What do we know? What don't we know?

The past year has been a period of intense local, national and international discussion about the future of the Great Barrier Reef, culminating in the launch of the Reef 2050 Long-Term Sustainability Plan (Reef 2050) in March, 2015.

These conversations about the Reef were informed by years of research by the Australian Institute of Marine Science (AIMS) and our partners. AIMS is Australia's national tropical marine research agency. This document summarises much of the information that we and others have gathered that have helped governments, industry and the wider community make informed decisions about the management of the Great Barrier Reef including:

- How has the Reef changed? AIMS scientists have been directly monitoring the state of the Reef for more than 30 years; we also have a range of tools to look further back in time. Dozens of scientific reports clearly show that the Reef has been in serious decline. This is most clearly demonstrated by the loss of half the coral cover since 1985.
- What is causing those changes? There are many factors at work and it varies – from north to south, from outer Reef to inner Reef. Storms, increasing ocean temperature and acidity, crown-of-thorns starfish (COTS), water quality and other factors all play a role. We don't have the complete story yet. Some impacts are well understood, others, like dredging, are not. We're working to fill the knowledge gaps.
- How will the Reef continue to change in response to continuing climate change and other pressures? What will the cumulative impact be? Is the Reef losing its capacity for repair? And can we help the Reef remain resilient and adapt to change? These questions require us to answer fundamental questions about coral biology which we're doing through a series of studies in our SeaSim aquaria, in the field, and by combining this knowledge into models that predict the future state of the Reef based on credible scenarios.

These are all complex questions and there are many gaps in our knowledge. So what do we know?

We know

The Great Barrier Reef has lost half its coral cover since 1985

We know this from direct monitoring, involving 2,258 reef surveys covering 214 reefs over a 27 year sampling period. These studies were undertaken as part of the AIMS Long Term Monitoring Program for the GBR–the most comprehensive monitoring program of any reef system in the world.

In 2012, AIMS published a paper that summarised the major trends in reef condition over the 27 years to 2012 and reported that the Reef had lost half its coral cover over this time. Subsequent studies have affirmed these trends. Some reefs are doing better, some are doing worse, and coral reefs go through cycles of disturbance and recovery. But the general trend over the past three decades shows that coral cover, the number of juvenile corals, and other important processes for coral reefs such as calcification, have been decreasing. For example, the rate of growth of Porites coral (measured by calcification) declined by 11 per cent between 1990 and 2005.

The recent decline in coral calcification is unprecedented in at least the past 400 years

We know this from studies of long coral core records. Coral growth can be measured by coral calcification–the speed at which their calcium carbonate skeleton is deposited. Sustained calcification is essential for coral recovery, and for repair to the Reef after physical erosion (such as from storms) and biological erosion. The recent slowing of coral growth rates on the Reef between 1990 and 2005 has also been reported for several other reef locations around the world. The observed decline in calcification in the field is likely to be due to warming seas. Laboratory experiments indicate that future declines in calcification will be driven by ocean warming and acidification.

Storms, spikes in sea temperature and crown-of-thorns starfish outbreaks are the major direct contributors to the decline in coral cover

The known causes of the observed decline in coral cover since 1985 were storm damage (48%), crown-of-thorns starfish (42%), and bleaching (10%) from extended periods of increased sea temperature. The Reef has been impacted by an unusually high number of severe storms over the past decade. The impact of crown-of-thorns begs the question: what causes these starfish outbreaks?

Water quality is the number one suspect for crown-of-thorns starfish outbreaks

We don't know precisely what causes the periodic crown-of-thorns outbreaks but water quality is the number one suspect and, in particular, the availability of more nutrients that increase the amount of plankton for the larvae of crown-of-thorns starfish to feed on. This means that river floods and associated sediment and nutrient run-off are strongly implicated.

A new outbreak of crown-of-thorns is developing now (mid 2015). The reefs between Cairns and Cooktown are currently carrying more than five million adult crown-of-thorns starfish. About 500,000 starfish have been killed by divers and this activity is protecting individual reefs. However, we also need a more systemic approach for long-term protection of the whole of the Great Barrier Reef from crown-of-thorns outbreaks. Ideally this would involve identifying and controlling the conditions that lead to outbreaks, and developing effective means for early detection and control.

Flood events are more frequent, more extreme, and they're impacting on the mid-shelf reefs

The frequency of large river floods affecting the central Great Barrier Reef (GBR) has increased since the late 19th century. High flow events are now occurring on average every six years (1948-2011), compared with every 20 years in the period 1748-1847. Three of the most extreme flood events have occurred within the past 40 years (1974, 1991, and 2011). Extreme flood events are also resulting in more frequent freshwater impacts on mid-shelf reefs. We know this from measurements of luminescent records of flood events contained in long cores taken from the skeletons of large massive corals.

Rising carbon dioxide levels will be bad for coral but good for seagrass

Rising carbon dioxide in the atmosphere will lead to ocean acidification and other changes in the seawater chemistry. Such acidification can reduce coral calcification and growth, and lead to a decline in coral diversity. Fish behaviour is also impacted by ocean acidification, increasing the risk of mortality in some species.

Ocean acidification may also encourage the growth of seaweeds, which compete for space with corals. The growth of seagrasses also benefits from ocean acidification. We know this from studies of naturally occurring carbon dioxide seeps in Papua New Guinea.

The Great Barrier Reef can recover - given time and a reduction in the cumulative impacts of cyclones, acidification, crown-of-thorns, hotter oceans, etc.

In the absence of tropical cyclones, crown-of-thorns starfish, and bleaching, the coral cover on the Reef could recover on average by nearly three per cent a year, so coral cover would come back if the Reef was given enough time between disturbances. However, rates of recovery depend in part on the type of coral present. For example, reefs with tabulate (plate-forming) *Acropora* corals recover faster from storm damage than massive corals. But they're also more vulnerable to damage.

The recovery potential of the Reef in the future will also depend on how sensitive coral growth (calcification) will be to future acidification of the oceans, continued warming, and to future extreme thermal stress events causing bleaching.

Inner reefs have shown some recovery, perhaps due to low rainfall and recovery following the devastation caused by Tropical Cyclone Yasi

Recent AIMS surveys indicate that over the past two years, coral decline on the inner Reef has paused but its condition is still 'poor'. In a parallel study, James Cook University researchers found that inshore seagrass has started to recover. These results may indicate that land management changes are working, or it may reflect the recent low rainfall years reducing the amount of runoff of freshwater, sediments and nutrients to the Reef, and/or recovery from Tropical Cyclone Yasi which destroyed many seagrass beds.

We don't know enough yet

We need to know more about the potential impact of dredging and other coastal development

Historically the focus on monitoring on the Reef was on the mid- and outer-reef systems so we know less about changes on the inner-reefs and their causes.

The recently published 'Dredging Synthesis Report' identified "significant areas of insufficient knowledge" including sediment dynamics, monitoring, and sensitivity of coral and seagrass to increased sediment exposure. AIMS is working to fill these knowledge gaps with field studies, analysis of water quality data from past dredging projects, and experiments in its SeaSim aquaria. The aim is to enhance capacity within government and the private sector to predict and manage the environmental impacts of dredging, and to facilitate more informed environmental decision-making.

We need to know more about what happens when everything comes together

Coral on the Reef faces multiple challenges. What happens when higher temperatures combine with higher acidity and changing water quality? Are existing pollutants more or less dangerous at higher temperatures? What about sediments, storms and other factors working together? And what will be the impact of these changes on fish?

These questions are being tackled by combining field data with experiments in SeaSIM, the AIMS research aquaria. SeaSIM can produce controlled combinations of warming oceans, sediment, pollutants, acidity, water flow and other factors, giving scientists unprecedented ability to simulate real-world environmental conditions.

We don't know how adaptable Reef life will be to cumulative impacts

Can corals or reef ecosystems adapt to warmer oceans? How will the bacteria and algae associated with coral cope? Can we help coral ecosystems adapt to change? These questions are the subject of a series of long-term experiments and field studies exploring such issues as

- Finding and breeding heat tolerant corals that might be suitable for reef rehabilitation
- Identifying reefs with heat tolerant coral communities and protecting them so that they naturally repopulate other reefs

The state of the Great Barrier Reef – key papers

The following are just a few of the scientific studies on the state of the Great Barrier Reef by AIMS and other researchers.

Coral cover and calcification

Bruno JF, Selig ER (2007) Regional Decline of Coral Cover in the Indo-Pacific: Timing, Extent, and Subregional Comparisons. PLoS ONE 2:e711

De'ath G, Fabricius KE, Sweatman H, 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 190:17995-17999

De'ath G, Lough JM, Fabricius KE (2009) Declining Coral Calcification on the Great Barrier Reef. Science 323:116-119

De'ath G, Fabricius K, Lough J (2013) Yes — Coral calcification rates have decreased in the last twenty-five years! Marine Geology 346:400-402

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

Sweatman H, Delean S, Syms C (2011) Assessing loss of coral cover on Australia's Great Barrier Reef over two decades, with implications for longer-term trends. Coral Reefs online first:1-11

Thompson A, Schroeder T, Brando V, Schaffelke B (2014) Coral community responses to declining water quality: Whitsunday Islands, Great Barrier Reef, Australia. Coral Reefs 33:923-938

Cyclones, crown of thorns starfish and temperature (bleaching)

Cantin NE, JM Lough (2014) Surviving coral bleaching events: *Porites* growth anomalies on the Great Barrier Reef. PLos ONE 9, doi:10.1371/journal.pone.0088720

De'ath G, Fabricius KE, Sweatman H, 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 190:17995-17999

De'ath G, Lough JM, Fabricius KE (2009) Declining Coral Calcification on the Great Barrier Reef. Science 323:116-119

Maynard, J. A., Anthony, K. R. N., Marshall, P. & Masiri (2008) Major bleaching events lead to increased thermal tolerance in corals. *Mar. Biol.* 155, 173–182

Water quality and its impact on inshore reefs and crown of thorns

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

Fabricius K, Okaji K, 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 29:593-605

Lough JM, SE Lewis and NE Cantin (2015) Freshwater impacts in the central Great Barrier Reef: 1648-2011. Coral Reefs, doi:10.1007/s00338-015-1297-8.

Schaffelke B, Anthony K, Blake J, Brodie J, Collier C, Devlin M, Fabricius K, Martin K, McKenzie L, Negri A, Ronan M, Thompson A, Warne M (2013). Supporting evidence to *Scientific consensus statement: Land use impacts on Great Barrier Reef water quality and ecosystem condition. Chapter 1, Marine and Coastal ecosystem impacts*, Reef Water Quality Protection Plan Secretariat, Brisbane. Available at: www.reefplan.qld.gov.au

Thompson A, Schroeder T, Brando V, Schaffelke B (2014) Coral community responses to declining water quality: Whitsunday Islands, Great Barrier Reef, Australia. Coral Reefs 33:923-938

Ocean acidification

Albright R, Langdon C, and K. R. N. Anthony (2013) Dynamics of seawater carbonate chemistry, production, and calcification of a coral reef flat, central Great Barrier Reef. Biogeosciences, 10, 6747–6758, 2013

Anthony KRN, Maynard JA, Diaz-Pulido G, Mumby PJ, Marshall PA, Cao L, Hoegh-Guldberg OVE (2011) Ocean acidification and warming will lower coral reef resilience. Global Change Biol 17:1798-1808

Anthony, K. R. N., Kline, D. I., Diaz-Pulido, G., Dove, S. & Hoegh-Guldberg, O. (2008) Ocean acidification causes bleaching and productivity loss in coral reef builders. *Proc. Natl. Acad. Sci.* 105, 17442–17446.

Fabricius KE, Langdon C, Uthicke S, Humphrey C, Noonan S, De'ath G, Okazaki R, Muehllehner N, Glas MS, Lough JM (2011) Losers and winners in coral reefs acclimatized to elevated carbon dioxide concentrations. Nature Climate Change 1:165-169

Fabricius KE, De'ath G, Noonan S, Uthicke S (2014) Ecological effects of ocean acidification and habitat complexity on reef-associated macroinvertebrate communities. Proceedings of the Royal Society B 281: 20132479

Fabricius KE, Kluibenschedl A, Harrington L, Noonan S, De'ath G (2015) In situ changes of tropical crustose coralline algae along carbon dioxide gradients. Scientific Reports 5: 9537. doi:10.1038/srep09537

Ow YX, Collier CJ and Uthicke S (2015) Responses of three tropical seagrass species to CO2 enrichment. Marine Biology, 162 (5). pp. 1005-1017

Uthicke S, Furnas M, Lønborg C (2014) Coral Reefs on the Edge? Carbon Chemistry on Inshore Reefs of the Great Barrier Reef. PLoS ONE 9:e109092

Vogel N, Fabricius KE, Strahl J, Noonan SHC, Wild C, Uthicke S (2015) Calcareous green alga Halimeda tolerate ocean acidification conditions at tropical CO2 seeps. Limnology & Oceanography (in press)