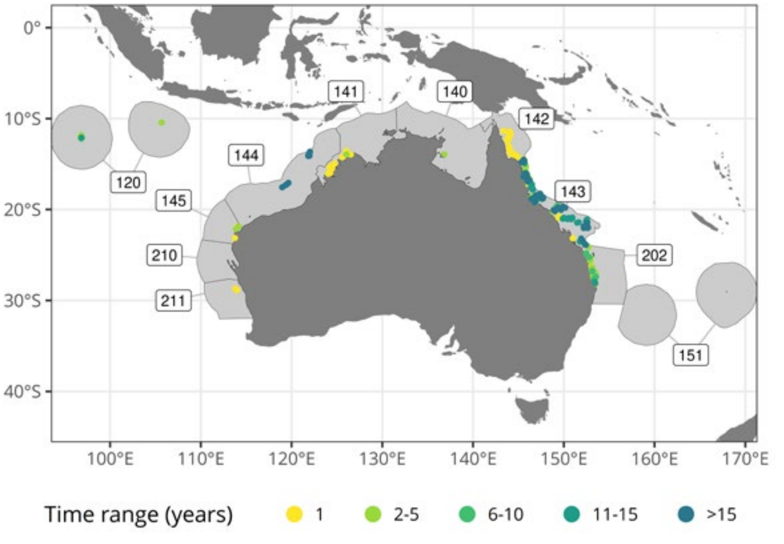

Figure 8.2. The distribution and duration of monitoring at sites across the Australia region. The colours of dots represent the time span between the first survey and the most recent survey at each site. Numbers refer to the MEOW ecoregions listed in Table 8.1.

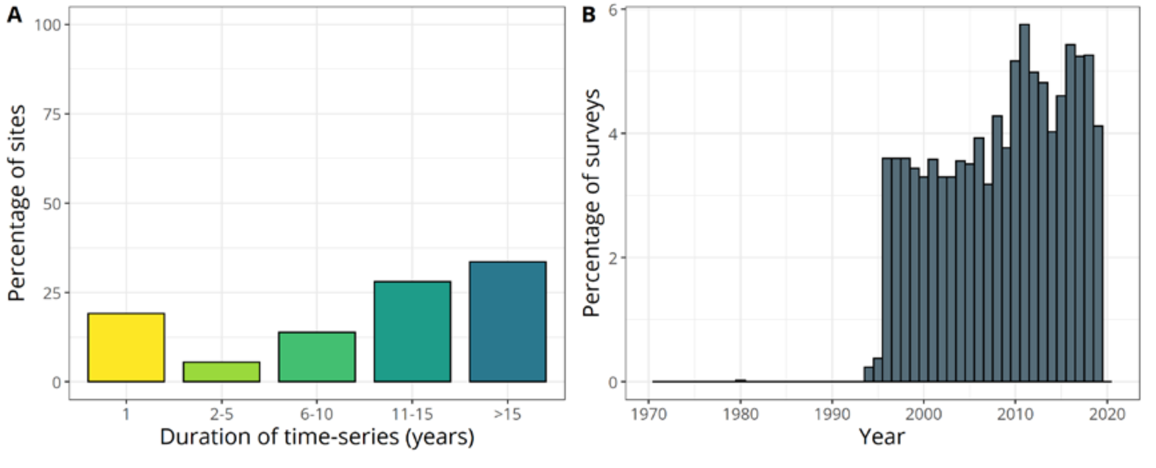

Figure 8.3. The proportion of sites in the Australia region within each category describing the time span between the first and most recent surveys (A), and the proportion of the total number of surveys conducted in each year (B). The total number of surveys was 3,804.

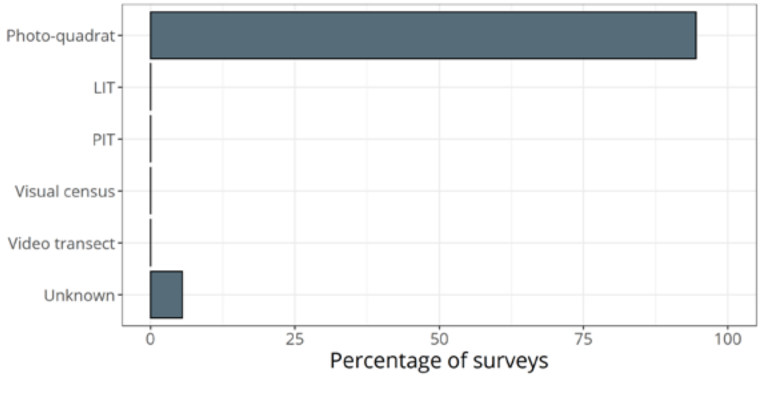

Figure 8.4. The proportion of the total number of surveys conducted in the Australia region using each survey method. PIT: Point Intercept Transect; LIT: Line Intercept Transect.

3. Status of coral reefs in the Australia region

- Regional trends in the cover of live hard coral and algae

In 1994, when the earliest data contributed to this report were collected, estimated average live hard coral cover across the Australia region was 35.2% (Fig. 8.5A). The next five years were characterised by a very small decline in average hard coral cover to 34.5%, although uncertainty associated with these early estimates was relatively high owing to the scarcity of data that were available from this time (Fig. 8.5A). Between 1999 and 2003, the rate of decline increased, with hard coral cover falling to 30.6% in 2003 as a consequence of large-scale coral bleaching events that affected coral cover on both the GBR and coral reefs in far north Western Australia in 1998 and the GBR in 2002. Substantial recovery occurred during the next four years, with average coral cover reaching 35.4% in 2007. However, between 2008 and 2014, coral cover declined to 27.4%, primarily due to the impacts of Tropical Cyclones Hamish (2009) and Yasi (2011), the initial stages of a CoTS outbreak on the GBR and coral bleaching on reefs in Western Australia from 2011-2013. This decline was arrested in 2015 and 2016 with increases to 29.2% and 30.9% respectively, but this recovery was short-lived, with back-to-back coral bleaching events occurring in 2016 and 2017 that resulted in a decline to the lowest coral cover (25.7%) in this time series in 2018. In 2019, the decline had halted with average coral cover reaching 26.0% (Fig 8.5A).

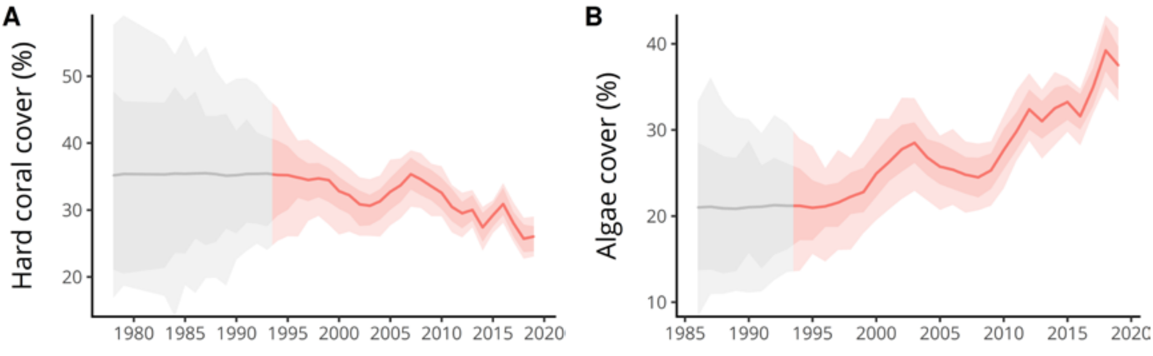

Figure 8.5. Estimated regional average cover of live hard coral (A) and algae (B) for the Australia region. The solid line represents the estimated mean and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods during which no field data were available.

Comparison of average hard coral cover between the three most recent five-year periods (2005-09, 2010-14, 2015-19), indicated (>89% probability) that there had been an overall decrease in coral cover during the last 15 years (Tab. 8.3). On average, there was 25.3% less coral on reefs in the Australian region in the period between 2015-19 compared with 2005-09, and almost 70% of this decline occurred between 2005-09 and 2010-14 (Tab. 8.3).

Table 8.3. Probability and magnitude of mean absolute and relative change in the percent cover of live hard coral in the Australia region between each of the three five-year periods comprising the last 15 years.

Comparison	Probability of change (%)	Mean absolute change (%)	Mean relative change (%)
2005-09 - 2010-14	99	-4.6	-19
2010-14 - 2015-19	89	-1.7	-7.7
2005-09 - 2015-19	100	-6.6	-25.3

The trend in the cover of algae on Australian coral reefs during the last 25 years was generally the inverse of coral cover. In 1994, the average cover of algae on Australian coral reefs was 21.2% (Fig. 8.5B). While there was little change between 1994 and 1996, the cover of algae increased substantially during the next seven years, reaching 28.5% in 2003. This corresponded with the decline in coral cover that occurred following the 1998 and 2002 mass coral bleaching events. Between 2004 and 2008, when coral cover on Australian reefs was recovering, the cover of algae progressively decreased to 24.5% in 2008. However, between 2009 and 2016, the cover of algae continued its upward trajectory but fluctuated, with small decreases occurring in 2013 and 2016. Substantial increases in the cover of algae were recorded in 2017 and 2018, peaking at 39.2%. This corresponds with the substantial decline in coral cover that occurred following the back-to-back coral bleaching events of 2016 and 2017. In 2019, the average cover of algae was 37.5%, indicating that there was 77% more algae on Australian reefs in 2019 compared with 1994 (Fig. 8.5B). Comparison of the average algal cover during the last three five-year periods indicates unequivocally (100% probability) that there was more algae on Australian reefs in 2015-19 compared with 2005-09 (Tab. 8.4).

Table 8.4. Probability and magnitude of mean absolute and relative change in the percent cover of algae in the Australia region between each of the three five-year periods comprising the last 15 years.

Comparison	Probability of change (%)	Mean absolute change (%)	Mean relative change (%)
2005-09 - 2010-14	100	6.3	36.9
2010-14 - 2015-19	100	4.0	20.4
2005-09 - 2015-19	100	10.2	65.8

- Primary causes of change in the cover of live hard coral and algae

The greatest cause of declines in hard coral cover on Australian coral reefs was coral bleaching caused by anomalously high sea surface temperatures (SSTs) associated with climate change. Anomalously high SSTs have occurred on the GBR every year since 2012 and have remained persistently high during the last two decades[2]. This is consistent with trends in Western Australia[5] and globally.

In 2016, unprecedented heat stress caused severe bleaching and coral mortality on coral reefs on both the east and west coasts of Australia. On the GBR, this caused severe coral bleaching on reefs in the northern third, where an estimated 30% of the coral on shallow water reefs was lost[7,8], and bleaching and mortality was recorded on mesophotic reefs at depths of 40 m[9]. In Western Australia, the most severe bleaching occurred primarily on northern reefs (Christmas Island, Ashmore Reef, Hibernia Reef, Scott Reef, Southern inshore Kimberley), with subsequent mortality of coral colonies exceeding 60% and declines in the amount of coral often exceeding 50%[5]. Coral reefs further south (Rowley Shoals, Pilbara, Ningaloo, Houtman Abrolhos) largely escaped[5] bleaching during El Niño conditions, but were typically affected during La Niña conditions, which caused moderate to severe bleaching at several Western Australian reefs between 2011 and 2013 and 2021.

[7] Great Barrier Reef Marine Park Authority 2017, Final Report: 2016 Coral Bleaching Event on the Great Barrier Reef, Great Barrier Reef Marine Park Authority, Townsville.

[8] 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: 492-496.

[9] 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): 3447.

On the GBR, the 2016 event was followed immediately by a second severe coral bleaching event in 2017, which primarily affected the central third of the GBR. In this region, the cumulative impacts of both the 2016 and 2017 bleaching events and an outbreak of CoTS reduced the amount of coral by more than 30%. The combined footprint of the back-to-back 2016 and 2017 coral bleaching events affected the northern two-thirds of the GBR[2].

Prior to the 2016 and 2017 coral bleaching events, the GBR had experienced three episodes of large-scale coral bleaching (1998, 2002, 2006). During both the 1998 and 2002 events, about 50% of reefs on the GBR exhibited bleaching, with the central GBR being most affected[10]. The 1998 event was largely confined to inshore reefs, while the 2002 event also included offshore reefs[10]. The 2006 event caused considerable coral mortality, but it was mostly confined to the Keppel Island area in the southern GBR, and recovery afterwards was rapid[11].

In Western Australia, coral bleaching has been more frequent. Since 1998, when Scott Reef in particular suffered significant bleaching-related coral mortality[12], coral bleaching has been observed on Western Australian coral reefs in 2003 (Ashmore Reef[5]), 2005 (Rowley Shoals[5]), 2010 (Christmas Island[5], Scott Reef), 2011 (Scott Reef[5], Ningaloo[5], Shark Bay[5] nearshore Pilbara[13,14]), 2013 (Scott Reef[5], Montebello and Barrow Islands[5], Dampier Archipelago[13], nearshore Pilbara[13,14], Ningaloo[5]), 2014 (nearshore Pilbara[13,14]) and most recently in 2016 (Scott Reef[5], Ashmore Reef[5], western Kimberley[5,15]). Since severe bleaching in 2016, several Western Australian coral reefs have suffered moderate bleaching from 2017 to 2020. More than half of Western Australia's coral reefs have been affected by coral bleaching since 2010. Coral mortality associated with these events varied, with southerly reefs being more affected by the 2010/11 events which were associated with a La Niña heatwave, while northern reefs are more susceptible to bleaching during El Niño phases.

In addition to coral bleaching, tropical cyclones are also a major cause of localised coral loss on both the GBR[16] and on coral reefs off the Western Australian coast, including Cocos-Keeling and Christmas Islands[5]. During the last two decades, 11 severe cyclones (Category 3 and above) have affected the GBR[17], with most of the GBR having been exposed to cyclonic winds and waves. Eight of those severe cyclones have occurred since 2009 when TC Hamish traversed almost half the length of the GBR from Cape Upstart to Bundaberg, affecting more than 50% of the coral reefs on the GBR[18]. In 2011, TC Yasi, one of the most powerful cyclones ever recorded in GBR waters, caused extensive damage to about 15% of reefs within the GBR, particularly between Cairns and Townsville[19].

[10] Berkelmans, R., De'ath, G., Kininmonth, S. & Skirving, W.J. 2004, A comparison of the 1998 and 2002 coral bleaching events on the Great Barrier Reef: spatial correlation, patterns and predictions. Coral Reefs, 23: (1) 74-83.

[11] Diaz-Pulido, G., McCook, L.J., Dove, S., Berkelmans, R., Roff, G., Kline, D.I., Weeks, S., Evans, R.D., Williamson, D.H. & Hoegh-Guldberg, O. 2009, Doom and boom on a resilient reef: climate change, algal overgrowth and coral recovery. PLoS ONE, 4(4): e5239.

[12] Gilmour, J.P., Smith, L.D., Heyward, A.J., Baird, A.H. and Pratchett, M.S. 2013, Recovery of an isolated coral reef system following severe disturbance, Science 340(6128): 69-71

[13] Babcock R.C., Thomson D.P., Haywood M.D.E, Vanderklift M.A., R Pillans R., Rochester W.A., Miller M., Speed C.W., Shedrawi G., Field S.N., Evans R.D., Stoddart J., Hurley T.J, A Thompson A. & M. Depczynski (2020). Recurrent coral bleaching in NW Australia and associated declines in coral cover. Marine and Freshwater Research. 72(5) 620-632 https://doi.org/10.1071/MF19378

[14] Evans R.D., Wilson S.K., Fisher, R., Ryan N.M., Babcock R.C., Blakeway D., Bond T., Dorji P., Dufois F., Fearns P., Lowe R.J., Stoddart J. & D. Thomson (2020). Early recovery dynamics of turbid coral reefs after recurring bleaching events. Journal of Environmental Management. 268: 110666. https://doi.org/10.1016/j.jenvman.2020.110666

[15] Hughes, TP, et al (2017) Global warming and recurrent mass bleaching of corals. Nature 543: 373-377.

[16] 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 of the United States of America 109(44): 17995-17999.

[17] http://www.bom.gov.au/cyclone/tropical-cyclone-knowledge-centre/history/past-tropical-cyclones/

[18] Great Barrier Reef Marine Park Authority 2010, Observed impacts from climate extremes on the Great Barrier Reef: summer 2008/2009, GBRMPA, Townsville.

[19] Great Barrier Reef Marine Park Authority 2011, Impacts of tropical cyclone Yasi on the Great Barrier Reef: A report on the findings of a rapid ecological impact assessment, GBRMPA, Townsville.

More recently, in 2017, TC Debbie caused a decline in coral cover of up to 97% on some reefs in the Whitsunday region of the GBR[20]. Cyclones are also a pervasive disturbance to Western Australian coral reefs. Scott Reef, Rowley Shoals and Ningaloo Reef have all experienced declines in hard coral cover as a consequence of multiple cyclones during the last 15 years. However, the highest and lowest latitude reefs are less exposed to cyclones.

In addition to coral bleaching and tropical cyclones, the GBR has also suffered from periodic outbreaks of the coral-eating CoTS since the early 1960s[16]. In 2010, a fourth outbreak commenced in the Cairns-Cooktown section, which has subsequently spawned secondary outbreaks that have affected reefs further south during the last decade. This pattern of progressive southward migration is consistent with previous outbreaks and has caused considerable loss of coral in the central third of the GBR and contributed to the decline in hard coral cover observed since 2009. In addition, an outbreak of CoTS was also detected in the Swains complex in the southern offshore GBR in 2017, which has been the primary cause of coral loss in this section of the GBR[2]. While local aggregations of CoTS have been recorded on some coral reefs in the Pilbara region, outbreaks of CoTS have not had a major impact on Western Australian coral reefs[5]. Localised outbreaks of the coral-eating snail (*Drupella cornus*) have occurred previously at some locations on Ningaloo reef. However, these peaked in the early 1990's and have been at manageable levels since[21].

Because there are few large river systems adjacent to Western Australia's coral reefs, and some of the reefs are located offshore, terrestrial run-off poses little threat to these reefs[5]. However, sediments, nutrients and pesticides from agriculture are recognised problems for coastal and inshore reefs of the GBR, and efforts to improve water quality are the targets of significant government investment[2,22,23]. While increased nutrients from terrestrial run-off in inshore waters undoubtedly contributes to algal growth, the primary responses in algal populations are likely to be driven by declines in hard coral cover.

While fishing on Australia's coral reefs is a significant commercial and recreational pursuit worth more than $100 million per year on the GBR alone[1], it is well regulated and not a significant influence on the condition of coral reefs. Moreover, the market for herbivorous fish, which are critical for keeping algal populations in check, is small in Australia so herbivorous fish populations remain healthy.

- Changes in resilience of coral reefs within the Australia region

To identify changes in the resilience of coral reefs in the Australian region, patterns of disturbance and recovery were examined at sites that had been surveyed repeatedly over a period of at least 15 years and had, at some point, experienced a relative decline in hard coral cover of at least 20%. Among the 135 such sites within the Australian region, 104 (77%) did not recover to at least 90% of their pre-disturbance hard coral cover (Tab. 8.5). On average, there was 45.3% less coral observed at long-term monitoring sites during the most recent surveys compared with the first surveys, and the average maximum loss of hard coral at these sites was 80.3% (Tab. 8.5).

[20] Australian Institute of Marine Science 2018, Long-term Reef Monitoring Program: Annual Summary Report on Coral Reef Condition for 2017/18, Australian Institute of Marine Science, https://www.aims.gov.au/reef-monitoring/gbr-condition-summary-2017-2018.

[21] Turner SJ (1994) Spatial variability in the abundance of the corallivorous gastropod Drupella cornus. Coral Reefs 13: 41-48.

[22] Great Barrier Reef Marine Park Authority 2009, Great Barrier Reef Outlook Report 2009, Great Barrier Reef Marine Park Authority, Townsville.

[23] Great Barrier Reef Marine Park Authority 2014, Great Barrier Reef Outlook Report 2014, Great Barrier Reef Marine Park Authority, Townsville.

Table 8.5. The mean maximum decline and the mean difference between first and last survey expressed as absolute and relative declines in percent live coral cover. N is the total number of sampling units for which >15 years of data were available and had experienced a relative decline in live coral cover of at least 20 percent. n is the number of sampling units that did not exhibit recovery to 90 percent of the initial live coral cover. Percent is the proportion of the total number of sampling units that did not exhibit recovery to 90 percent of the initial live coral cover. A sampling unit is defined as the specific area that was surveyed repeatedly. Depending on the survey methods used and how the data were provided, a sampling unit could be a transect, a quadrat or even a site.

N	n	Percent	Mean maximum absolute decline	Mean maximum relative decline	Mean long-term absolute decline	Mean long-term relative decline
135	104	77	24.0	80.3	10.0	45.3

4. Subregional trends in the cover of live hard coral and algae within the Australia region

After an initial period of stability from 1996 to 1999, when average coral cover was about 34%, the trend in average coral cover on the GBR (subregion 1) fluctuated in response to periodic disturbances (Fig. 8.6). Between 1999 and 2003, average coral cover declined from 34% to 29.2% as a result of coral bleaching events in 1998 and 2002. This was followed by a period of recovery when coral cover returned to 34.3% in 2007. However, the cumulative effects of prolonged thermal stress, CoTS outbreaks and tropical cyclones have caused widespread losses of coral since 2007. Between 2007 and 2014, the cumulative impacts of tropical cyclones (Hamish, 2008 and Yasi, 2011), significant flooding in the summer of 2010/11 that affected inshore reefs along virtually the entire length of the GBR, and an outbreak of CoTS that began in 2010, caused average coral cover to decline to 25.5% by 2014. Some recovery occurred in 2015 and 2016, but these gains were erased by the back- to-back severe coral bleaching events in 2016 and 2017, which caused average hard coral cover on the GBR to decline to its lowest level (23.7%) in 2018. Average hard coral cover on the GBR in 2019 was 24%, which equates to an overall loss of 27.6% of the coral on the GBR between 1996 and 2019.

In general, average hard coral cover on Western Australian coral reefs (subregion 2) was greater than on the GBR and around Cocos Keeling and Christmas Islands (Fig. 8.6). However, similar to the GBR, coral bleaching events and tropical cyclones have caused fluctuations in coral cover during the last 25 years. Initial estimates of hard coral cover indicated a decline of 5.7% from 43.5% (1994) to 37.8% (1999). Almost half of this decline was attributable to the impacts of the 1998 mass coral bleaching event. During the next six years, hard coral cover recovered to 42% in 2005 and remained stable until 2010. However, between 2010 and 2016, several tropical cyclones and bleaching events in 2010, 2011, 2013 and 2016 caused a decline in average hard coral cover to 36.5%. By 2019, average hard coral cover had recovered to 40.4%, representing only a small loss of coral over the last 25 years.

At the Cocos Keeling and Christmas Islands (subregion 3), a considerable decline in average hard coral cover was evident between 1997 and 1999 (Fig. 8.6), which was attributable to widespread coral bleaching at Christmas Island in 1998. Over the next decade, average hard coral cover progressively increased from 19.8% (1999) to 35.8% (2008). More recent data were not available to quantify the impacts of increased sea temperatures that caused coral bleaching on other reefs off the Western Australian coast, but available evidence suggests that the 2016 heat stress caused little bleaching at Cocos Keeling and at least moderate bleaching at Christmas Island.

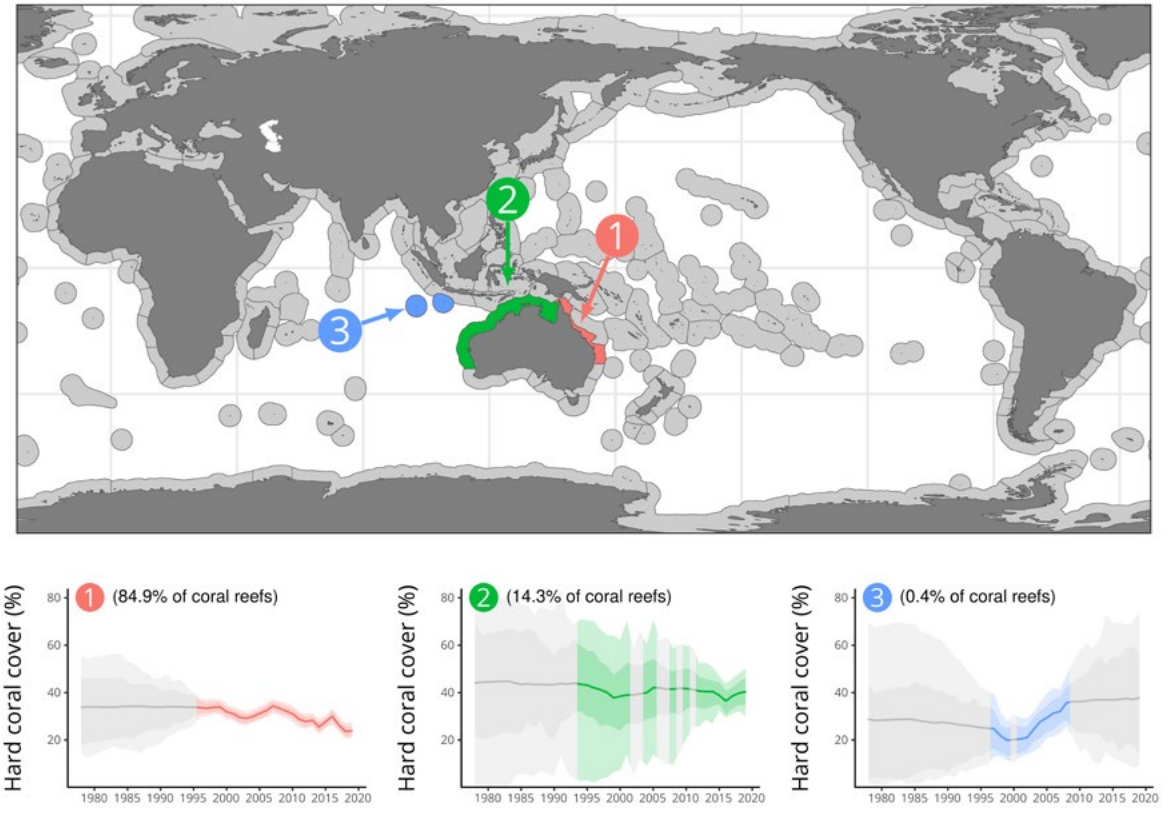

Figure 8.6. Estimated average cover of live hard coral within each subregion comprising the Australia region. The solid line represents the estimated mean and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods during which no field data were available. The proportion of all coral reefs in the Australia region within each subregion is indicated by the % of coral reefs.

The cover of algae on the GBR (subregion 1) has almost doubled between 1996 and 2019 (Fig. 8.7). During that time, fluctuations in the average cover of algae were generally the inverse of those exhibited by the average cover of coral. Between 1996 and 2003, the cover of algae progressively increased from 19.9% to 27%, coinciding with a period of decline in coral cover. Between 2004 and 2008, when coral cover was recovering, the cover of algae declined slightly to 23.1%. However, during the next decade, the cover of algae progressively increased from 23.1% (2008) to 40.3% (2018), as multiple disturbances reduced coral cover on the GBR and facilitated the growth of algae. A small decline in the cover of algae was recorded in 2019 (38.2%).

The cover of algae on Western Australian coral reefs (subregion 2) was generally higher than on the GBR, but exhibited similar responses to disturbance (Fig. 8.7). Initially, the average cover of algae increased from 30.1% in 1994 to 41.4% in 2002. More than 70% of that increase occurred during the two years immediately after the 1998 coral bleaching event. Between 2002 and 2013, the cover of algae progressively declined to 32.8%, as the coral cover recovered and stabilised. The cover of algae increased again after 2013, reaching 37% in 2017, before declining slightly to 36.2% in 2019. Similar to the response after the 1998 coral bleaching event, the average cover of algae increased by 3.3% between 2016 and 2017, which equates to almost 10% more algae on Western Australian reefs after the 2016 mass coral bleaching event.

Data describing the cover of algae on the coral reefs around Cocos Keeling and Christmas Islands (subregion 3) were collected only between 2003 and 2007. Those data that were collected suggest the cover of algae was low (<6%) and remained stable during that period (Fig. 8.7).

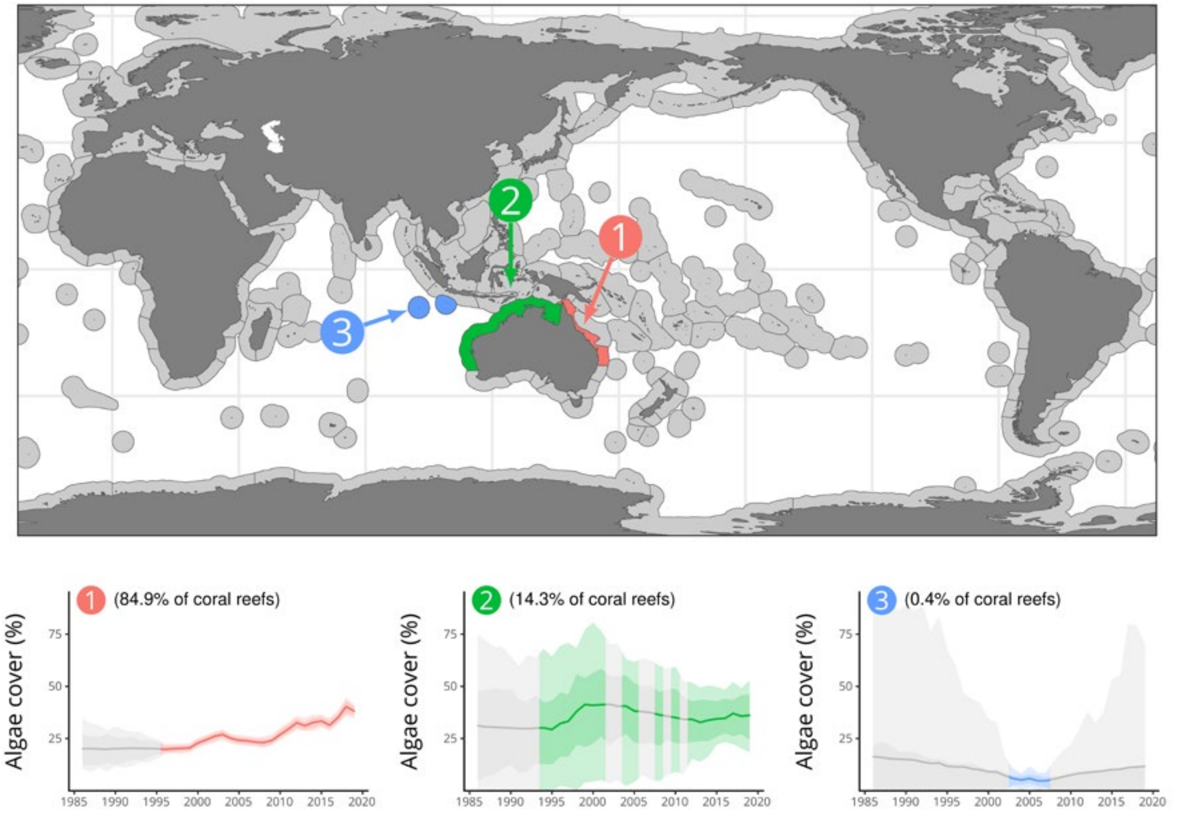

Figure 8.7. Estimated average cover of algae within each subregion comprising the Australia region. The solid line represents the estimated mean and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods during which no field data were available. The proportion of all coral reefs in the Australia region within each subregion is indicated by the % of coral reefs.

Box 5.

Transforming coral reef science and conservation with digital technologies

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Digital transformation has changed lives, economies, cultures, and societies, and is a primary source of change for many industries around the world. Today, data are the new gold. Advances in machine learning algorithms now mean those who have the best data win. Cheap sensors and the Internet of Things also mean we have more data than ever streaming in real-time. Further, cloud computing technology is enabling a raft of applications to be accessible online with the click of a button. These digital technologies are changing the conservation of nature in profound ways, and the same technological advances are helping us protect coral reefs.

Why is digital transformation relevant?

Globally, coral reefs are changing rapidly. Maintaining ecological integrity is paramount to ensure food and economic security for the 500+ million people who depend on coral reefs. Readily available knowledge of how and where coral reefs are changing, how fast they are changing, and what is causing those changes is critical to inform best practices in conservation, from local management to global policies.

The GCRMN *Status of Coral Reefs of the World: 2020* report draws on coral reef monitoring efforts from at least 73 countries and is a testament to the complex and laborious task of collating and analysing such valuable information. Simple technologies like underwater cameras, slates and pencils allow for practical and agile monitoring of key metrics such as live coral cover or fish abundance. However, challenges in data integration and limited resources often impair the capacity to fully utilise monitoring data generated by different monitoring programs across the world, or even within a country, to inform decision making.

As the pressures on coral reefs increase, it is critical that coral reef monitoring remains accurate, compatible, timely, relevant, and collaborative to support coral reef science and conservation. Digital technologies will be instrumental in the essential tasks of collecting, collating, standardising, analysing, and sharing data from global monitoring efforts. As new technological solutions emerge, we must ensure broad access to these technologies to maximise the global impact of coral reef monitoring and conservation.

Current solutions

In recent years, technological solutions for coral reef monitoring have rapidly emerged. Here, we present three examples that are changing monitoring by envisioning a world where coordinated scientific information is used for rapid evidence-based decision making to protect and manage coral reefs. Common to these solutions is the open-access nature, ecological robustness, truly multidisciplinary collaboration, and purposeful design to standardise, expedite, and broadly communicate the results of coral reef monitoring from around the world.

MERMAID - a Marine Ecological Research Management AID (www.datamermaid.org) is a collaborative platform of field-ready technologies for coral reef scientists. By developing online-offline data collection for common transect-based methods, with access to real-time reporting, analysis and dashboards, MERMAID delivers real-time data for crucial indicators of coral reef health using cutting-edge cloud and API-based technologies.

CoralNet (www.coralnet.ucsd.edu) is a repository and a collaborative resource for the analysis of benthic imagery that seamlessly integrates machine learning algorithms to support researchers to expedite the assessment of coral reef condition.

ReefCloud (www.reefcloud.ai) is a collaborative platform that builds on data management practices, machine learning algorithms, and statistical analyses to standardise and secure benthic monitoring data, enhance change detection using automated technologies and communicate where and how reefs are changing.

Next steps

Timing is everything. In 2021, new global targets will be adopted by governments under the Convention on Biological Diversity to halt, and ideally reverse, biodiversity loss in the coming decades. In addition, more than 1,400 voluntary commitments by nations and organisations worldwide are set to address the Sustainable Development Goals relevant to "Life Under Water" (Target 14), and the UN Decade of Ocean Science for Sustainable Development will bring together global efforts to reverse declines in ocean health. Tracking impact will be measured using ecosystem-specific indicators, like those supported by the International Coral Reef Initiative, that will require data collection, analysis and reporting at different scales.

Aligning the technologies and tools used for data collection and analysis within and between these initiatives is critical as the ability to achieve these goals relies on actions underpinned by evidence and data-driven measures and metrics. Collaborative tools and technologies can empower countries and organisations to report on and track the impact of these initiatives at local, national, and global scales, and suggest course corrections to meet desired outcomes. Therefore, proactive frameworks are needed that promote the integration of emerging technologies to embrace innovation, support the democratisation of data, and ultimately, support and strengthen desired conservation outcomes. They can also guide various types of investment in coral reef conservation amid ongoing global change, including climate change.

Box 6.

Scaling up coral restoration and accelerating adaptation in a warming world

By Ian McLeod, Tom Moore, Tali Vardi and David Mead

As coral reef health declines globally, it is clear that saving the world's coral reefs will require a multi-pronged approach that requires actions at local through to global scales. Immediate and aggressive action on climate change is paramount for the long-term survival of coral reefs. In addition, interventions, such as large-scale coral restoration, will be needed to complement traditional management and conservation strategies. Locally, we need to manage threats such as overfishing and pollution, while at the same time repopulating target reefs with resilient, genetically diverse and reproductively viable populations through restoration and novel ecological and geophysical interventions. This realization is not only leading to the generation of new interventions and approaches, but also greater coordination and collaboration to manage coral reefs globally.

In Australia, the Reef Restoration and Adaptation Program (RRAP, www.gbrrestoration.org), which was designed between 2018 and 2020, is developing new interventions to protect, adapt and restore coral reef systems. The design study assessed dozens of potential interventions deployed at different scales, either individually and in combinations. It found that improvements in reef condition can be achieved during the next 25-30 years if we deploy combinations of restoration interventions in concert with traditional management mechanisms (Fig. 1). However, unless there are concerted and parallel efforts to bring carbon emissions under control, climate-related pressures will overwhelm management and conservation efforts, closing this brief window of opportunity. The study identified several interventions with high potential, but all required significant research and development to be made operational at the required scales.

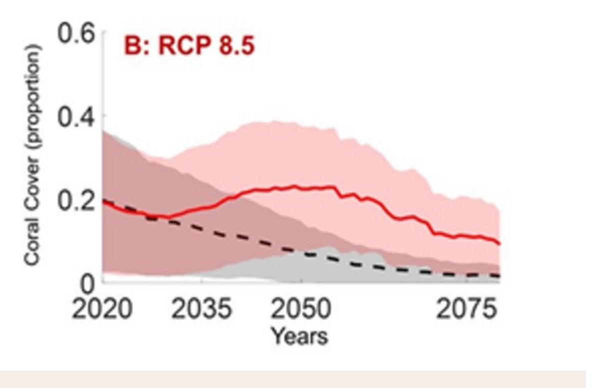

Figure 1: Combination of interventions deployed under RCP 8.5 conditions. They have an impact under RCP8.5 but perform much better under RCP 2.8.

Core funding for the first Research and Development phase (2021-2025) of AUD150 million is being provided by the Australian Government through the Reef Trust Partnership. As restoration will only be economically viable at high value sites, the program also has a strong focus on preventing further coral losses (e.g. through large-scale shading) and assisting reef systems to adapt (e.g. using genomic methods combined with aquaculture to accelerate temperature adaptation). Success for the RRAP will be measured by the successful development of deployable interventions at scales that have impact and stakeholder support. As such, RRAP is a multidisciplinary program that includes the development of industry pathways for deployment (Fig. 2). Some interventions will be deployed by volunteers, while others will require industrial scale autonomous systems and larger investments.

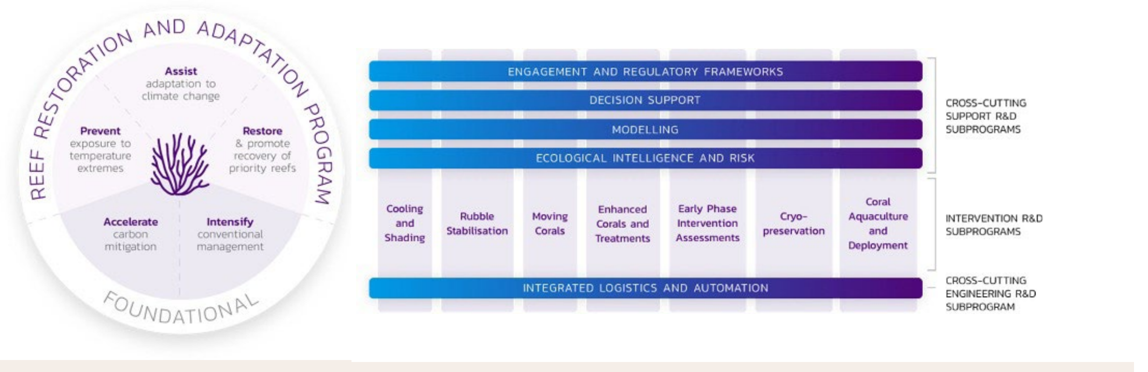

Figure 2. RRAP research and development program structure.

In the Florida Keys in 2019, in response to catastrophic (90%) declines in coral cover and little recovery, NOAA and partners launched *Mission: Iconic Reefs* to restore seven highly degraded, but historically significant reef sites. Phase 1 (USD100 million) aims to return coral cover to 15% by 2028 by using the best available restoration science while laying the groundwork for Phase 2, which will return the reef sites to their historic levels of coral cover by 2035 (Fig. 3).

Figure 3. The four phases of ***Mission: Iconic Reefs***

Coral reefs are one of the most vulnerable ecosystems to climate change, and it will take a global effort to reverse recent declines. Two organisations that are driving collaboration are the International Coral Reef Initiative (ICRI) and the Coral Restoration Consortium (CRC). ICRI is an informal partnership of 90 countries and organisations striving to preserve coral reefs and related ecosystems around the world. ICRI formed an Ad Hoc Committee on Reef Restoration (2019-2021) to share knowledge and enhance collaboration between countries, and hosts a 'Restoration Hub' to share coral restoration information. CRC is a community of practice comprising scientists, managers, coral restoration practitioners, and educators that aims to foster collaboration and technology transfer among participants and facilitate scientific and practical innovation. CRC, ICRI, the United Nations and others are working to further champion efforts as part of the UN Decade of Ecosystem Restoration (2021 to 2030) with the goal to massively increase restoration efforts to enhance food security, water supplies, and biodiversity, and combat the climate emergency.

We need to embrace this international call to action, and continue to collaborate, restore and invest in novel interventions that can help us buy time while we take urgent action to reduce greenhouse emissions and return ocean temperatures to levels at which coral reefs can thrive again. If we hesitate, even briefly, in our willingness to consider unconventional approaches, then it is likely the pace of change will outstrip our capacity to successfully intervene.

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