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INTERNATIONAL CORAL REEF INITIATIVE

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AUSTRALIAN INSTITUTE OF MARINE SCIENCE

Status of Coral Reefs of the World: 2020

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Image: Gaetan Luci/Palais Princier

Foreword

On 4th July 2018, during the ceremony marking the beginning of the co-chairmanship of Australia, Indonesia and Monaco of the International Coral Reef Initiative, I highlighted the huge responsibility of our society vis-à-vis the threats hanging over the coral reefs.

At a global scale, where they occupy less than 0.2% of the seabed, it is quite remarkable that coral reefs provide a habitat for close to 30% of all known marine species.

The socio-economic benefits they generate are clear, both in terms of food resources and attractiveness for tourists; consequently, their degradation poses a danger to the populations who depend on them.

These ecosystems represent a key indicator for ocean health. They not only suffer global impacts but also innumerable local pressures. Coastal development, overfishing and the use of destructive fishing techniques, sediments swept along by rivers containing nutrient overloads and pollutants such as pesticides, are among the main examples.

However, the greatest threat to date is warming waters brought about by human activities. Over the last decade, bleaching events have increased in frequency and intensity, preventing the corals from recovering between disturbances and resulting in a gradual decline to their status.

According to the scenarios put forward in the IPCC's special report on the ocean and cryosphere (the preparation of which was strongly advocated by Monaco), a 1.5°C increase in water temperatures in the course of this century could lead to a loss of 70% to 90% of reef areas. This loss would be almost total with a 2°C increase.

Equally, deleterious ecological changes affect ocean and coral health, such as acidification which results from the absorption of human-generated carbon dioxide emissions by the ocean, and the dramatic decline in oxygen levels linked to global warming and accelerated coastal pollution.

Faced with these observations and pessimistic outlook, the *Status of Coral Reefs of the World: 2020* report produced by the Global Coral Reef Monitoring Network (GCRMN) under the auspices of ICRI, gives us all the more reason to take action.

I would like to commend the work carried out by GCRMN's international team which resulted in a detailed analysis of global trends in the status of coral reefs, whilst underlining regional patterns. The comprehensive global dataset that underpins this report includes almost 2 million observations collected during the last 40 years from more than 12,000 sites in 73 countries.

The report shows the recovery capacity of coral reefs and offers real hope regarding the effectiveness of measures to promote large-scale restoration in order to foster their recovery in the absence of major disturbances.

This report and the analyses therein are also a remarkable source of information on which current negotiations regarding the future framework for global biodiversity and 2030 goals should be based. In this respect, I call upon coral reef countries and the international community to draw on this information to pursue ambitious but realistic targets founded on Science.

As this ICRI co-chairmanship draws to a close, I am delighted to have witnessed the strong desire for cooperation demonstrated by all the members. This report serves as an example, and I hope that this momentum will continue.

The priorities identified in this study give us further reason to take action towards reducing greenhouse gases through the development of a low-carbon economy.

H.S.H. Albert II
Prince of Monaco

Foreword

Coral reefs count among the world's most precious resources. Found throughout the world's oceans, in more than 100 countries, these natural treasures, unique in their diversity and productivity, have enormous ecological, economic and cultural value. The services reefs deliver are fundamental for assuring the safety, nutrition, economic security, health and wellbeing of many millions of people.

Conserving these important global assets has been a preoccupation of the international community since the 1992 UN Conference on Environment and Development (UNCED) adopted its *Agenda 21* blueprint for sustainable development and identified coral reefs and associated ecosystems as a high priority for protection. When The International Coral Reef Initiative (ICRI) emerged in 1994, it raised the stakes, declaring in the opening statement of its 1995 *Framework for Action* that maintaining the condition, resources and values of coral reefs and related ecosystems was a matter of global urgency.

Despite that recognition - and the substantial effort committed since then by governments, UN agencies, research institutes, ICRI and other organisations to reef protection and management - the outlook for the world's reefs, in 2021, is bleak. The need for action to address reef degradation has moved from "high priority" to "urgent" to "critical". Reefs are at crisis point, linked to the impacts of our changing climate.

Estimates and predictions of reef loss and degradation now and in the future vary. Some scientists assess that more than a fifth of the world's coral reefs have already been lost or severely damaged. Others maintain the figure is closer to half - that over 50% of the world's coral reefs have died in the last 30 years. Some suggest that by 2070, coral reefs could be gone altogether. Predictions by the Intergovernmental Panel on Climate Change (IPCC) suggest that with global warming of 1.5 °C coral reefs would decline by 70-90% and be virtually lost with 2°C of warming. The most recent report by the IPCC shows that warming will continue at least until mid-century under all emissions scenarios and predicts that 1.5 °C and 2 °C will be exceeded this century unless deep reductions in greenhouse gas emissions occur in coming decades.

Since they first appeared more than 400 million years ago, coral reefs have faced and survived many threats. We know they have a capacity for recovery, but the time frames for those previous recoveries were long, often measured in millennia. Now the stresses and changes from human activities are happening faster than their ability to adapt. The window for action is closing. In July 2021, scientists at the International Coral Reef Symposium said the coming decade will likely offer the last chance for policy makers at all levels to prevent coral reefs from heading towards worldwide collapse. If coral reefs disappear, other marine realms will follow.

For those policy makers, and everyone involved with reef management, the need to have the most up to date and comprehensive information on the condition of the world's coral and coral reefs is fundamental: and that is exactly what this report provides. After a hiatus of 13 years, the Global Coral Reef Monitoring Network, established in 1995 to support the ICRI Framework for Action, has delivered the first global statement on the condition of coral reefs since 2008. Importantly, it is in a new quantitative format, the first to be based on a quantitative analysis of a global dataset that contains almost 2 million observations collected by more than 300 scientists from more than 12,000 sites in 73 coral-reef bearing nations.

Production of the report in its new form was a monumental task, which benefited from the commitment and generous support of the ICRI Secretariat, hosted by Australia, Monaco and Indonesia, the Australian Government, through the Department of Foreign Affairs and Trade and the Australian Institute of Marine Science, which hosts the GCRMN, the Principality of Monaco, the Government of Sweden, the UN Environment Program, the Prince Albert II of Monaco Foundation, CRIOBE, CORDIO and NOAA.

The timing of the Report's release, marking the hand-over of the ICRI Secretariat to the USA, is especially fortuitous. With parties to the Convention on Biological Diversity soon to consider a new post-2020 global biodiversity framework to guide actions to preserve and protect nature and its essential services to people over the coming decade; and the world's governments convening at the UN Climate Change Conference in Glasgow later this year, the report provides timely input regarding the condition of one of Earth's most vulnerable ecosystems to climate change.

As someone involved with the inception of ICRI and the GCRMN, still deeply engaged with efforts to protect coral reefs, I welcome warmly the decision to reinvigorate the GCRMN and the return of this important global report on the status of the world's coral reefs. I congratulate everyone involved with its production, including data contributors, authors, editors, regional coordinators, the working group established to reinvigorate the GCRMN and the GCRMN Steering Committee. I have every confidence it will become an essential reference for managers and decision-makers, and make a strong contribution to global, regional and national efforts to address the critical challenges facing the world's coral reefs.

Penelope Wensley

The Honourable Penelope Wensley AC

Chairman
Australian Institute of Marine Science Council

Chairman
Great Barrier Reef 2050 Plan Advisory Committee

Foreword

The ICRI Secretariat Co-chairs

Coral reefs are critically important ecosystems that underpin ocean sustainability and the economic, social and cultural security of hundreds of millions of people around the world. Despite their immense value, they are uniquely vulnerable to the increasing global threat of climate change, as well as other anthropogenic impacts.

Over 25 years ago, the International Coral Reef Initiative (ICRI) was started by eight countries, all focussed on protecting and managing our coral reef resources. ICRI established the Global Coral Reef Monitoring Network (GCRMN) in 1995 to report on the condition of the world's coral reefs, recognising the need for accurate and comprehensive information on the state of reefs.

In 2018 at the first ICRI General Meeting under the Australia-Indonesia-Monaco Secretariat, ICRI members agreed to strengthen and reinvigorate the GCRMN under the ICRI Secretariat Plan of Action. A major outcome of this has been the development of this report, which could not have been realised without tremendous effort and cooperation among ICRI members and the GCRMN regions along with the leadership of the Australian Institute of Marine Science.

The report is pivotal as it allows us to understand the condition and trend of the global coral reef estate. As the report reveals, we have already witnessed large-scale losses of coral from the world's coral reefs over the last 40 years. It is increasingly evident that to prevent further declines in coral reefs we must take bold and collective action to reduce pressures and build reef resilience.

In this context, we recall the important role that science has to play in ensuring our actions to protect and restore coral reefs are informed by accurate and evidence-based information. Science underpins effective management and can be used to galvanise action at local, regional and global scales. The GCRMN will continue to build regional capability to collect data and provide the most accurate picture to inform these efforts.

While the results of the report are sobering, there are examples of the ability of coral reefs to recover in the absence of major disturbances. This reinforces our conviction that we need to step up and accelerate efforts at all levels to address key threats and increase global action at all levels to reduce the extent of climate change impacts. If we act together, we can make a difference to secure the future of coral reefs for generations to come.

M Johnson

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May 2019	GCRMN Global technical workshop	Thailand
June 2019	Workshop on regional data analysis of coral monitoring in the East Asia region	Malaysia
September 2019	Workshop on regional data analysis of coral reef monitoring in the Red Sea region	Egypt
November 2019	Workshop on regional data analysis of coral reef monitoring in the Regional Organization for the Protection of the Marine Environment (ROMPE) Sea Area (West Asia)	Oman
January 2020	Workshop on regional data analysis of coral reef monitoring in the South Asia Sea region	Maldives
January 2020	Regional Workshop on regional data analysis of coral reef monitoring for the Wider Caribbean	Bonaire
February 2020	Data validation workshop	Thailand

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Membership of the GCRMN Steering Committee is comprised of:

- ICRI Host Secretariat representatives (chair)
    - Australia
    - Indonesia
    - Monaco
- UN Environment
- Non-government/technical ICRI members
    - WWF International
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- Global Coordinator
    - Australian Institute of Marine Science
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    - East Asia Region
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- Host institution
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Kim, Tadashi Kimura, Chao-Yang Kuo, David J.W. Lane, Jiansheng Lian, Wilfredo Y. Licuanan, Salai Mon Nyi Nyi Lin, Nguyen Van Long, Zau Lunn, Desimawati Hj Metali, Carol Milner, Cleto L. Nañola, Takeshi Nakamura, Chin Soon Lionel Ng, Heung-sik Park, Lorna Parry, Manuel Gonzalez Rivero, Ni Wayan Purnama Sari, Rikoh Manogar Siringoringo, Keryea Soong, Daniel Steadman, Suharsono, Makamas Sutthacheep, Augy Syahailatuha, Marianne Teoh Jr., Tai Chong Toh, Vo Si Tuan, Karenne Tun, Ouk Vibol, Zarinah Waheed, Chelsea Waters, Thamasak Yeemin, Apple Chui Pui Yi, Emily Yong,

Australia: Dave Abdo, Debbie Bass, Hawthorne Beyer, Scott Burgess, Dani Ceccarelli, Alistair Cheal, Caroline Christie, Greg Coleman, Ellen D'Cruz, Mike Emslie, Richard Evans, Jan Freiwald, Andrew Halford, James Gilmour, Jordan Goetze, Ove Hoegh-Guldberg, Thomas Holmes, Kerryn Johns, Michelle Jonker, Alan Kendrick, Abbi MacDonald, Ian Miller, Stephen Neale, Kate Osborne, Will Oxley, Lorna Parry, Manuel Gonzalez Rivero, William Robbins, Claire Ross, Nicole Ryan, Tane Sinclair-Taylor, Hugh Sweatman, Angus Thompson

Pacific: Lara Ainley, Abigail Alling, David Benavente, Hawthorne Beyer, Chico Birrell, Mary Bonin, Eric Brown, Rodney Camacho, Sara Cannon, Kitty Currier, Emily Darling, Orla Doherty, Simon Donner, Sirilo Dulunaqio, Janelle Eagle, Margaret Fox, Jan Freiwald, Antoine Gilbert, Marine Gouezo, Nicolas Guillemot, Tom Heintz, Ove Hoegh-Guldberg, Eryn Hooper, Peter Houk, Arielle Inès Hoamby, John Iguel, Sandrine Job, Johanna Johnson, Geoffrey Jones, Stacy Jupiter, Emma Kabua-Tibon, Roberto Jean Luc Komeno, James Kora, Alice Lawrence, Florian Le Bail, Enelio Liufau, Sangeeta Mangubhai, Mark McCormick, Sheila McKenna, Carol Milner, Bradley Moore, Kirby Morejohn, Yashika Nand, Stephen Neale, Lorna Parry, Denise Perez, Serge Planes, Volanirina Ramahery, Ravaka Ranaivoson, Manuel Gonzalez Rivero, Shannon Seeto, Maya Srinivasan, Heather Summers, Helen Sykes, Anthony Tenorio, Erica Towle, Maunoa Vesarikaro, Laurent Wantiez, Jane Waterhouse, David Welch, Andra Whiteside

Eastern Tropical Pacific: Juan José Alvarado, Tatiana Araya, Andrea Arriaga, Arturo Ayala-Bocos, Jorge Cortés, Alan Friedlander, Priscila Martínez, Ana María Millán, Manuel Olán, Damien Olivier, Alejandro Pérez-Matus, Juan Pablo Quimbayo, Héctor Reyes-Bonilla, Fernando Rivera, Franz Smith, Evie Wieters, Fernando Zapata

Brazil: Maria Bernadete Barbosa, Maurizelia Brito, Mariana Sofia Coxey, Jarian Dantas, Camila Brasil Louro da Silveira, Eduardo Cavalcante de Macedo, Fábio Negrão Ribeiro de Souza, Ismael Escote, Caroline Vieira Feitosa, Beatrice Padovani Ferreira, Leonora Fritzsche, Ana Lídia Bertoldi Gaspar, Luiza Gomes, Carlos Henrique Lacerda, Daniel Lino Lippi, Mauro Maida, Simone Marques, Zaira Matheus, Leonardo Tortoriello Messias, Ana Paula Prates, Sergio Rezende, Lara Braga Sommer, Gil M.R. Strenzel,

Caribbean: A. Acosta-Chaparro, Mary E. Allen, Juan José Alvarado, Lorenzo Alvarez-Filip, Fabian Pina Amargos, Fabien Barthelat, Paulo Bertuol, Tadzio Bervoets, Claude Bouchon, Yolande Bouchon-Navaro, Ruleo Camacho, Esmeralda Pérez Cervantes, Julien Chalifour, Michael Colella, Rachel Collin, Nicole Craig, Marcia Creary Ford, Aldo Croquer, Monique Curtis, Thomas Dallison, Emma Doyle, Ian Drysdale, Caren Eckrich, Peter Edmunds, Peter E.T. Edwards, Jerry Jermain Enoe, Horacio Pérez España, Dan Exton, Graham E. Forrester, Roxanne-Liana Francisca, Jan Freiwald, David Gilliam, Ana Giro, Martha Catalina Gomez-Cubillos, Diana Gómez-López, Jesus Ernesto Arias Gonzalez, J. Gonzalez-Corredor, Silvia Patricia González Díaz, Carlos González-Gándara, Hector Guzman, Jane Hawkridge, Nicole Hayes, Mike Helion, Alex Henderson, Quetzalli Hernández, Emma Hickerson, Francisco Armando Arias Isaza, Ayumi Kuramae Izioka, Michelle Johnston, Kimani Kitson-Walters, Patricia Kramer, Jean-Philippe

Maréchal, Gloria Marino, Melanie McField, Melanie Meijer zu Schlochtern, Fiama Molina, Belkis Carolina Montalvan, Peter Mumby, Thaddeus J.T. Murdoch, Juan Carrasco Navas, R. Navas-Camacho, Marissa Nuttall, Yunier Olivera, Hazel Oxenford, Fernando J. Pardo-Urrutia, Maria Pena, José Luis Cabrera Pérez, Joaquín Rodrigo Garza Pérez, Sandrine Pivard, Angela Randazzo-Eisemann, Andrea Rivera-Sosa, Robert Ruzicka, L. Sanchez-Valencia, G.P. Schmahl, Janina Seemann, Nuno Simões, Melina Soto, David Souter, Johan Stapel, Robert Steneck, Ruben Torres, Erica K. Towle, Ewan Trégarot, Henri Valles, Jelle van der Velde, Mark J.A. Vermeij, Luis Andres Gradiz Villalobos, Gabrielle-Jae Watson, Sven Zea

Data collation and processing: Jérémy Wicquart

Statistical methods: Murray Logan

Executive Summary

Coral reefs occur in more than 100 countries and territories and whilst they cover only 0.2% of the seafloor, they support at least 25% of marine species and underpin the safety, coastal protection, wellbeing, food and economic security of hundreds of millions of people. The value of goods and services provided by coral reefs is estimated at US$2.7 trillion per year, including US$36 billion in coral reef tourism. However, coral reefs are among the most vulnerable ecosystems on the planet to anthropogenic pressures, including global threats from climate change and ocean acidification, and local impacts from land-based pollution such as input of nutrients and sediments from agriculture, marine pollution, and overfishing and destructive fishing practices. Maintaining the integrity and resilience of coral reef ecosystems is essential for the wellbeing of tropical coastal communities worldwide, and a critical part of the solution for achieving the Sustainable Development Goals under the 2030 Agenda for Sustainable Development.

The Global Coral Reef Monitoring Network (GCRMN) is an operational network of the International Coral Reef Initiative that aims to provide the best available scientific information on the status and trends of coral reef ecosystems for their conservation and management. The GCRMN is a global network of scientists, managers and organisations that monitor the condition of coral reefs throughout the world. The GCRMN operates through 10 regional nodes (Fig. 1).

The flagship product of the GCRMN is the *Status of Coral Reefs of the World* report that describes the status and trends of coral reefs worldwide. This sixth edition of the GCRMN *Status of Coral Reefs of the World* report is the first since 2008, and the first based on the quantitative analysis of a global dataset compiled from raw monitoring data contributed by more than 300 members of the network. The global dataset spanned more than 40 years from 1978 to 2019, and consisted of almost 2 million observations from more than 12,000 sites in 73 reef-bearing countries around the world (Fig. 1, Tab. 1)

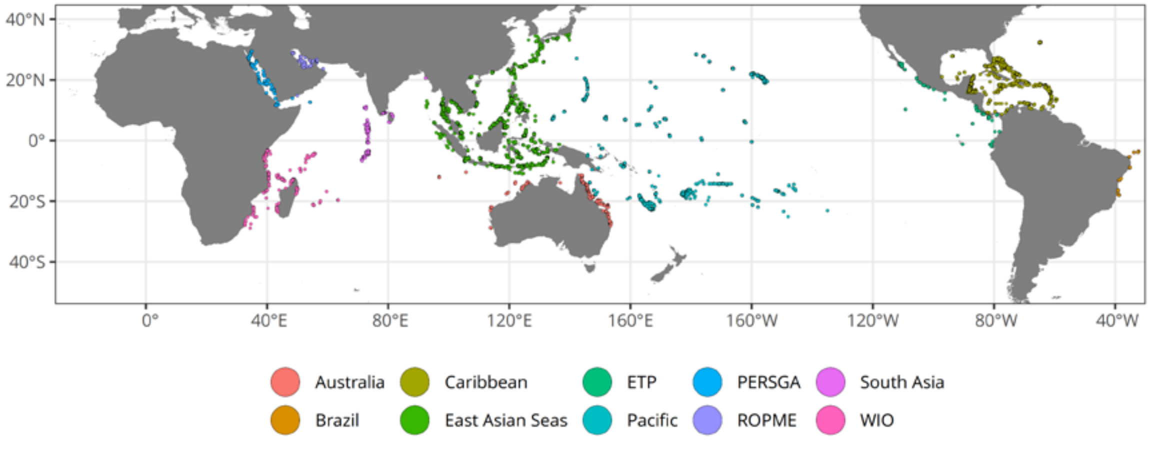

Figure 1. Distribution of monitoring sites within each of the 10 GCRMN regions from which data were compiled for the GCRMN *Status of Coral Reefs of the World: 2020* report. ETP is the Eastern Tropical Pacific. PERSGA is the area included within the Regional Organization for the Conservation of the Environment of the Red Sea and Gulf of Aden. ROPME is the sea area surrounded by the eight Member States of the Regional Organisation for the Protection of the Marine Environment. WIO is the Western Indian Ocean.

Data contributed by scientists and organisations were collated and homogenised into a standard format that enabled statistical analysis of common variables. From the full suite of variables included within the contributed data that described benthic and fish communities, only live hard coral cover and algal cover were measured in a sufficiently consistent manner by different monitoring programs around the world to support a quantitative global analysis. Live hard coral cover is a globally accepted and universally used indicator of coral reef health, while changes in the cover of algae relative to corals is a recognized indicator of ecological change on coral reefs.

In order to estimate subregional, regional and global trends in the cover of live hard coral and algae, a Bayesian hierarchical modelling approach was used in which individual statistical models (fitted to biogeographical subsets of the full dataset according to Marine Ecoregions of the World[1] boundaries) were combined at progressively larger spatial scales. Because the area of coral reefs within each GCRMN region varies by two orders of magnitude, ranging from 780 km² in the Eastern Tropical Pacific to 78,272 km² in the East Asian Seas region (Tab. 1), statistical models and their spatial aggregation were weighted according to the area of coral reefs in each ecoregion, subregion and GCRMN region, based on the Tropical Coral Reefs of the World[2]. This hierarchical approach also enabled trends at a range of scales to be verified by local experts familiar with the coral reefs in those locations, and provided a credible foundation on which to build a much larger, more complex statistical model that enabled trends in hard coral and algal cover to be confidently examined and reported at multiple spatial scales. Furthermore, this approach helped reduce potential biases associated with long-term monitoring data, particularly the limited number, spatial coverage and representation of early data series; variation across programmes in site selection, methods, expertise, resources and capacity; and the remoteness and inaccessibility of many coral reef sites.

Global coral reef monitoring effort has increased substantially since 1978, with more than 91% of surveys conducted after the first mass coral bleaching event in 1998, and the majority (78%) collected between 2005 and 2018 (Fig. 2). Fewer surveys in 2019 was a consequence of applying a cut-off date at the end of 2019 for data contributions for this analysis.

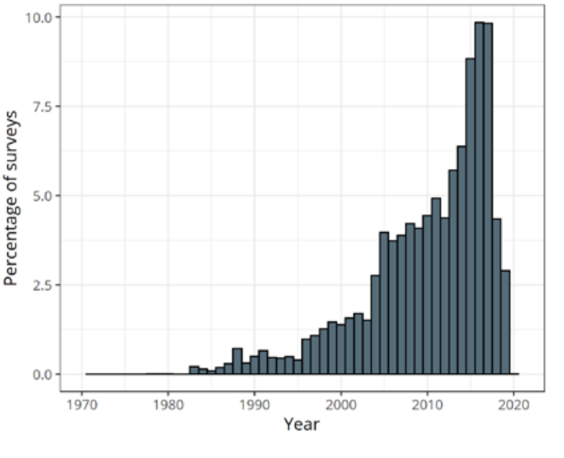

Figure 2. Histogram illustrating the proportion of the total number of surveys conducted in each year.

[1] 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

[2] Institute for Marine Remote Sensing, University of South Florida (IMaRS/USF), Institut de Recherche pour le Développement (IRD), UNEP-WCMC, The WorldFish Center, and WRI, (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

Table 1. Summary statistics describing the number of countries, sites and surveys from which data were compiled for the global dataset, and the area of coral reefs in each GCRMN region. A site is a unique GPS position where data were collected. A survey is a sampling event at one site in a given year.

GCRMN Region	Number of countries contributing data/ Number of countries in the GCRMN Region with coral reefs	Reef Area		Sites		Surveys	
		Area (km²)	Proportion of global total (%)	Total Number	Proportion of global dataset (%)	Total Number	Proportion of global dataset (%)
Australia	1/1	41,802	16.10	372	3.06	3,804	10.91
Brazil	1/1	1,226	0.47	35	0.29	261	0.75
Caribbean	20/25	26,397	10.17	3,166	26.04	7,127	20.44
East Asian Seas	11/14	78,272	30.15	2,570	21.13	9,785	28.06
Eastern Tropical Pacific	6/6	780	0.30	352	2.89	1,277	3.66
Pacific	15/17	69,424	26.74	4,050	33.31	7,565	21.69
Red Sea and Gulf of Aden	6/9	13,605	5.24	243	2	574	1.65
ROPME Sea Area	7/9	2,009	0.77	68	0.56	200	0.57
South Asia	5/7	10,949	4.22	389	3.2	1,635	4.69
Western Indian Ocean	9/10	15,179	5.85	915	7.52	2,642	7.58
TOTAL	73/83*	259,647	100	12,160	100	34,870	100

*** Because** some countries contribute to more that one GCRMN region (e.g Saudi Arabia contributes to both the Red Sea and Gulf of Aden and the ROPME Sea Area regions), the totals reported are not simply the sum of all countries from which data were contributed and the sum of all countries within each GCRMN region.

At the global scale, the estimated average cover of living hard coral exhibited distinct fluctuations during the last 40 years (Fig. 3). Prior to the first mass coral bleaching event in 1998, the global average cover of hard coral was high (>30%) and stable, although the scarcity of data prior to 1998 reduced the level of certainty in estimates. The 1998 coral bleaching event killed approximately 8% of the world's coral. To put this into context, this represents more than the total amount of living coral in any one of the Caribbean, Red Sea and Gulf of Aden, South Asia or Western Indian Ocean regions. During the subsequent decade, the global average cover of hard coral recovered to pre-1998 levels (33.3% in 2009), but between 2009 and 2018, there was a progressive loss amounting to 14% of the coral from the world's coral reefs, which is more than all the coral currently living on Australia's coral reefs.

This decline was due primarily to recurring large-scale coral bleaching events. During this period, the increasing frequency and geographic extent of mass coral bleaching events have prevented coral cover from recovering. While the influences of local or regional disturbances, such as coral diseases, crown-of-thorns starfish outbreaks, tropical storms, overfishing and destructive fishing and poor water quality resulting from land-based pollution have undoubtedly played a role in the decline of coral reefs, their specific contributions were difficult to assess directly from the data without the input of local and regional experts. There is mild evidence of a small recovery in 2019, although this may be an artifact of the limited data compiled for 2018-2019.

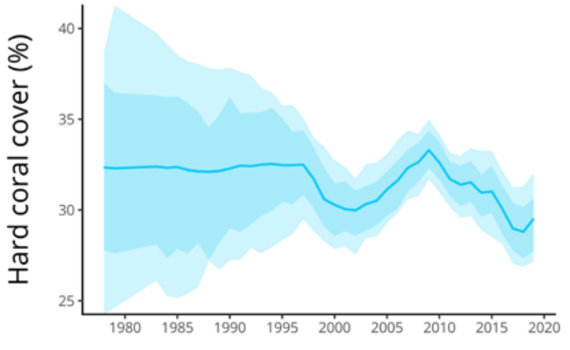

Figure 3. Estimated global average cover of hard coral (solid blue line) and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty.

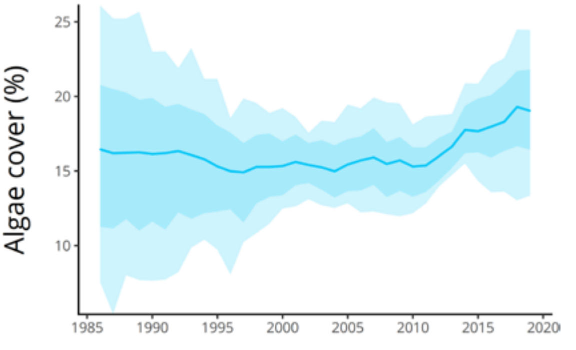

Figure 4. Estimated global average cover of algae (solid blue line) and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty.

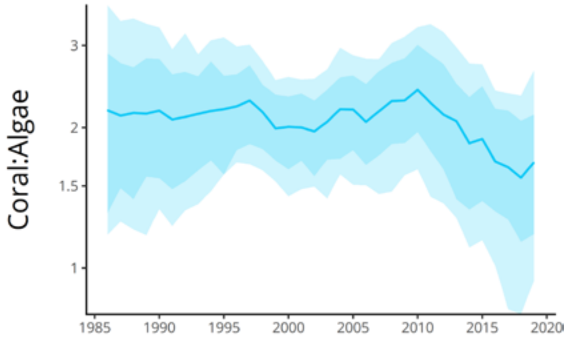

Figure 5. Estimated ratio between the global average covers of coral and algae (solid blue line) and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty.

Prior to 2011, the estimated global average cover of algae was low (~16%) and stable for 30 years (Fig. 4). Since 2011, the amount of algae on the world's coral reefs has increased by about 20%, mirroring the decrease in hard coral cover. Prior to 1998, there was, on average, more than twice as much coral on the world's reefs as algae (Fig. 5). Following the 1998 mass coral bleaching event, the cover of coral decreased but there was no complementary increase in the cover of algae, and coral cover recovered to its initial level. However, since 2011, there has been an increase in the cover of algae commensurate with the decline in coral cover. A progressive transition from coral to algae dominance in a reef community reduces the complex three-dimensional habitat that is essential to support high biodiversity and provide valuable goods and services for reef-dependent human communities.

Large-scale coral bleaching events caused by elevated sea surface temperatures (SST) are the greatest disturbance to the world's coral reefs. At a global level, strong positive global SST anomalies correspond with the major episodes of coral decline (Fig. 6), with short, sharp SST anomalies (dark red) corresponding with acute episodic declines in coral cover in 1998 and 2016, and weaker, but protracted SST anomalies (light red) corresponding with the long-term decline from 2009 to the present.

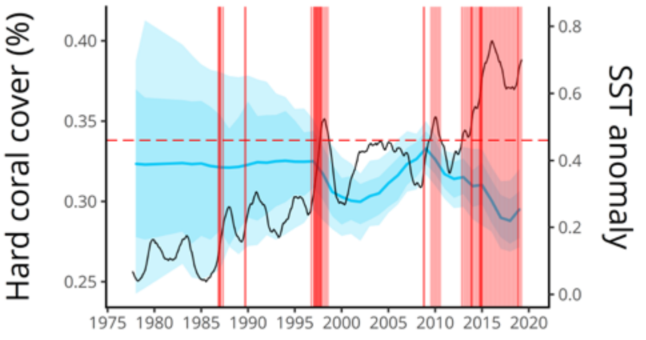

Figure 6. Estimated global average hard coral cover with the sea surface temperature (SST) anomaly from 1977 to 2020 superimposed. The blue line is the estimated global average hard coral cover with 80% (darker blue) and 95% (lighter blue) credible intervals. The black line represents the SST anomaly smoothed with an 18 month rolling mean. Periods of rapid increase in SST anomaly (darker red vertical lines) were calculated by estimating the derivatives (via numerical integration) of the smoothed SST anomaly time series. Darker red vertical red bars indicate when the rate of smoothed SST change exceeded 0.15 for two consecutive months. Lighter red vertical bars indicate when the smoothed SST anomaly exceeded 0.45 (marked by horizontal red dashed line).

Prior to 1998, regional trends in hard coral cover were broadly consistent with the global trend. The greatest impacts of the 1998 mass bleaching event were observed in the Indian Ocean, Japan and the Caribbean, with smaller impacts observed in the Red Sea, the Inner ROPME Sea Area, the northern Pacific in Hawaii and the Caroline Islands, and the southern Pacific in Samoa and New Caledonia. Subsequently, the greatest recovery was seen in those places most affected by the bleaching event, demonstrating that coral cover on some reefs was able to recover within about a decade. However, after 2010, almost all regions exhibited a decline in average hard coral cover. At the same time, most regions exhibited an increase in the cover of algae, particularly in the ROPME Sea Area, Eastern Tropical Pacific, Red Sea and Gulf of Aden, Caribbean, Australia and Brazil. The East Asian Seas and Western Indian Ocean regions were exceptions, although the cover of algae was already high in the latter.

The East Asian Seas region, which includes the Coral Triangle and contains 30% of the world's coral reefs and is the center of global hard coral diversity, showed distinctly different trends from all other GCRMN regions. This was the only region where coral cover was sustantially greater in 2019 (36.8%) than when the earliest data contributed to this analysis were collected in 1983 (32.8%) (Fig. 7A). Also, in contrast with other regions, the cover of algae progressively decreased (Fig. 7B), resulting in an average of five times more coral than algae on these reefs (Fig. 7C).

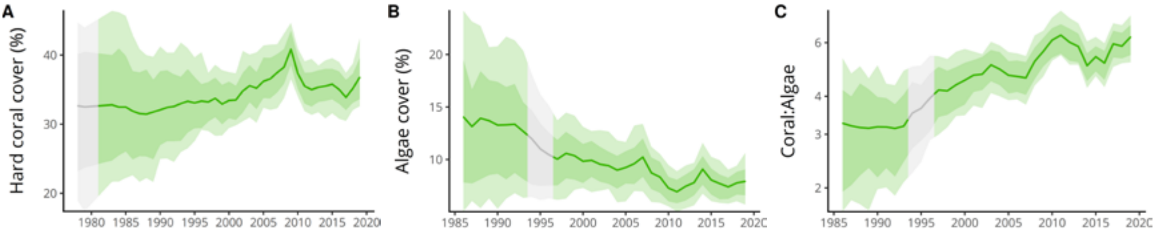

Figure 7. Estimated average cover of hard coral (A), and algae (B), and ratio of the average covers of hard coral to algae (C) for the East Asian Seas region. The solid line represents the estimated mean with 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods for which no observed data were available.

Despite SST anomalies in the East Asian Seas region being similar to those experienced in other regions, hard coral cover at the regional scale appears less affected until the last decade, when the impacts of coral bleaching events in 2010 and 2016 were evident. This suggests that the high coral cover and diversity on the coral reefs within this critically important region may have conferred a degree of natural resistance to elevated SSTs, but that more recent events were beginning to overwhelm these reefs' resistive capacity.

The key findings of this report are:

- Large scale coral bleaching events are the greatest disturbance to the world's coral reefs. The 1998 event alone killed 8% of the world's coral.
- Subsequent disturbance events, occurring between 2009 and 2018, killed 14% of the world's coral.
- There was 20% more algae on the world's coral reefs in 2019 than in 2010. Increases in the amount of algae, a globally recognised indicator of stress on coral reefs, were associated with declines in the amount of hard coral.
- Declines in global coral cover were associated with periods of either rapid increase in sea surface temperature (SST) anomaly or sustained high SST anomaly.
- Since 2010, almost all regions exhibited a decline in average coral cover. Projections of increased SSTs in the future suggest coral reefs will experience further declines in the coming decades.
- Increases in global average coral cover between 2002 and 2009, and in 2019, suggest that many of the world's coral reefs remain resilient and can recover if conditions permit.
- High coral cover and diversity may confer a degree of natural resistance to elevated SSTs. Coral reefs in the East Asian Seas region, which includes the Coral Triangle and 30% of the world's coral reefs have, on average, more coral in 2019 than they did in 1983, despite being affected by large scale coral bleaching events during the last decade.
- Reducing local pressures on coral reefs in order to maintain their resilience will be critical while global threats posed by climate change are addressed.
- Monitoring data collected in the field are essential to understand the status of, and trends in, coral reef condition. Ongoing investment in the development of methodological approaches, new technologies, capability and capacity that expands geographic coverage and enhances the quality, accessibility and interoperability of data is essential.

Chapter 1.

Introduction

The International Coral Reef Initiative (ICRI)

The International Coral Reef Initiative (ICRI) is the only international partnership, between nations and organizations, focussing solely on the protection of coral reefs and related ecosystems worldwide.

The Initiative was founded in 1994 by eight governments: Australia, France, Japan, Jamaica, the Philippines, Sweden, the United Kingdom, and the United States of America. It was announced at the First Conference of the Parties of the Convention on Biological Diversity (CBD) in December 1994, and at the high-level segment of the Intersessional Meeting of the United Nations Commission on Sustainable Development in April 1995. The work of ICRI has been pivotal in continuing to highlight globally the importance of coral reefs and related ecosystems to environmental sustainability, food security and social and cultural wellbeing. The work of ICRI is regularly acknowledged in United Nations documents, highlighting the Initiative's important cooperation, collaboration and advocacy role within the international arena. Most recently, ICRI's engagement has been pivotal in providing technical contributions on coral reefs to the post-2020 global biodiversity framework of the CBD, which establishes the next generation of biodiversity conservation targets to 2030 and 2050, and the indicators required to monitor progress toward their achievement.

The Global Coral Reef Monitoring Network (GCRMN)

The Global Coral Reef Monitoring Network (GCRMN) was established as an operational network of ICRI in 1995. It has worked through regional nodes, with a mandate to aggregate data and report on coral reef health at regional and global levels, to build local and national capacity in coral reef reporting, and to improve actions to sustain coral reefs in response to priorities set across all these levels. In December 2018, an Implementation and Governance Plan[1] (IGP) was adopted to strengthen GCRMN in tracking and reporting on coral reef status and trends.

The primary outputs of the GCRMN are regional, global and thematic reports on coral reef status and trends. The role of regions in coordinating and organising the aggregation and reporting of data is central to the GCRMN and in many regions, relies on the UNEP Regional Seas Programme. Key partners and supporters to the GCRMN include other international and inter-governmental bodies and entities with relevant mandates and expertise that support coral reef monitoring.

[1] GCRMN 2019. GCRMN Implementation and Governance Plan. International Coral Reef Initiative (ICRI). Available: https://www.gcrmn.net/about-gcrmn/igp/

GCRMN Status Reports

2018 - Status of Coral Reefs in East Asian Seas Region
2018 - Status and Trends of Coral Reefs of the Pacific
2017 - Status of Coral Reef in the Western Indian Ocean
2014 - Status of Coral Reefs in East Asian Seas Region
2012 - Status and Trends of Caribbean Coral Reefs: 1970-2012
2011 - Status of Coral reefs of the Pacific and outlook
2010 - Status of Coral Reefs in East Asian Seas Region
2008 - Status of Coral Reefs of the World
2005 - Status of Coral Reefs in Tsunami-affected Countries
2005 - Status of Caribbean Coral Reefs after Bleaching and Hurricanes
2004 - Status of Coral Reefs of the World
2004 - Status of Coral Reefs in East Asian Seas Region
2002 - Status of Coral Reefs of the World
2000 - Status of Coral Reefs of the World
1998 - Status of Coral Reefs of the World

UNEP Regional Seas with coral reefs

- **Caribbean Environment Programme (CEP)** – member of the GCRMN Steering Committee
- **Coordinating Body on the Seas of East Asia (COBSEA)**
- **Regional Organisation for Protection of the Marine Environment (ROPME) Sea Area**
- **The Regional Organization for the Conservation of the Environment of the Red Sea and Gulf of Aden (PERSGA)**
- **South Asia Cooperative Environment Programme (SACEP)** – supports the South Asian Coral Reef Task Force. Member of the GCRMN Steering Committee
- **The Nairobi Convention** - supports the Nairobi Convention Coral Reef Task Force (CRTF)
- **Secretariat of the Pacific Regional Environment Programme (SPREP)** – recently released a Pacific Coral Reef Action Plan 2020- 2030. Member of the GCRMN Steering Committee

The international policy context for coral reefs

Coral reefs feature prominently in global policy initiatives owing to their immense value for biodiversity and for peoples' livelihoods and welfare, and their increasingly threatened status. The 2019 global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Service (IPBES), and the Intergovernmental Panel on Climate Change (IPCC) Special Report on the Ocean and Cryosphere in a Changing Climate, warn that:

- Over half of the world's coral reefs have been lost;
- At warming of 1.5^{o}C, 70-90% of the world's coral reefs are expected to be lost. At 2^{o}C degrees, this increases to >99% loss of coral reefs.

Value of ecosystem services provided by coral reefs

- **Human health and wellbeing:** 70% of the protein in the diets of Pacific Islanders comes from reef-associated fisheries (SDGs 2, 3, 6, 9 & 14; Aichi Biodiversity Targets 13, 14, 16).
- **Shoreline protection:** a healthy coral reef can reduce coastal wave energy by up to 97%. Globally, USD6 billion of built capital is protected from flooding by coral reefs (SDGs 1, 8, 11, 13, 14).
- F**ood security and livelihoods:** coral reef fisheries support as many as six million people and are worth USD6.8 billion per year, providing an average annual seafood yield of 1.42 million tonnes (SDGs 2, 4, 5, 8, 12, 13, 14, 16).
- **Tourism:** coral reef tourism contributes USD36 billion to the global tourism industry annually (SDGs 2, 4, 5, 6, 8, 9, 12, 14).
- **Biodiversity:** coral reefs support approximately 4,000 species of fish and 800 species of hard corals, Globally, about 830,000 species of multicellular plants and animals are estimated to occur on coral reefs, of which an estimated 13% are unnamed and 74% are yet to be discovered. Most of these species are cryptic, small and relatively rare.
- **Medicines:** coral reefs are the medicine chests of the 21st century, with more than half of all new cancer drug research focusing on marine organisms.

Reflecting their importance and the urgency of their predicament, over 230 international policy instruments, and more than 590 voluntary commitments support conservation and sustainable management of coral reef ecosystems[2]. In 2019, the United Nations Environment Assembly (UNEA), the world's highest-level decision-making body on the environment, adopted a resolution on 'Sustainable coral reef management'. During the G7 Environment Ministers' Meeting in Metz, France (May, 2019), coral reefs were highlighted on the ministers' agenda. In 2018, Governments of the Commonwealth adopted the Commonwealth Blue Charter, a principles-based agreement by all 54 member governments to actively cooperate to tackle ocean-related challenges, including coral reef protection and restoration.

In 2017, His Serene Highness Prince Albert II of Monaco was joined by His Royal Highness the Prince of Wales and Her Majesty Queen Noor of Jordan, and by the Heads of State, Ministers and high-level representatives of 12 countries to launch the Coral Reef Life Declaration[3].

The years 2020 and 2021 present new opportunities for major global policy changes to support coral reefs. Under the CBD, the post-2020 global biodiversity framework (GBF) will succeed the Strategic Plan for Biodiversity 2011–2020 and the Aichi Targets. ICRI submitted a recommendation to the CBD to include coral reefs in the new framework to ensure that matters relating to the critical status of

[2] UN Environment (2019) Analysis of Policies related to the Protection of Coral Reefs-Analysis of global and regional policy instruments and governance mechanisms related to the protection and sustainable management of coral reefs. Karasik, R., Pickle, A., Roady, S.A., Vegh, T. and Virdin, J. (Authors). United Nations Environment Programme, Nairobi, Kenya. https://www.icriforum.org/wp-content/uploads/2020/05/Coral_Policy%20(1).pdf

[3] To date the the Coral Reef Life Declaration was signed by the following countries and economies (alphabetic order): Australia, Cook Islands, Costa Rica, Ecuador, Fiji, France, French Polynesia, Grenada, Indonesia, Mexico, Monaco, Mozambique, Niue, New-Caledonia, Palau, the Philippines, Seychelles, United Kingdom, Vanuatu.

enormously diverse ecosystems will be appropriately addressed. The recommendation identified six key indicators for incorporation into the monitoring framework of the GBF to effectively track coral reef health and status. Further, at its 26th Conference of Parties at the end of 2021, the UN Framework Convention on Climate Change will evaluate Nationally Determined Contributions of countries in achieving the Paris Agreement, and much higher ambition will be needed to keep warming within safe levels for coral reefs.

Coral reef indicators recommended by ICRI for inclusion in the monitoring framework of the Global Biodiversity Framework.

- Hard coral cover* and composition+
- Cover of fleshy algae* and other benthic groups+
- Fish abundance and biomass+
- Global coral reef extent
- Red List of Ecosystems
- Protected area coverage of coral reefs
- Index of coastal eutrophication

*** indicates indicators analysed in this report;**

+ indicates indicators collected by the GCRMN but not yet with sufficient consistency to compile and quantitatively analyse at a global scale.

The 2030 Agenda for Sustainable Development, adopted by all United Nations Member States in 2015, provides a shared blueprint for peace and prosperity for people and the planet, across all countries. At its heart are the 17 Sustainable Development Goals (SDGs), providing a narrative for how ending poverty must go hand-in-hand with strategies that improve health and education, reduce inequality, and spur economic prosperity, all while preventing dangerous climate change and halting and reversing declines in nature. Coral reefs and associated ecosystems directly support at least 10 of the goals and 25 targets within the goals.

This report

This report provides new findings on the status and trends of the world's coral reefs, and is the first such report in 13 years. It is targeting a large audience from national policy makers, to coral reef managers, and of course, the general public.

During 2021-22, against the backdrop of the COVID-19 pandemic, key global policy processes will redefine the environmental agenda for the next decade and beyond. Thus, the timing of the release of this report provides an unprecedented opportunity to contribute to global decisions on biodiversity, climate and sustainable development. We hope that this report, and its findings, will help inform decision-makers to set ambitious targets in the global biodiversity framework of the Convention on Biological Diversity, to strengthen the climate action of all countries to keep the Paris

Agreement-aligned temperature limit within reach, and revitalise actions to deliver on the Sustainable Development Goals.

This report also supports calls by the International Coral Reef Society at its 16th Symposium in July 2021 to reinvigorate commitment to coral reef conservation by reducing global threats, building reef resilience locally to withstand change, and support innovations in restoration and rehabilitation tools to get coral reefs through the coming decades of threats and rebuild them at scale in the future.

This report is also a concrete step reaffirming the GCRMN as the reference network for reporting on the status and trends of coral reefs worldwide. As part of the global 'ecosystem' of data and monitoring networks reporting on biodiversity in the ocean (i.e. the Global Ocean Observing System and Marine Biodiversity Observing Network of GEOBON), and as the UN Decade on Ocean Science for Sustainability opens, this report presents the GCRMN's ongoing role and commitment towards building capacity at national and regional levels, sharing scientific information and knowledge, and building technical and scientific cooperation, technology transfer and innovation. The report focuses on two key indicators proposed in the monitoring framework of the GBF, establishing a baseline for the GBF and the Ocean Decade for coral reefs.

Box 1.

Policy and Management Solutions

Gabriel Grimsditch[1], Caren Eckrich[2], Lina Mtwana Nordlund[3], Ulrike Kloiber[4], Joannie Jomitol[5]

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Coral reefs are resilient to disturbance events when anthropogenic stressors on the ecosystem are managed and reduced. Coral reefs 'bounce back' from major disturbance events such as mass coral bleaching when they are remote from human influence or when management and policy interventions reduce causes of degradation. Integrated coastal management and policy approaches that include all stakeholders in the management of coral reefs and benefit local communities can improve the chances of survival for coral reefs in an uncertain future. Here we highlight three case studies that illustrate different scales and approaches to coral reef management with benefits to both local communities and coral reef resilience.

Case study 1: Chumbe Island Coral Park, Tanzania

Chumbe Island Coral Park (CHICOP), is a privately established and managed island nature reserve and includes a 55.06 ha reef sanctuary with diverse habitats such as sandy shores, seagrass meadows, a fringing coral reef, and a 16.64 ha forest reserve with mangrove and tropical dry forest[1]. The island is located off the west coast of Unguja island, Zanzibar, Tanzania. Some of the main threats to coral reefs in the area include beach seining, overfishing, coral mining, and pollution from sewage and coastal development[2]. The reserve was recognized by the Government of Zanzibar in 1994, definings the area as a no-take-area where "no fishing or any extractive use shall be permitted in the area so declared", even for research[3]. CHICOP started ecotourism operations in 1998 and, since 2006, the income has been sufficient to cover recurrent management costs, making the marine park financially sustainable[4]. By working with a broad section of stakeholders, including government agencies; fishers and local communities; schools, universities and academic institutions; non-governmental organizations; and the tourism Industry, CHICOP has shown remarkable success in coral reef

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1 CHICOP (2017) 3rd Ten Year Management Plan for Chumbe Island Coral Park. https://chumbeisland.com/wp-content/uploads/2017/12/Chumbe_Management_Plan_2017-2027.pdf

2 UNEP (2019): Enabling Effective and Equitable Marine Protected Areas –guidance on combining governance approaches. Case Study Compendium. Authors -Jones PJS, Murray RH and Vestergaard O. https://wedocs.unep.org/bitstream/handle/20.500.11822/27851/MPA_CS.pdf?sequence=1&isAllowed=y

3 Nordlund et al 2013. Chumbe Island Coral Park—governance analysis https://doi.org/10.1016/j.marpol.2012.018

4 OECD, 2017. Marine Protected Areas: Economics, Management and Effective Policy Mixes (https://dx.doi.org/10.1787/9789264276208-en)

management. The advisory committee for the marine protected area has two representatives from private sector entities and eleven representatives from different stakeholder groups and institutions, mainly departments of the Government of Zanzibar, research organizations and community leaders from adjacent villages. CHICOP works in collaboration with the Department of Fisheries Development for any legal prosecutions needed to enforce the 0.55 km^2 no-take-zone[2]. This is a good example of a successful public-private partnership for coral reef conservation. Local fishers have also been retrained as unarmed park rangers who "enforce" the protected area by informing local fishers of the value of the protected area for fisheries and livelihoods. Thanks to enforcement efforts, benthic communities within the reserve have remained healthy, with increases in both hard and soft coral cover, and decreases in the cover of algal turf and macroalgae. In 2015, Chumbe Reef had live hard coral cover of around 75%, with at least 59 genera of scleractinian coral present[5]. In addition, the incidence of coral disease is very low[1] and recovery from bleaching events has been good[6]. The reef has 514 recorded reef fish species and has had a steady increase of fish biomass over the past 10 years[1]. Spillover catch benefits for the local fishing community have been reported, enhancing local support for the park and keeping illegal fishing incidents low[4]. Positive relationships and frequent communication of the livelihoods benefits for the local community have been critical for the success of Chumbe Island, which is today one of the most biodiverse and resilient coral reefs in East Africa.

Case study 2: Bonaire National Marine Park

Bonaire is a small island north of Venezuela whose economy is based largely on coral reef tourism. For 40 years, STINAPA, the national parks authority of this Dutch Caribbean island, has been actively managing the coral reefs through regulation and outreach initiatives. Since the 1970s, there has been a steady decline in coral reef cover throughout the Caribbean[7]. However, biennial monitoring since 2003 demonstrates evidence of coral reef resilience on Bonaire's reefs, with an increase in coral cover, an increase in the density of juvenile corals and a decrease in macroalgal cover since 2015[8]. In addition, recent coral restoration projects with endangered staghorn and elkhorn corals (*Acropora palmata* and *A. cervicornis*) have been highly successful[9]. Some highlights in a long history of local conservation measures include: a ban on spearfishing in 1971; the legal protection of all corals in 1975; mooring buoys replacing anchoring in 1978; the establishment of the Bonaire National Marine Park (BNMP) in 1979 with marine park orientations mandatory for all divers; the creation of no-fishing zones in 2008; the passing of legislation protecting vulnerable marine species including parrotfish, sharks and rays in 2010; the implementation of a lionfish control program in 2010; the listing of BNMP under the Specially Protected Areas and Wildlife Protocol in 2012; and

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5 Zvuloni, Assaf, V.W. Robert and Y. Loya (2010) Diversity partitioning of stony corals across multiple spatial scales around Zanzibar Island, Tanzania. Plos One 5(3), pp.e9941

6 Obura et al, 2017. Coral reef status report for the Western Indian Ocean https://gcrmn.net/wp-content/uploads/2019/03/COI-REEF-LR-F2.compressed.pdf

7 Jackson JBC (author), Donovan MK, Cramer KL, Lam VV (editors; 2014). Status and Trends of Caribbean Coral Reefs: 1970-2012. Global Coral Reef Monitoring Network, IUCN, Gland, Switzerland.

8 Steneck RS and Wilson M (2019). Status and Trends of Bonaire's Reefs in 2019: managing to stay healthy but concerns remain. Report to STINAPA Bonaire. (https://stinapabonaire.org/wp-content/uploads/2019/02/2017_-Steneck-Wilson_Status-and-Trends-of-Bonaire%E2%80%99s-Reefs-in-2017-.pdf)

9 Reef Renewal Bonaire Annual Report 2019

the installation of a wastewater treatment plant that treats wastewater from large hotels and businesses near the coast in 2015. Furthermore, STINAPA provides nature education classes and field trips as an integral part of the local school curriculum. After-school programs for youth, such as the Tortuganan program since 1995 and the Junior Ranger program since 2010, raise awareness of nature conservation from a young age. In Bonaire, the dive industry and other tourism operators are largely responsible for collecting the nature conservation fees that finance the park. With an island economy increasingly dependent on tourism, a major challenge is to regulate recreation and uncontrolled urban development. The BNMP demonstrates that sustained local action and transparent governance can effectively increase coral reef resilience.

Case study 3: Tun Mustapha Park, Malaysia

The Tun Mustapha Park (TMP) in Sabah State, Malaysia was gazetted in 2016 after more than 13 years of negotiation, lobbying, capacity-building, scientific research and community outreach by a range of government agencies, non-government organizations and international supporters. It covers an area of almost 900,000 hectares, making it the largest multi-use park in Malaysia where conservation, sustainable resource use and development can occur under a common management system[10]. The establishment of TMP as a multiple-use park under IUCN Category VI (Protected Area with Sustainable Use of Natural Resources) is the first of its kind in Malaysia, and the first under the Coral Triangle Initiative[11,12]. TMP is regarded as a priority seascape within the Coral Triangle, which is acknowledged as the centre of the world's coral reef biodiversity. It is a home to more than 250 species of hard corals, around 430 species of fish, endangered turtles and dugongs, and significant mangroves and seagrass meadows. It supports more than 85,000 coastal people through fisheries, which collectively produce around 100 tonnes of fish per day with an estimated value of USD200,000. However, it is threatened by overfishing, destructive fishing that causes habitat degradation, land conversion and pollution as well as climate change.

There are three main objectives for the park: 1) to eradicate poverty; 2) to develop economic activities that are environmentally sustainable; and 3) to conserve habitats and threatened species. The zoning and planning process for the marine park was facilitated by a Zoning Working Group under a multi-stakeholder committee representing the region's interests and chaired by the Sabah Ministry of Tourism, Culture and Environment. Systematic conservation planning using Marxan software was used to zone the park into no-take and multiple-use areas, based on scientific data describing both social and ecological aspects of the ecosystem. Many communities depend on the coral reefs for subsistence and livelihoods through small-scale fishing, and impacts on these communities were minimized by maintaining access to fishing grounds in community-managed or multi-use zones. While zones were planned

[10] Jumin, R., Binson, A., McGowan, J., Magupin, S., Beger, M., Brown, C., . . . Klein, C. (2018). From Marxan to management: Ocean zoning with stakeholders for Tun Mustapha Park in Sabah, Malaysia. Oryx, 52(4), 775-786. doi:10.1017/S0030605316001514

[11] Weeks , R., Alino, P.M., Atkinson, S., Belida, II, P., Binson, A., Campos, W.L. et al. (2014) Developing marine protected area networks in the Coral Triangle: good practices for expanding the Coral Triangle marine protected area system. Coastal Management ,42, 183 - 205

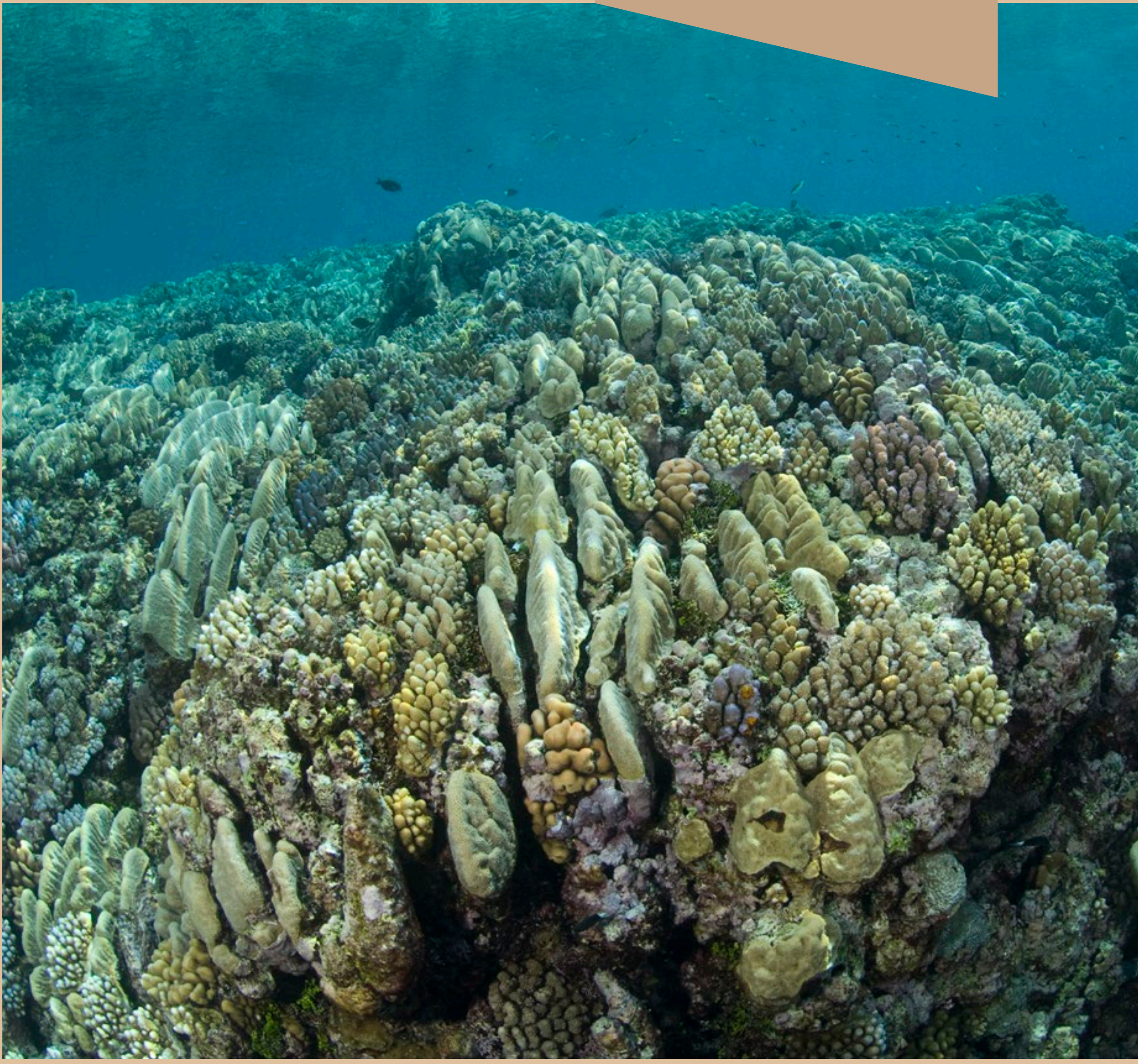
[12] Beger, M., McGowan, J., Treml, E.A., Green, A.L., White, A.T., Wolff, N.H. et al. (2015) Integrating regional conservation priorities for multiple objectives into national policy. Nature Communications, 6

and prioritized using Marxan software, comprehensive stakeholder consultations were key to their implementation. The final Marxan scenario used a target of 30% of key habitats to be designated in fully protected no-take zones, with 70% of traditional fishing grounds remaining accessible.

Four priority zones were identified: 1. Preservation zones - where all extractive activities are prohibited; 2. Community managed zones - where non-destructive small-scale and traditional fishing activities are allowed; 3. Multiple-use zones - where non-destructive and small-scale fishing activities and other sustainable development activities, including tourism are allowed; and 4. Commercial fishing zones - where all legal commercial fishing activities are allowed. Further, an innovative approach using climate change scenarios was used to make the management plan and zoning as climate-resilient as possible. Climate vulnerability assessments identified areas of higher or lower potential exposure and resilience to climate change impacts, and climate model projections of future coral bleaching stress were combined with knowledge of spatial variation in human activities to prioritize areas for conservation. Using climate data in marine spatial planning is a key innovation in this marine park.

Through an 'Ecosystem-Approach to Fisheries Management (EAFM)', the promotion of sustainable fishing was achieved by engaging the fishing communities and addressing issues such as the status of the resource, the health of the marine environment, and post-harvest technology and trade. Economic valuations and cost-benefit analyses were also key tools in informing stakeholder engagements and making the case for the value of the marine park and zoning plan. The multiple-use park management approach has ensured that all the interests of the various stakeholders have been taken into consideration to achieve the social and ecological objectives of the TMP.

Part 1:
Global Status of Coral Reefs



Chapter 2.

Status of coral reefs of the World

Status and trends in the global average cover of hard coral

Trends in the estimated annual global average cover of hard coral between 1978, when the earliest data contributed to this report were collected, and 2019 are presented in figure 4.1. Between 1978 and 1997, the global average cover of hard coral was high and stable, ranging between 32.1% and 32.5%. However, because data were scarce and regional representation within the global dataset was poor in these early years, there is comparatively high uncertainty associated with these estimates.

In 1998, the first global-scale coral bleaching event occurred, affecting nearly all coral reef regions. As a consequence, global average hard coral cover declined from 32.5% to 30% between 1997 and 2002. This represented a loss of 7.8% of the world's hard coral, or the equivalent of approximately 6,500 km^2 of coral during these five years. To put this into context, this represents more than the total amount of hard coral living in any one of the Caribbean, Red Sea and Gulf of Aden, South Asia or Western Indian Ocean regions.

The 1998 mass coral bleaching event also triggered a substantial increase in global monitoring effort to measure the impacts of this event on the world's coral reefs. As a result, estimates of global average coral cover were more precise as more data were available. Since then, most monitoring programs have been maintained and new programs have been established, often in response to more recent mass coral bleaching events, resulting in even greater confidence in coral cover estimates.

Between 2002 and 2009, global average hard coral cover returned to pre-1998 levels, reaching 33.3% in 2009. This demonstrates that in the absence of major global disturbances, many of the world's coral reefs have remained resilient and capable of recovering, despite the influence of local stressors.

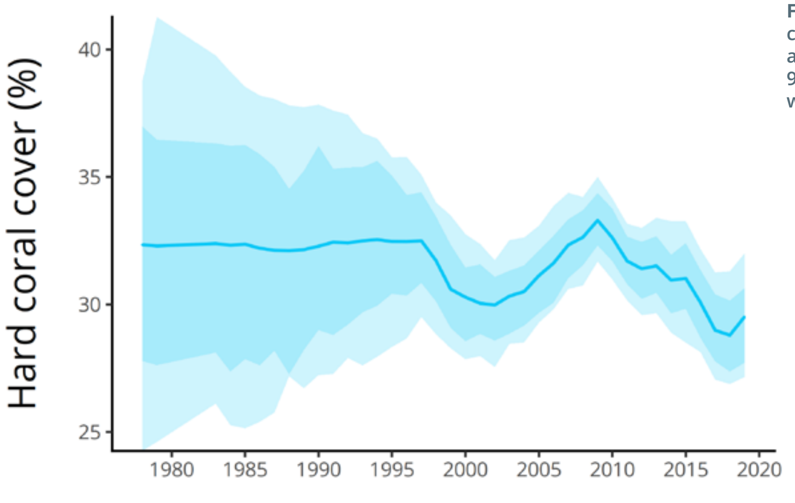


Figure 2.1. Estimated global average cover of hard coral (solid blue line) and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty.

Since 2009, the overwhelming trend in global average hard coral cover has been downward. Between 2009 and 2018, global average hard coral cover declined from 33.3% to 28.8%, which represents a loss of 13.5% of the world's hard coral. To put this into context, this equates to about 11,700 km^2 of coral, which is approximately the equivalent of losing all the hard coral currently living on Australia's coral reefs. Although fewer data were available for 2019, global average coral cover showed the first signs of recovering, with an increase of 0.7%.

The robustness of recent trends described above was confirmed by comparing global average coral cover between each of the three five-year periods comprising the last 15 years (Tab. 2.1). This period corresponds with when most data were available and when confidence in estimates of annual global average hard coral cover was greatest (Fig. 2.1). There was strong evidence (> 90% probability) that global average coral cover declined between 2005-09 and 2010-14 and again between 2010-14 and 2015-19. These declines suggest that, on average, there was 13.7% less hard coral on reefs in 2015-19 compared with 2005-09 (Tab. 2.1).

Table 2.1. Probability and magnitude of mean absolute and relative change in the percent cover of live hard coral on the world's coral reefs 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	90	-1.2	-5.2
2010-14 - 2015-19	96	-2.0	-8.8
2005-09 - 2015-19	99	-3.2	-13.7

Status and trends in the global average cover of algae

The global average cover of algae was low and relatively stable between 1986, when the first algal cover data contributed to this report were collected, and 2011, ranging between 14.9% (1997) and 16.5% (1986) (Fig. 2.2). However, since 2011, the cover of algae on the world's coral reefs has increased progressively from 15.4% to a maximum of 19.3% in 2018, before a small (0.3%) decline in 2019 (Fig. 2.2). This indicates that during the last decade, the amount of algae on the world's coral reefs has increased by approximately 20%.

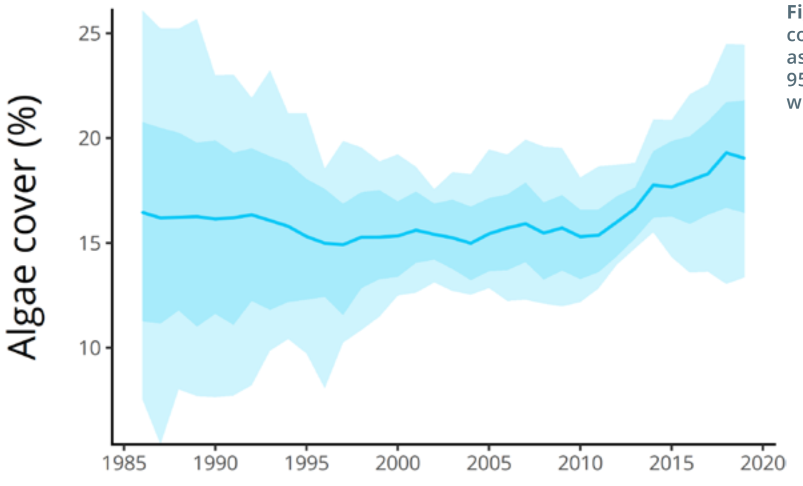


Figure 2.2. Estimated global average cover of algae (solid blue line) and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty.

In contrast with hard coral cover, the global average cover of algae did not change in response to the 1998 global coral bleaching event. However, the cover of algae increased substantially between 2011 and 2019 (Fig. 2.2), which corresponded with the decline in global average hard coral cover that began in 2009 (Fig. 2.1). Comparison of the global average cover of algae during the three five-year periods comprising the last 15 years (2005-09, 2010-14 and 2015-19) provides strong evidence (>84% probability) that the amount of algae on the world's coral reefs has increased during this time (Tab. 2.2). On average, the absolute change in the cover of algae between 2005-09 and 2015-19 was 3.1%, which translates to 26.3% more algae on the world's coral reefs in 2015-19 compared with 2005-09 (Tab. 2.2). These results provide strong evidence that generally, the amount of algae on the world's reefs is increasing while the amount of hard coral is decreasing, which is a strong indication that the condition of the world's reefs is declining.

Table 2.2. Probability and magnitude of mean absolute and relative change in the percent cover of algae on the world's coral reefs 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	84	1.1	9.2
2010-14 - 2015-19	88	2.0	15.5
2005-09 - 2015-19	93	3.1	26.3

Trends in the ratio between the global average covers of live hard coral and algae

Changes in the global average covers of hard coral and algae are reflected in the trend in the ratio between these two important indicators of coral reef condition (Fig. 2.3). Between 1986 and 1997, the ratio was relatively stable, ranging between a minimum of 2.1 (1991) and a maximum of 2.3 (1997), indicating that during this period there was, on average, more than twice as much coral on the world's coral reefs as there was algae. Following the 1998 global coral bleaching event, the coral:algae ratio declined to 2.0 in 2002, due to the bleaching-related coral mortality and subsequent loss of coral cover. As coral cover recovered during the course of the next decade, the ratio of coral:algae also increased, reaching a maximum of 2.4 in 2010. However, since 2010, the ratio of coral to algae has progressively declined, reaching a minimum of 1.6 in 2018, before a slight increase to 1.7 in 2019. This decline in the coral:algae ratio corresponds with both the loss in coral cover (Fig. 2.1) and the increase in algae cover (Fig. 2.2) observed during the last decade.

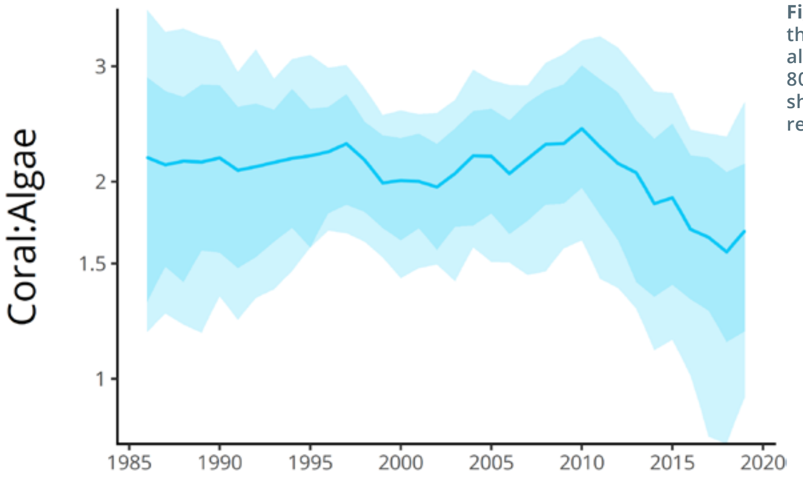


Figure 2.3. Estimated ratio between the global average covers of coral and algae (solid blue line) and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty.ainty.

The relatively high uncertainty in the coral:algal ratio prior to 1998 was a consequence of the scarcity of available data and poor geographic representation within the global dataset in these early years.

Status and trends in the cover of hard coral in each region

In regions where historical data (e.g. pre-1995) were available (Caribbean, East Asian Seas, Western Indian Ocean, Pacific and Australia), coral cover (and associated uncertainty) was relatively high and showed little change or only a slight decline (Fig. 2.4).

From 1997/98, steep declines in hard coral cover were evident in South Asia, particularly in the Chagos Archipelago and Maldives, in the Western Indian Ocean (WIO), especially the East African Coral Coast and Seychelles, in Western Australia (Exmouth to Broome), South Kuroshio, and some areas of the Caribbean (Southern Caribbean and Greater Antilles). Smaller declines were recorded in the Northern and Central Red Sea and the Inner ROPME Sea Area, the Western Caroline Islands, New Caledonia, Hawaii and Samoa Islands. Some of these trends have been partially described in recent GCRMN regional reports for the Caribbean, Western Indian Ocean and Pacific.

Increases in global average live hard coral cover between 2002 and 2008 were driven primarily by reefs in South Asia (Chagos and Maldives), the WIO, Australia (Western Australia, and to a smaller extent Torres Strait and the Northern Great Barrier Reef), Brazil (Northeastern and Eastern Brazil), the Inner ROPME Sea Area and the Red Sea and Gulf of Aden (North and Central Red Sea) regions. The Fiji Islands and Solomon Archipelago subregions within the Pacific also showed an increase in live hard coral cover during this period, but coral cover on reefs within other Pacific subregions remained stable. The greatest increases in coral cover were observed in regions where the impacts of the 1998 coral bleaching event were greatest, demonstrating that recovery in hard coral cover can occur in less than 10 years.

During the last 15 years, almost all regions have experienced a decline in average coral cover, with South Asia, Australia, the Pacific, the ROPME Sea Area and the East Asian Seas regions exhibiting the greatest declines (Tab. 2.3). In these regions, probabilities of decline exceeded 82% in these regions (Tab. 2.3). Together, these regions support almost 50% of the world's coral reefs. The only exceptions were the Brazil and Caribbean regions which showed increases in average hard coral cover of 3% and 1.6% respectively (Tab. 2.3).

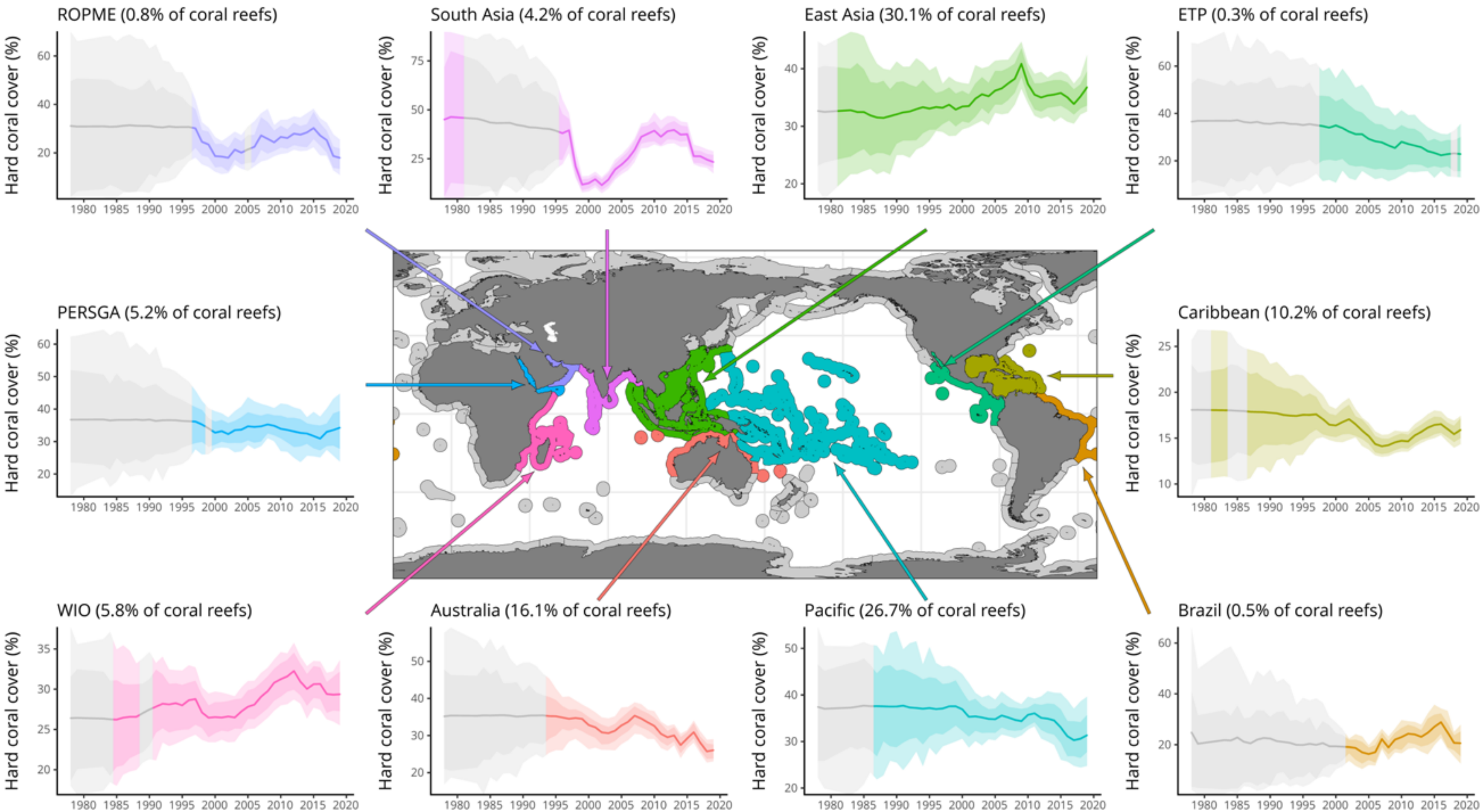


Figure 2.4. Long-term trends in the average cover of live hard coral in each of the ten GCRMN regions. The solid line represents the estimated mean with 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods for which no observed data were available. Trends are coloured to match the GCRMN regions represented on the central map. The proportion of the world's coral reef area supported by each region is indicated by % of coral reefs. ETP is the Eastern Tropical Pacific. PERSGA is the Red Sea and Gulf of Aden. ROPME is the ROPME Sea Area. WIO is the Western Indian Ocean.

Table 2.3. Mean absolute change in percent live hard coral cover (and associated probability as a percentage) between pairs of five-year periods within the last 15 years in each region.

Region	Comparison 2005-09 - 2010-14	Comparison 2010-14 – 2015-19	Comparison 2005-09 – 2015-19
Australia	-4.6 (99%)	-1.7 (89%)	-6.6 (100%)
Brazil	4.1 (98%)	-1.0 (69%)	3.0 (92%)
Caribbean	1.2 (99%)	0.3 (70%)	1.6 (99%)
East Asian Seas	-2.7 (96%)	-0.2 (54%)	-2.8 (96%)
Eastern Tropical Pacific	-0.9 (53%)	-0.6 (54%)	-1.4 (54%)
Pacific	0.4 (61%)	-3.9 (95%)	-4.3 (93%)
Red Sea and Gulf of Aden	-2.0 (76%)	0.2 (47%)	-1.7 (71%)
ROPME Sea Area	2.9 (80%)	-6.1 (96%)	-3.2 (82%)
South Asia	4.3 (94%)	-12.9 (100%)	-8.7 (100%)
Western Indian Ocean	1.3 (88%)	-1.4 (84%)	-0.1 (52%)

Resilient coral reefs experience fluctuations in coral cover over time as disturbances, which cause declines in coral cover, are interspersed with periods of recovery during which coral cover is restored. To identify changes in the resilience of coral reefs, patterns of disturbance and recovery were examined within sampling units in each region 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 eight regions with such sampling units, all had a proportion of sampling units that did not recover fully following disturbance (i.e. did not recover to at least 90% of their pre-disturbance coral cover, Tab. 2.4) . The average proportion of long-term sampling units that did not fully recover was 71%, with the greatest proportions occurring within the Eastern Tropical Pacific (100%), South Asia (93%), Caribbean (81%) and Australian (77%) regions (Tab. 2.4).

Long-term declines in average hard coral cover among those sampling units examined ranged between 1.7% in the East Asian Seas region and 60.4% in the Eastern Tropical Pacific, with most regions experiencing long-term declines between 4.1% and 7.2% (Table 4.4). The Eastern Tropical Pacific (60.4%), South Asia (20.8%) and Australian (10%) regions experienced the greatest absolute declines in coral cover where long-term monitoring was conducted. Relatively little long-term monitoring occurred in the Western Indian Ocean, ROPME Sea Area, Red Sea and Gulf of Aden, Eastern Tropical Pacific and Brazil regions, either because sites were not repeatedly sampled or because sites had not been monitored for 15 years or more.

Table 2.4. The mean maximum decline and the mean difference between the first and last survey (long-term decline) 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.

Region	N	n	Percent	Mean maximum absolute decline (%)	Mean maximum relative decline (%)	Mean long-term absolute decline (%)	Mean long-term relative decline (%)
Australia	135	104	77	24.0	80.3	10.0	45.3
Brazil	11	7	63.6	10.4	38.8	5.8	17.2
Caribbean	247	199	80.6	12.3	77.6	7.2	57.4
East Asian Seas	55	25	45.5	18.9	69.3	1.7	4.7
Eastern Tropical Pacific	6	6	100	63.5	96.7	60.4	95.1
Pacific	120	69	57.5	24.7	73.3	7.0	21.4
Red Sea and Gulf of Aden	10	5	50	20.5	57.1	4.1	13.6
ROPME Sea Area	0	-	-	-	-	-	-
South Asia	30	28	93.3	27.2	65.6	20.8	55.1
Western Indian Ocean	0	-	-	-	-	-	-

Status and trends in the average cover of algae in each region

Regional trends in the average cover of algae were generally the inverse of those exhibited by regional average coral cover, with most regions showing increases (Fig. 2.5). Over the period for which data were available in each region, increases in algal cover were most pronounced in Australia, Brazil and the ROPME Sea Area (Fig. 2.5). Moderate increases in the cover of algae were recorded in the Caribbean, Eastern Tropical Pacific, Pacific, South Asia and the Red Sea and Gulf of Aden regions, while there was little overall change in the Western Indian Ocean region. The East Asian Seas region was the only region in which the average cover of algae decreased (Fig. 2.5).

Based on a comparison of the three five-year periods comprising the last 15 years (Tab. 2.5), the probability that the cover of algae increased between 2005-09 and 2015-19 was 100% in Australia, Brazil, the Caribbean and the ROPME Sea Area, and 99% in South Asia. On average, increases in the cover of algae within these regions over this period ranged between 3.9% (South Asia) and 13.4% (ROPME Sea Area). In the Pacific, the Red Sea and the Gulf of Aden and the Eastern Tropical Pacific, the probability of increases in algal cover were more moderate ranging between 73% and 87%, and increases in algal cover ranged between 3.1% and 5.9% (Tab. 2.5) . Together, these regions comprise 64% of the world's coral reefs, indicating that two-thirds of the world's coral reefs are experiencing an increase in algae cover. In contrast, the East Asian Seas and Western Indian Ocean regions exhibited moderate probabilities of declines in the cover of algae in the order of 1.1% and 2.9% respectively during the last 15 years (Tab. 2.5).

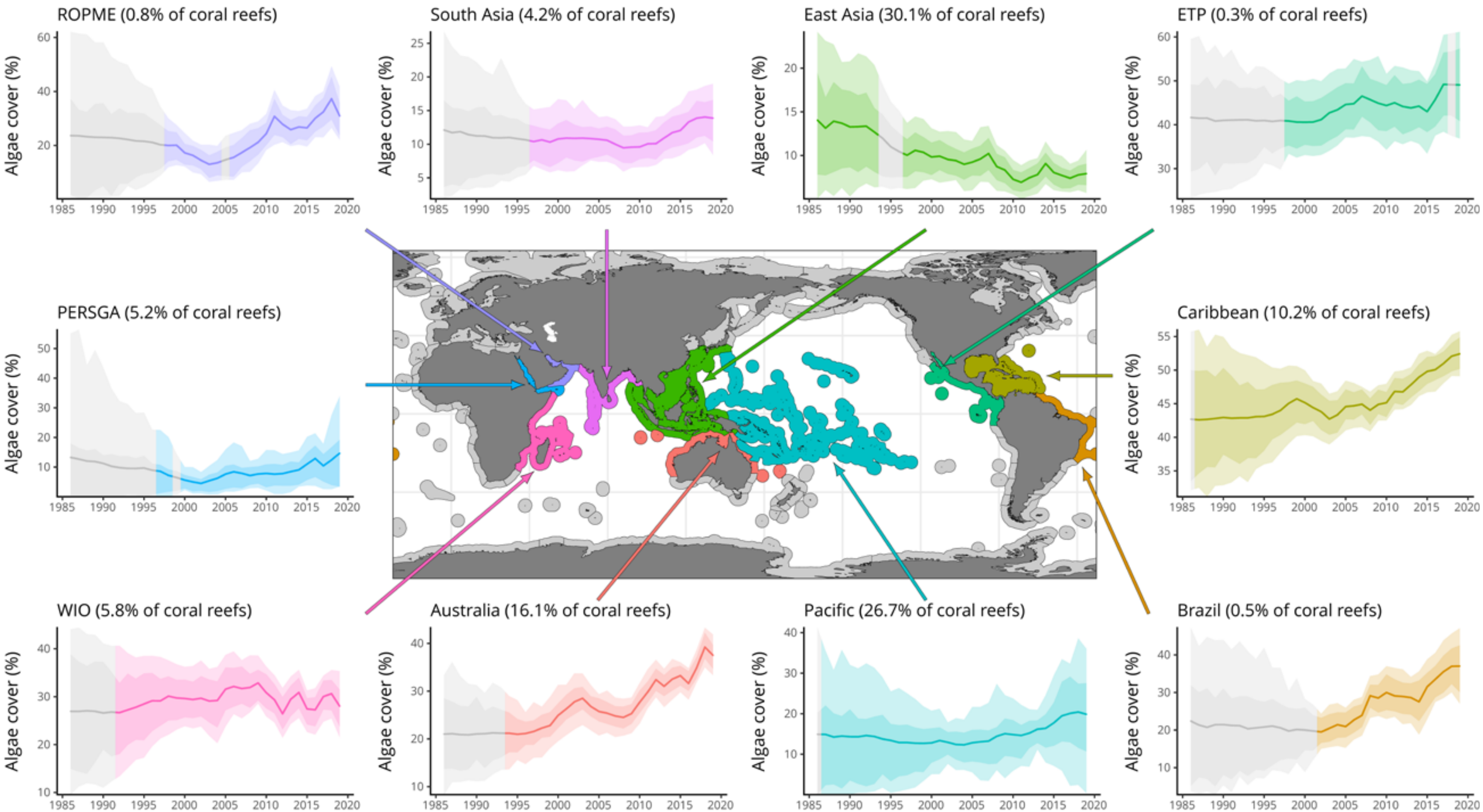


Figure 2.5. Long-term trends in the average cover of algae in each of the ten GCRMN regions. The solid line represents the estimated mean with 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods for which no observed data were available. Trends are coloured to match the GCRMN regions represented on the central map.The proportion of the world's coral reef area supported by each region is indicated by % of coral reefs. ETP is the Eastern Tropical Pacific. PERSGA is the Red Sea and Gulf of Aden. ROPME is the ROPME Sea Area. WIO is the Western Indian Ocean.

Table 2.5. Mean absolute change in percent cover of algae (and associated probability as a percentage) between pairs of five-year periods within the last 15 years in each region.

Region	Comparison 2005-09 – 2010-14	Comparison 2010-14 – 2015-19	Comparison 2005-09 – 2015-19
Australia	6.3 (100%)	4.0 (100%)	10.2 (100%)
Brazil	2.4 (88%)	6.6 (99%)	9.0 (100%)
Caribbean	3.3 (100)	3.4 (99%)	6.7 (100%)
East Asian Seas	-0.9 (87%)	-0.1 (59%)	-1.1 (86%)
Easter Tropical Pacific	-1.2 (32%)	4.3 (83%)	3.1 (74%)
Pacific	1.9 (84%)	4.1 (82%)	5.9 (87%)
Red Sea and Gulf of Aden	1.0 (68%)	3.8 (81%)	4.8 (85%)
ROPME Sea Area	8.3 (99%)	5.1 (92%)	13.4 (100%)
South Asia	1.1 (79%)	2.8 (95%)	3.9 (99%)
Western Indian Ocean	-3.2 (91%)	0.3 (53%)	-2.9 (88%)

Long-term changes in the average cover of algae were examined in each region within sampling units that had been surveyed repeatedly over a period of at least 15 years and had, at some point, experienced a relative increase in algal cover of at least 20%. Among the eight regions with sampling units that matched these criteria, all had a proportion of sampling units within which the cover of algae remained elevated (Tab. 2.6). The average proportion of long-term sampling units that did not fully recover was 82%, with the greatest proportions occurring within the Brazil (100%), Eastern Tropical Pacific (100%) and Red Sea and Gulf of Aden (100%) regions (Tab. 2.6).

Long-term increases in the average cover of algae among those sampling units examined ranged between 2% in South Asia and 49% in the Eastern Tropical Pacific (Tab. 2.6). The Eastern Tropical Pacific (49%), Brazil (34.3%) and Australia (21.1%) experienced the greatest absolute increases in the cover of algae where long-term monitoring was conducted. South Asia (2%), East Asian Seas (4.1%) and the Pacific (5.9%) recorded the smallest absolute increases in the cover of algae where long-term monitoring was conducted.

Table 2.6. The mean maximum increase and the mean difference between the first and last survey (long-term increase) expressed as absolute and relative increases in average percent cover of algae. N is the total number of sampling units for which >15 years of data were available and had experienced a relative increase in the cover of algae of at least 20 percent. n is the number of sampling units that did not recover to 110 percent (i.e. 10% above) of the initial algal cover. Percent is the proportion of the total number of sampling units that did not recover to 110 percent of the initial algal 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

Region	N	n	Percent	Mean maximum absolute increase (%)	Mean maximum relative increase (%)	Mean long-term absolute increase (%)	Mean long-term relative increase (%)
Australia	135	112	84	37.4	203	21.1	154
Brazil	15	15	100	43.1	389	34.3	327
Caribbean	198	160	81	30.3	614	15.2	321
East Asian Seas	50	29	58	26.0	527	4.1	142
Eastern Tropical Pacific	5	5	100	51.3	264	49.0	254
Pacific	86	52	60	25.8	266	5.9	130
Red Sea and Gulf of Aden	2	2	100	27.5	642	13.1	357
ROPME Sea Area	0	0	0	-	-	-	-
South Asia	13	10	76	8.0	303	2.0	153
Western Indian Ocean	0	0	0	-	-	-	-

Trends in the ratio between average covers of live hard coral and algae in each region

The ratio of average live hard coral cover to average algal cover varies between regions from approximately 0.5 (which indicates more algae than coral) in the ROPME Sea Area, Eastern Tropical Pacific and Caribbean, to approximately 1 (indicating similar average covers of coral and algae) in the Western Indian Ocean, Australia and Brazil to more than 2 (indicating at least twice the average cover of coral compared with algae) in South Asia, East Asian Seas, Red Sea and Gulf of Aden and the Pacific regions (Fig. 2.6). Moreover, the temporal trends also vary across regions, and do so independently of whether coral or algae was initially dominant.

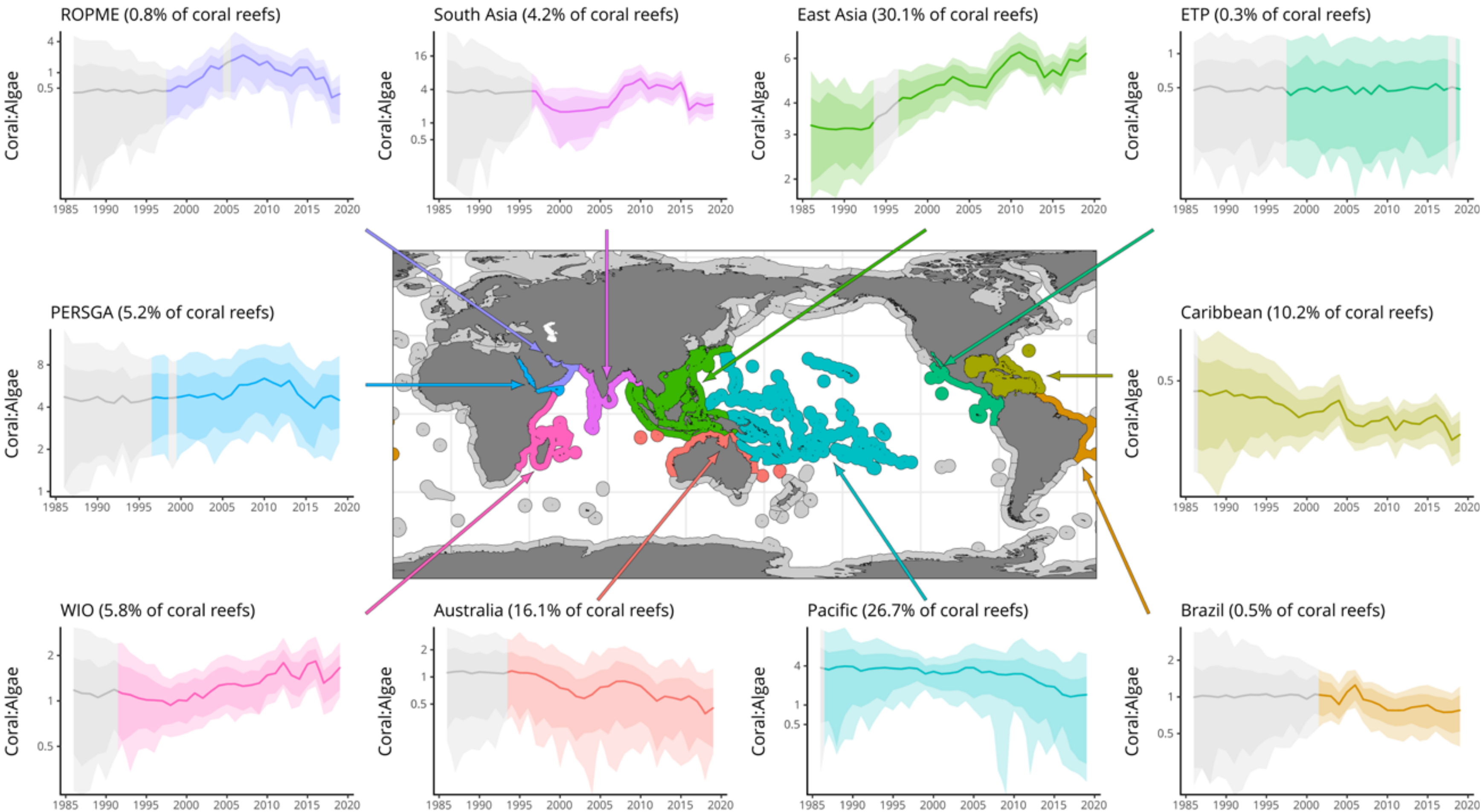


Figure 2.6. Long-term trends in the ratio between the average covers of live hard coral and algae in each of the ten GCRMN regions. The solid line represents the estimated ratio with 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods for which no observed data were available. Trends are coloured to match the GCRMN regions represented on the central map. The proportion of the world's coral reef area supported by each region is indicated by % of coral reefs. ETP is the Eastern Tropical Pacific. PERSGA is the Red Sea and Gulf of Aden. ROPME is the ROPME Sea Area. WIO is the Western Indian Ocean.

Overall, there is variation between the regions in terms of the dominance of coral in benthic reef communities and in the trends in the ratio of the average covers of coral:algae. While this variation is likely to be due to differences in reef community status, composition and resilience, and the stressors affecting them, further investigation of the drivers of this heterogeneity is required not only to improve our overall understanding of the differences observed, but also to help strengthen adaptive management actions that enhance natural resilience capabilities.

In contrast to most other regions, the East Asian Seas region, which includes the Coral Triangle, the center of global hard coral diversity, and accounts for nearly a third of the world's coral reefs by area, shows a progressive increase in coral cover until 2010 (Fig. 2.7A), then a sharp decline as a consequence of the second global coral bleaching event occurred in 2010. In addition, the average covers of cover of algae shows a marked decline prior to 2010, after which it stabilizes (Fig. 2.7B). The ratio of the average covers of coral:algae changed dramatically from >2 in the 1980s to ≈5 in 2010 (Fig. 2.7C). Despite thermal stresses in the East Asian Seas region being similar to those experienced in other regions, hard coral cover at the regional scale appears less affected until the last decade when the impacts of coral bleaching events in 2010 and 2016 were evident (Fig. 2.7A). The smaller impact of ocean warming events to coral reefs in the East Asian Seas region warrants further investigation as they may provide important insights into the factors that promote coral reef resilience.

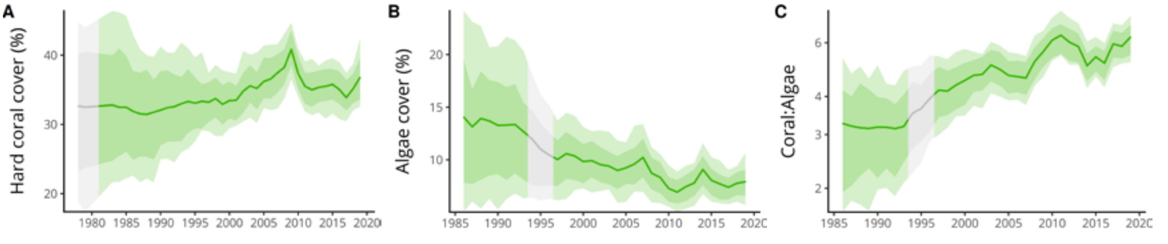


Figure 2.7. Estimated average cover of hard coral (A), and algae (B), and ratio of the average covers of hard coral to algae (C) for the East Asian Seas region. The solid line represents the estimated mean with 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods for which no observed data were available.

Global climatic drivers

Since global trends in the average cover of hard coral were derived from the aggregation of many localized trends, obvious changes in global trends, such as those that occurred following the large scale mass coral bleaching events in 1998, 2010 and 2016, were only apparent when similar changes occurred simultaneously across a large proportion of the world's coral reefs. While coral reefs are affected by numerous different types of disturbances (e.g. tropical storms, sedimentation, eutrophication, destructive fishing), only those that occur at very large scales will have sufficient impact to influence global trends. Hence, in exploring the drivers of change in global trends in average coral cover, the most obvious candidates were large-scale, climate-driven events.

Figure 2.8 examines the relationship between trends in the global average cover of hard coral cover and sea surface temperature (SST) anomalies during the last four decades. Trends in global average coral cover showed strong associations with mean global sea surface temperature (SST) anomalies. In particular, periods of decline in global average coral cover coincided with two features of the trend in SST anomaly: consecutive months of rapid increases in SST anomaly (dark red bars); and periods of sustained high SST anomalies (lighter red bars) (Fig. 2.8). All three global coral bleaching events (1997-98, 2010 and 2015-2017) that resulted in declines in global average coral cover coincided with consecutive months of rapidly increasing SST anomalies (Fig. 2.8), while sustained high SST anomalies after the 2010 event and from 2013 onwards (Fig. 2.8) may have hindered the recovery of corals and facilitated progressive increases in the cover of algae. The relationship between trends in global average coral cover and fluctuations in the El Niño Southern Oscillation Index was also examined, but no association was found.

Additional analyses at regional scales will determine if the global relationship between average hard coral cover and the SST anomaly holds at smaller spatial scales, or if the ENSO signal or local stressors are more important at these scales. The influence of SST anomalies on global average coral cover reinforces the importance of real time monitoring of SST to coral reef management and conservation (see NOAA Coral Reef Watch Box).

The strong association between SST anomaly and declines in global average coral cover resulting from large-scale coral bleaching events emphasises the importance of climate-related factors as primary drivers of the long-term health of the world's coral reefs, particularly as climate also influences other smaller scale disturbances that affect coral reefs, such as tropical storms, terrestrial run-off and coral disease.

Further, while the SST anomaly has progressively increased since the 1970s (Fig. 2.8), global average coral cover has only declined during periods when the SST anomaly has rapidly increased or exceeded 0.45 (Fig. 2.8). However, in 2019, global average coral cover increased despite the SST anomaly being at historically high levels. This suggests that world's coral reefs still retain their ability to recover from disturbances, despite the unfavourable climate conditions, and that potentially, corals are demonstrating some capacity for acclimation and adaptation. However, the limits to such adaptive capacity is as yet, unknown, and anecdotal evidence suggests that adaptive capacity is not equal among all coral species, resulting in shifts in community composition.

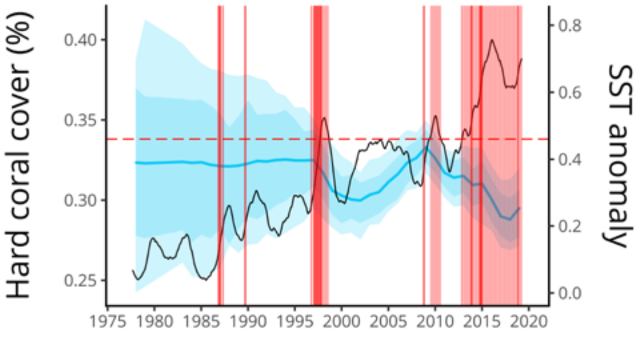


Figure 2.8. Estimated global average hard coral cover with the sea surface temperature (SST) anomaly from 1977 to 2020 superimposed. The blue line is the estimated global average hard coral cover with 80% (darker blue) and 95% (lighter blue) credible intervals. The black line represents the SST anomaly smoothed with an 18 month rolling mean. Periods of rapid increase in SST anomaly (darker red vertical lines) were calculated by estimating the derivatives (via numerical integration) of the smoothed SST anomaly time series. Darker red vertical red bars indicate when the rate of smoothed SST change exceeded 0.15 for two consecutive months. Lighter red vertical bars indicate when the smoothed SST anomaly exceeded. 0.45 (marked by horizontal red dashed line).

Part 2:
Regional Status of Coral Reefs

Chapter 3.

Status and trends of coral reefs of the Red Sea and Gulf of Aden

Collaborators: Maher Amer, Roberto Arrigoni, Tamer Attalla, Aden Elmi, Abdullah Abu Awali, Mohammed Al-Tawaha, Khadija Abaker, Michael Berumen, Jessica Bouwmeester, Darren Coker, Nouran Elsawy, Jan Freiwald, Chloe Harvey, Amy Johnson, Tullia Terraneo

1. Geographic information and context

Key numbers:

- Total area of coral reefs 13,605 km^2
- Proportion of the world's coral reefs: 5.24%
- Number of countries with coral reefs: 9
- Number of Marine Ecoregions of the World (MEOW) ecoregions: 3

Regional Context:

The Red Sea contains the most biologically diverse coral reef communities outside of Southeast Asia's coral triangle. It shares many of the species found elsewhere in the Indo-Pacific, but approximately 10% of species are endemic[1], making this region one of the most valuable repositories for marine biodiversity in the world. Coral reefs within the Red Sea and Gulf of Aden region cover 13,605 km^2, which is about 5.3% of the total global area of coral reefs.

The Red Sea and Gulf of Aden region is bordered by nine countries: Djibouti, Egypt, Eritrea, Israel, Jordan, Saudi Arabia, Somalia, Sudan and Yemen. Populations in these countries have steadily increased over the last 60 years with the greatest growth occurring in most countries between the 1960s and early 1990s. The region now supports an estimated 240 million people, with an increasing proportion of these people living in urban centres and along the coast to obtain the economic benefits associated with ocean navigation, fisheries, tourism and recreation. Impacts of population growth on marine ecosystems are most intense where growth occurs close to the coast.

The Red Sea is one of the world's major tourist destinations, and reef-associated tourism is a major source of income for some Red Sea countries. For example, coral reef-related tourism contributes 3.5% to Egypt's Gross Domestic Product (GDP)[2]. To date, coastal tourism has been concentrated along Egypt's eastern coastline. However, with the establishment of Saudi Arabia's Vision 2030 economic plan, which seeks to diversify the kingdom's economy and reduce its reliance on revenues from oil[3,4],

[1] De Vantier, L.; Turak, E.; Al-Shaikh, K. and De'ath, G., (2000). Coral communities of the central-northern Saudi Arabian Red Sea. Fauna of Arabia, 18, 23:66.

[2] Hilmi, N., Safa, A., Reynaud, S., Allemand, D., (2012). Coral reefs and tourism in Egypt's Red Sea topics in middle eastern and African economies.

[3] Fattouh, B., Sen, A., (2016). Saudi Arabia's Vision 2030, Oil Policy and the Evolution of the Energy Sector. Oxford Institute for Energy Studies, Oxford Energy Comment, July https://www.oxfordenergyorg/wpcms/wpcontent/uploads/2016/07/Saudi-Arabias-Vision-2030-Oil-Policy-and-the-Evolutionof-the-Energy-Sectorpdf.

[4] Gazette, S., (2016). Full text of Saudi Arabia's vision 2030. Saudi Gazette 26.

tourism, including coastal tourism, is considered the most prospective element of the kingdom's diversification plan, particularly given their long coastline and many attractive coral reefs.

While the current contribution of fisheries to national GDP is relatively small (<1%), except in Yemen where this sector accounts for 15% of GDP, the value of the Red Sea and Gulf of Aden fishery resources to the prosperity of the region has long been recognized. Artisanal fisheries provide food and employment for thousands of the region's inhabitants, particularly in Yemen where more than 220,000 people depend on fishing as their principal source of income. Potential to expand marine fisheries in the future exists, but this will depend on the continued upgrading of infrastructure and development of export markets.

The Red Sea and Gulf of Aden region is comprised of three Marine Ecoregions of the World (MEOW) ecoregions[5] (Tab. 3.1, Fig. 3.1). Data from each ecoregion are reported here.

Table 3.1. The subregions comprising the Red Sea and Gulf of Aden region, the area of reef they support, and the constituent Marine Ecoregions of the World (MEOW)[1].

Subregion	Reef Area (km^2)*	Proportion of Reef Area within the Red Sea and Gulf of Aden Region(%)	Constituent Marine Ecoregions of the World
1	7,800	57.3	87: Northern and Central Red Sea
2	4,896	36.0	88: Southern Red Sea
3	911	6.7	89: Gulf of Aden

*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

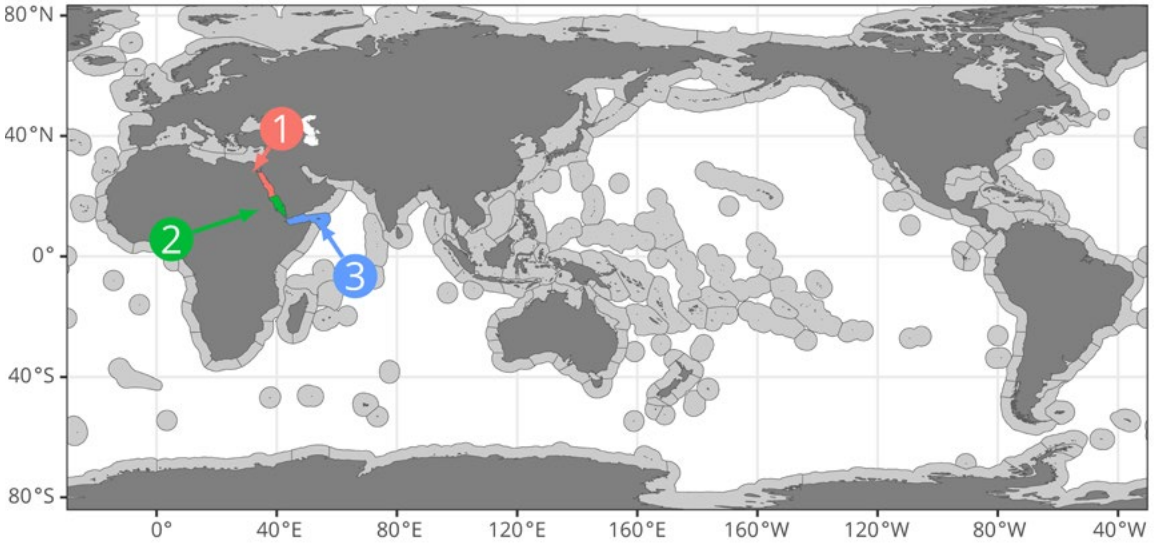


Figure 3.1. Map of each subregion comprising the Red Sea and Gulf of Aden region. The number ascribed to each subregion corresponds with that in Table 3.1.

5 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

2. Summary of data contributed to this report

Key numbers:

- Number of countries from which monitoring data were used: 6 (of 9)
- Number of sites: 243
- Number of observations: 6,416
- Longest time series: 15 years

General features:

The great majority of observations (75%) in the Red Sea and Gulf of Aden region were recorded in the northern and central Red Sea (subregion 1) (Fig. 3.2, Tab. 3.2). Approximately one-quarter of all observations were recorded in the southern Red Sea (subregion 2), and a very small number of observations were recorded in the Gulf of Aden (subregion 3). Although fewer reefs occur in the southern Red Sea and Gulf of Aden compared with the northern and central Red Sea (Tab. 3.2), the disproportionately small number of observations recorded in these two subregions means that their condition may not be accurately reflected in the overall regional status and trends.

The vast majority (84%) of sites in the region have been surveyed only once (Fig. 3.3A). Only about 7% of sites were surveyed over periods longer than a decade (Fig. 3.2 & 3.3A). Unfortunately, metadata describing the methods used to conduct many of the surveys were not provided (Fig. 3.4). However, point intercept and line intercept transects were the most common methods when a description of the methods was provided (Fig. 3.4). Although not represented in figure 4, permanent photo-quadrats were used at some sites along the Egyptian coast.

Table 3.2. Summary statistics describing data contributed from the Red Sea and Gulf of Aden 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.

Red Sea and Gulf of Aden 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	6,416	0.66	243	2	7	0.01
1	4,793	0.49	161	1.32	7	0.01
2	1,583	0.16	69	0.57	0	0
3	40	0	13	0.11	0	0

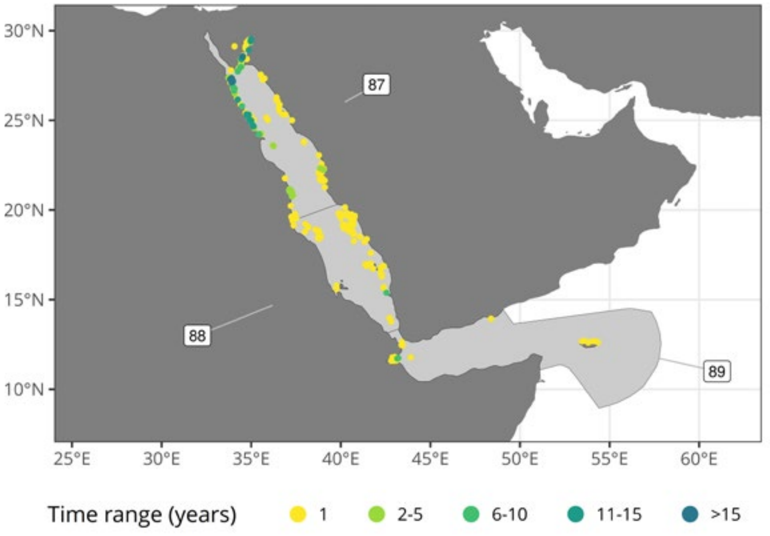


Figure 3.2. The distribution and duration of monitoring at sites across the Red Sea and Gulf of Aden region. The colours of dots represent the time span between the first survey and the most recent survey at each site. Numbers refer to the MEOW ecoregions listed in Table 3.1.

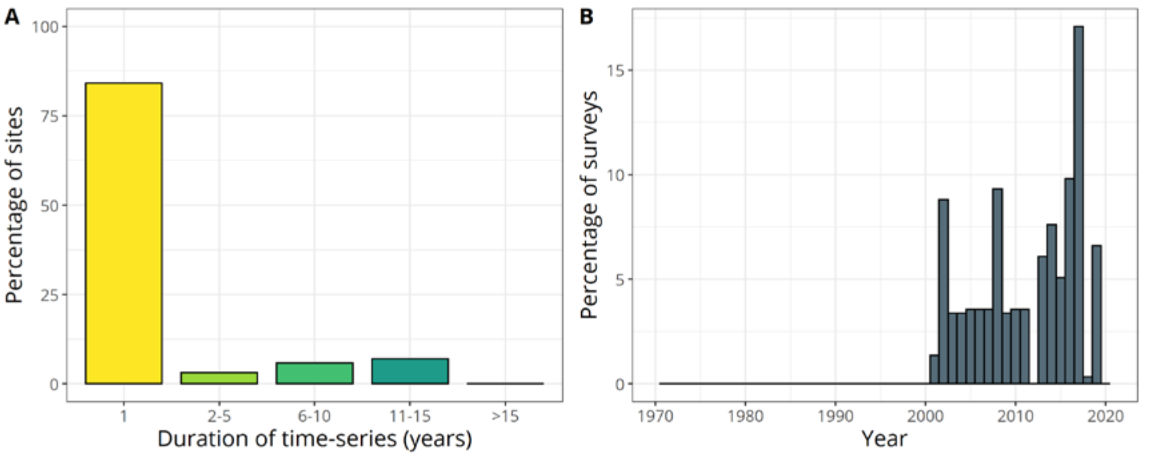


Figure 3.3. The proportion of sites in the Red Sea and Gulf of Aden region within each category describing the time span between the first and most recent surveys (A), and the proportion of the total number of surveys conducted in each year (B). The total number of surveys was 574.

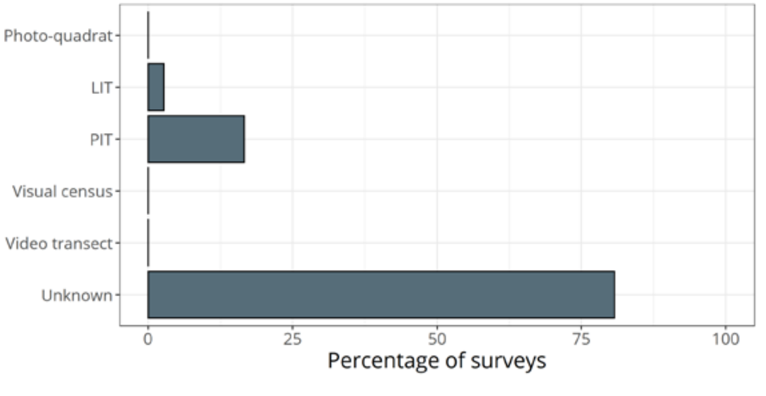


Figure 3.4. The proportion of the total number of surveys conducted in the Red Sea and Gulf of Aden region using each survey method. PIT: Point Intercept Transect; LIT: Line Intercept Transect.

3. Status of coral reefs in the Red Sea and Gulf of Aden region

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

In 1997, when the first data contributed to this analysis were collected, the estimated average cover of hard coral in the region was 36.1%, which was the highest at any point in the 22 year time series (Fig. 3.5A). Between 1997 and 2002, coral cover declined to 32.3% as a consequence of the mass coral bleaching event that occurred in 1998, when one-third of coral reefs in the region were affected[6.] During the next six years, coral cover almost recovered to pre-1998 levels, reaching 35.3% in 2008, but progressively declined again during the next eight years to 30.9% in 2016 . Since 2016, average coral cover has increased again to 34.3% in 2019 (Fig. 3.5A).

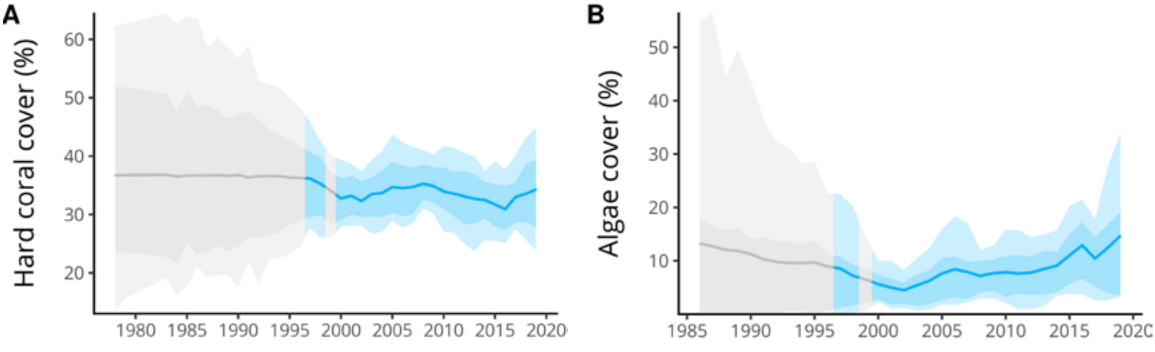


Figure 3.5. Estimated regional average cover of live hard coral (A) and algae (B) for the Red Sea and Gulf of Aden region. The solid line represents the estimated mean and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods during which no field data were available.

Comparison of the average hard coral cover between three five-year periods (2005-2009, 2010-2014, 2015-2019) over the last 15 years provided weak evidence (71% probability) of a decline in coral cover between 2005-09 and 2010-14, and no evidence (47% probability) of any change between 2010-14 and 2015-19 (Tab. 3.3). The relatively low probabilities of change were attributable to the timing of fluctuations in coral cover within and between 5-year periods resulting in small absolute and relative changes in coral cover (Tab. 3.3).

Table 3.3. Probability and magnitude of mean absolute and relative change in the percent cover of live hard coral in the Red Sea and Gulf of Aden 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	76	-2.0	-7.6
2010-14 - 2015-19	47	0.2	1.7
2005-09 - 2015-19	71	-1.7	-6.0

The average cover of algae on coral reefs in the region was generally low (<8.6%), particularly prior to 2012 (Fig. 3.5B). Between 1997 and 2006, the cover of algae exhibited a similar trend to that of coral cover, with an initial decline from 8.6% in 1997 to 4.5% in 2002, which was followed by a progressive

[6] PERSGA, 2006. The State of the marine environment report for the Red Sea and Gulf of Aden (SOMER I). Wilkinson, G.; Facey, R. and Hariri, K. (eds), PERSGA, Jeddah, 241 pp.

increase to 8.4% in 2006. The cover of algae varied little during the next six years, but increased from 7.8% in 2012 to 14.7% in 2019, almost doubling the amount of algae on reefs in the region during that time (Fig. 3.5B). The stability in the cover of algae between 2006 and 2012 was confirmed by the low probability of change (68%) when comparing average algal cover between 2005-09 and 2010-14 (Tab. 3.4). However, there was a greater probability (85%) of an increase in the cover of algae between 2005-09 and 2015-19, and a mean relative change of 105.1% (Tab. 3.4) is consistent with the doubling of the amount of algae on the region's coral reefs since 2012 illustrated in figure 5b.

Table 3.4. Probability and magnitude of mean absolute and relative change in the percent cover of algae in the Red Sea and Gulf of Aden 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	68	1.0	25.6
2010-14 - 2015-19	81	3.8	65.7
2005-09 - 2015-19	85	4.8	105.1

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

Local-scale causes of coral loss vary across the region. In the northern Red Sea, tourism activities and coastal development are the main causes of coral loss, while in the central region, land runoff, eutrophication and overfishing have degraded coral reefs and stimulated algal growth. In the southern Red Sea, overfishing and poor management are considered the main causes of declines in coral cover.

At a regional scale, one-third of coral reefs in the Red Sea and Gulf of Aden were affected by coral bleaching in 1998. Impacts were most severe in the central-northern Red Sea of Saudi Arabia (especially near Rabigh) and in Yemen (Belhaf, Hadhramaut, Socotra Archipelago). Fortunately, most bleached reefs recovered[6].

- Changes in resilience of coral reefs within the GCRMN PERSGA region

Increases in the frequency of disturbances to coral reefs in the Red Sea and Gulf of Aden have changed long-term disturbance-recovery patterns, particularly on reefs along the Egyptian coast and submerged reefs, such that many reefs are not recovering completely between one disturbance and the next. The result is a stepwise decline in live hard coral cover. Among the 10 sampling units for which there was greater than 15 years of data (all of which occurred along the Egyptian coast of the Red Sea) and had experienced at least a 20% decline in relative hard coral cover, half did not recover to at least 90% of their pre-disturbance hard coral cover (Tab. 3.5). The average absolute decline in hard coral cover between the first survey and the last survey at these sites was 4% which, in relative terms, means that these sites had 13.6% less hard coral. The average maximum absolute decline in hard coral cover was 20.5%, which equates to 57% less hard coral.

Table 3.5. 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
10	5	50	20.5	57.1	4.1	13.6

4. Subregional trends in the cover of live hard coral and algae within the Red Sea and Gulf of Aden region

Trends in the cover of hard coral differed among the three subregions comprising the Red Sea and Gulf of Aden region (Fig. 3.6), indicating some variation in disturbance-recovery regimes across the region. This also highlights the need to survey reefs in all subregions. Average hard coral cover on reefs in the northern and central Red Sea (subregion 1) showed an initial decline from 35.2% in 1997 to 29.7% in 2002, attributable to the 1998 mass coral bleaching event. However, after 2002, average coral cover on reefs in this subregion slowly increased, reaching a maximum of 39.1% in 2019 (Fig. 3.6). Fewer data were available from the southern Red Sea (subregion 2) but those that were collected suggested a progressive decline in coral cover on reefs in this subregion, particularly between 2008 (37.3%) and 2016 (24.1%), with the first sign of potential recovery in 2017 (26.7%). Trends in coral cover on reefs in the Gulf of Aden (subregion 3) were difficult to describe as data were collected in only five years between 1998 and 2008. However, those data that were collected indicated that coral cover fluctuated, ranging between 29.6% (2005) and 37.3% (2001).

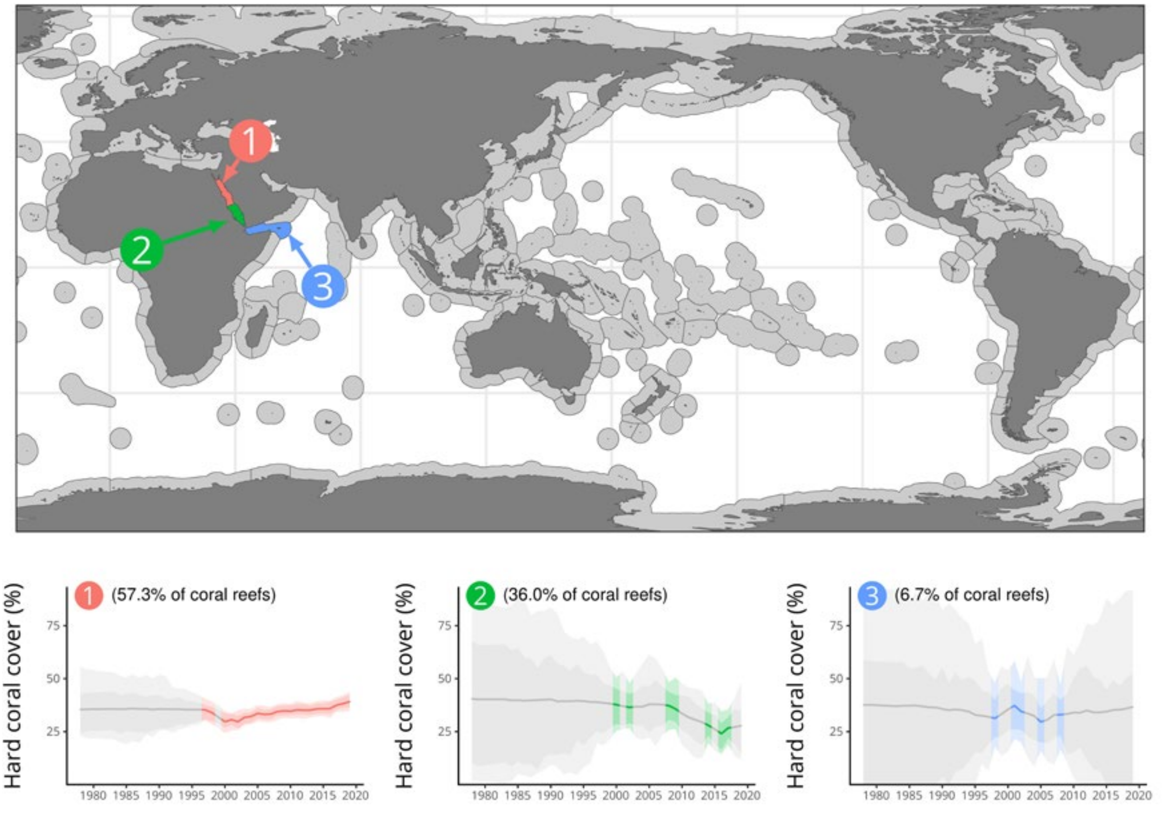


Figure 3.6. Estimated average cover of live hard coral within each subregion comprising the Red Sea and Gulf of Aden region. The solid line represents the estimated mean and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods during which no field data were available. The proportion of all coral reefs in the East Asian Seas region within each subregion is indicated by the % of coral reefs.

Similar to hard coral cover, trends in the cover of algae varied among the three subregions (Fig. 3.7). Algal cover on coral reefs in the northern and central Red Sea (subregion 1) exhibited little overall change between 1997 (5.6%) and 2010 (5.2%), but slowly increased to 11.5% in 2019. Despite this increase, algal cover remained low throughout compared with the other two subregions. This may be attributable to bans established by Egypt and Jordan on any discharge into marine waters. Data describing the cover of algae on reefs in the southern Red Sea (subregion 2) were collected in only seven years between 2000 and 2017. These data indicated that algal cover was generally greater on these reefs but varied considerably, ranging between 6.4% (2002) and 25.5% (2016). More abundant algae on these reefs could be attributable to land run-off or discharge, or that waters in the southern Red Sea and Gulf of Aden are naturally more nutrient-rich. The few data collected from reefs in the Gulf of Aden (subregion 3) suggested that the cover of algae in this subregion was low (<6.8%).

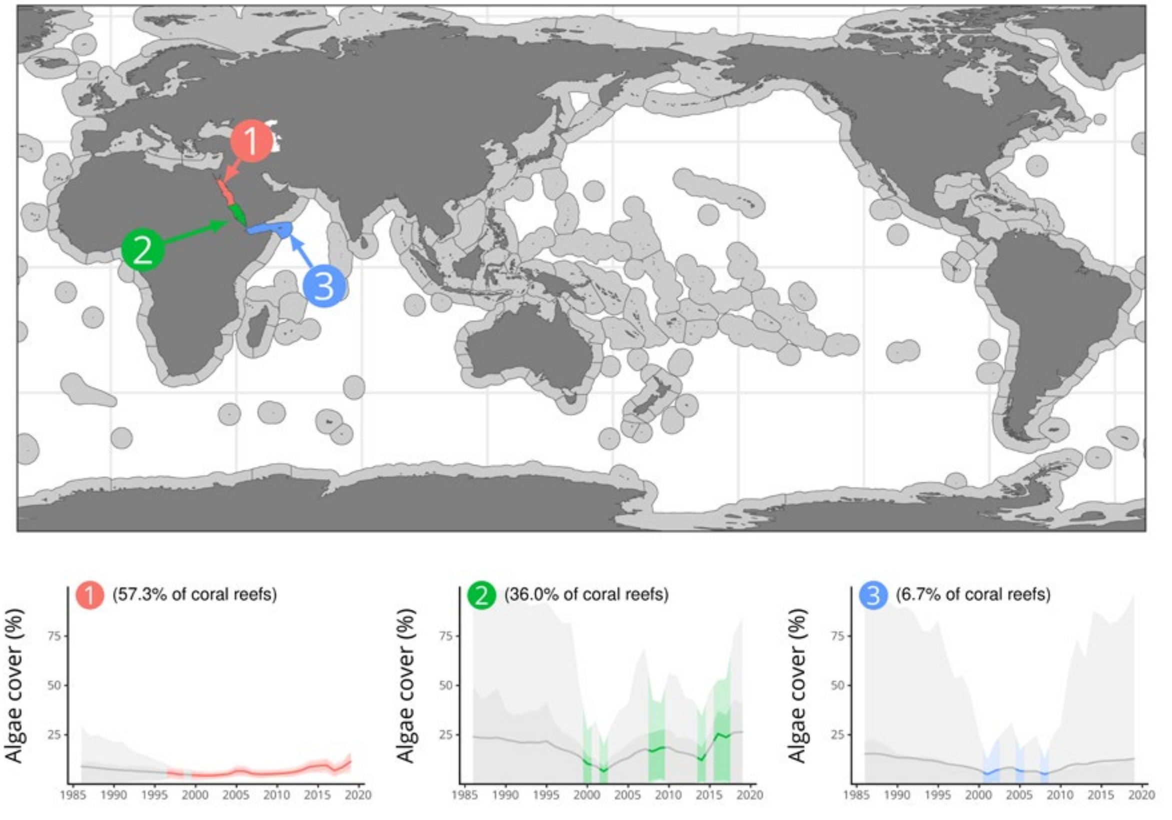


Figure 3.7. Estimated average cover of algae within each subregion comprising the Red Sea and Gulf of Aden region. The solid line represents the estimated mean and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods during which no field data were available. The proportion of all coral reefs in the Red Sea and Gulf of Aden region within each subregion is indicated by the % of coral reefs.

Chapter 4.

Status and trends of coral reefs of the ROPME Sea Area

Collaborators: John A. Burt, Pedro Range, Michel Claerboudt, Reem Al Mealla, Parisa Alidoost Salimi, Mahsa Alidoost Salimi, Radhouan Ben-Hamadou, Mehdy Bolouki, Jessica Bouwmeester, Oliver Taylor, Shaun Wilson

1. Geographic information and context

Key numbers:

- Total area of coral reefs: 2,009km^2
- Proportion of the world's coral reefs: 0.77%
- Number of countries with coral reefs: 9
- Number of Marine Ecoregions of the World (MEOW) ecoregions: 3

Regional Context:

The Regional Organization for the Protection of the Marine Environment (ROPME) Sea Area is situated to the northeast of the Arabian plate. It is divided into three geographically and environmentally distinct parts. The division referred to as the Inner ROPME Sea Area consists of the marine area west of 56ºE longitude that extends along the NW/SE axis from the north State of the boundary of the ROPME Sea Area to the north of Strait of Hormuz. The Middle ROPME Sea Area covers the Sea of Oman, and the Outer ROPME Sea Area stretches over the entire southern boundary of the RSA across the Arabian Sea that starts from Ra's Al-Hadd to the southern border of Oman. Each of these areas overlaps with Marine Ecoregions of the World (MEOW) ecoregions[1] (Fig. 4.1). The region contains just under 1% (2,009 km^2) of the total global area of coral reefs. Nearly three-quarters of the total reef area occurs within the Inner ROPME Sea Area ecoregion (Tab. 4.1), with the remainder largely bordering coastal Oman. Marine environments in this region vary dramatically, with extreme temperatures characterizing the Inner ROPME Sea Area and monsoon-related upwelling influencing seasonal temperatures and productivity in the Arabian Sea[2,3]. As a result, reefs across the region vary markedly in terms of their structure, biodiversity, proximity to urban stressors and frequency and intensity of natural or climate-related disturbances.

The GCRMN region known as the ROPME Sea Area is bordered by the eight member nations of ROPME (Bahrain, Iran, Iraq, Kuwait, Oman, Qatar, Saudi Arabia and the United Arab Emirates) and Yemen,

[1] 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

[2] Vaughan GO, Al-Mansoori N, Burt J (2019) The Arabian Gulf. In: Sheppard C (ed) World Seas: An Environmental Evaluation, second edition. Elsevier Science, Amsterdam, NL, pp1-23 https://doi.org/10.1016/B978-0-08-100853-9.00001-4

[3] Claereboudt MR (2019) Oman. In: Sheppard C (ed) World Seas: an Environmental Evaluation (Second Edition). Academic Press, pp25-47 https://doi.org/10.1016/B978-0-08-100853-9.00002-6

each of which contain coral communities. Coral reefs are the most biodiverse ecosystem in this arid region, and they support a fisheries sector that is second only to petroleum as an economic sector[4]. Since the oil boom of the 1970s, population growth rates in the region have been nearly double the global average, growing nearly threefold from 46.5 million people in 1970 to approximately 150 million by 2010. However, populations vary considerably along coastlines, ranging from 5.4 million people in cities such as Dubai, to large stretches of coastal Oman where only isolated villages occur, which influences the amount of coastal development and urban pressure being applied to reefs[2,3,5]. There are also dramatic differences in fishing pressure among regional nations, with landings ranging from 11,810 tonnes in Iraq to 5,518,100 tonnes in Iran, leading to variation in direct and indirect impacts to reefs from fishing activities.

Table 4.1. The subregions comprising the ROPME Sea Area, the area of reef they support.

Subregion	Reef Area (km^2)*	Proportion of Reef Area within the ROPME Sea Area (%)	ROPME Sea Area Regions
1	1,482	73.77	90: Inner ROPME Sea Area
2	196	9.78	91: Middle ROPME Sea Area
3	330	16.46	92: Outer ROPME Sea Area

*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

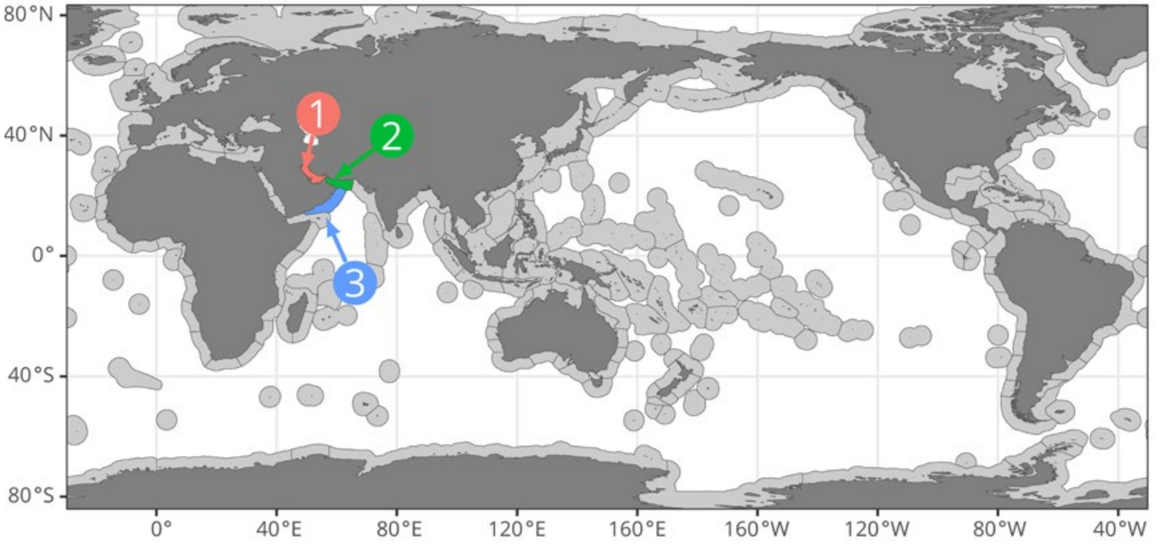


Figure 4.1. Map of each subregion comprising the ROPME Sea Area. The number ascribed to each subregion corresponds with that in Table 4.1.

4 van Lavieren H, Burt J, Feary D, Cavalcante G, Marquis E, Benedetti L, Trick C, Kjerfve B, Sale PF (2011) Managing the growing impacts of development on fragile coastal and marine systems: Lessons from the Gulf. A Policy Report, United Nations University - Institute for Water, Environment, and Health. Hamilton, ON, Canada.

5 Burt JA, Coles S, van Lavieren H, Taylor O, Looker E, Samimi-Namin K (2016) Oman's coral reefs: A unique ecosystem challenged by natural and man-related stresses and in need of conservation. Mar Pollut Bull 105:498-506 https://doi.org/http://dx.doi.org/10.1016/j.marpolbul.2015.11.010

2. Summary of data contributed to this report

Key numbers:

- Number of countries from which monitoring data were used: 7 (of 9)
- Number of sites: 68
- Number of observations: 45,477
- Longest time series: 12 years

General features:

Over 45,000 observations collected across 68 sites were available for the ROPME Sea Area, representing nearly 5% of the overall global dataset. The vast majority of these records (90% of observations and 77% of sites) occurred within the Inner ROPME Sea Area subregion (Tab. 4.2), with nearly all of the remainder occurring in the Middle ROPME Sea Area subregion; only two observations at one site occurred in the Outer ROPME Sea Area subregion. Within the Inner ROPME Sea Area subregion, observations were available for all nations except Iraq, which contains only one recently discovered reef community, although data were not available from all known reefs within Inner ROPME Sea Area nations (Fig. 4.2). In the Middle ROPME Sea Area subregion, observations were available for most known major reef habitats, while data were available from only two sites in the Outer ROPME Sea Area. The vast majority of sites have less than a single year of survey data available (77%; Fig. 4.2, Fig. 4.3A), and no sites in the ROPME Sea Area contain long-term (>15 years) monitoring records (Tab. 4.1; Fig. 4.3A). Only 7% of records extend beyond a decade (Fig. 4.3A), and these occur exclusively around Muscat in the Middle ROPME Sea Area subregion (Fig. 4.2). Photo-quadrats were used for most surveys (82%), although unknown methods were employed for 10% of all surveys (Fig. 4.4).

Table 4.2. Summary statistics describing data contributed from the ROPME Sea Area. 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.

ROPME 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	45,477	4.69	68	0.56	0	0
1	40,696	4.2	52	0.43	0	0
2	4,779	0.49	15	0.12	0	0
3	2	0	1	0.01	0	0

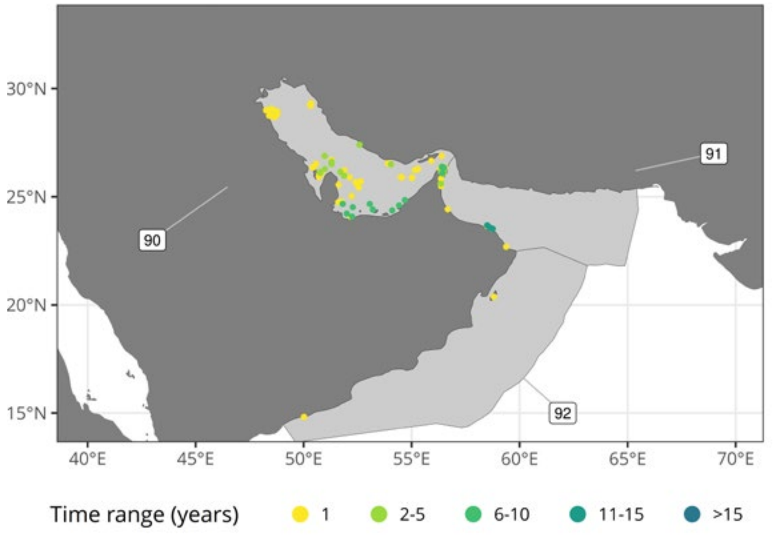


Figure 4.2. The distribution and duration of monitoring at sites across the ROPME Sea Area. The colours of dots represent the time span between the first survey and the most recent survey at each site. Numbers refer to the MEOW ecoregions listed in Table 4.1.

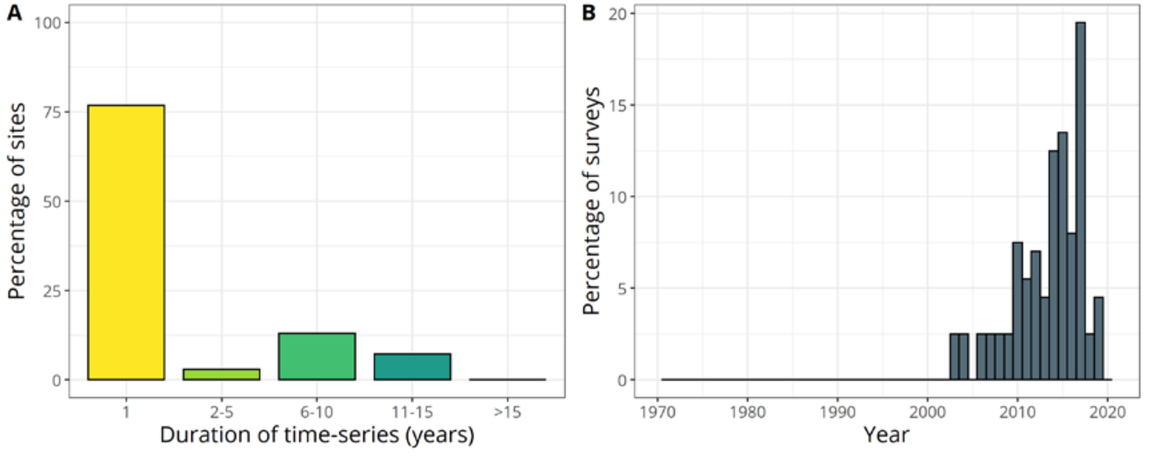


Figure 4.3. The proportion of sites in the ROPME Sea Area within each category describing the time span between the first and most recent surveys (A), and the proportion of the total number of surveys conducted in each year (B). The total number of surveys was 200.

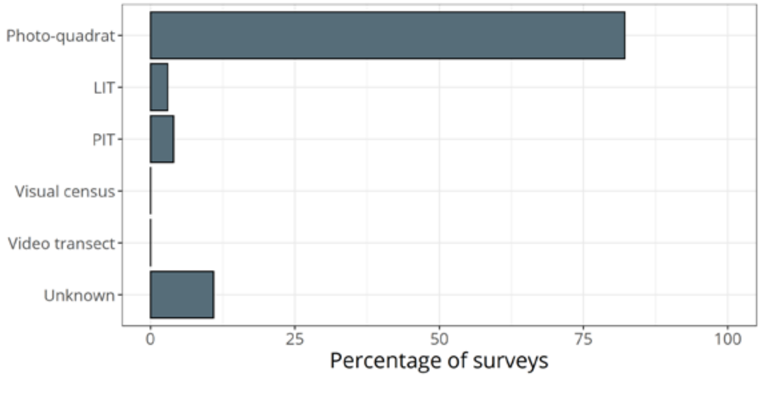


Figure 4.4. The proportion of the total number of surveys conducted in the ROPME Sea Area using each survey method. PIT: Point Intercept Transect; LIT: Line Intercept Transect.

3. Status of coral reefs in the GCRMN ROPME Sea Area

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

Between 1997, when monitoring began, and 2002, estimated average live coral cover declined from 30.1% to 18.0% (Fig. 4.5A), representing a loss of 40.1% of the cover of living coral from the region. This coincides with the occurrence of two severe back-to-back bleaching events in 1996 and 1998 that caused widespread coral mortality, particularly in the Inner ROPME Sea Area subregion[6]. From 2002, there was a long period of recovery that extended over a decade, with average live hard coral cover peaking again in 2015, when it reached 30.2%, a level comparable to the earliest pre-bleaching records. This was followed by an abrupt decline in coral cover to a record low of 17.9% in 2019, which followed bleaching during the hottest summer on record in the Inner ROPME Sea Area in 2017[7]. This equates to an overall loss of 40.1% of the living coral cover between 1996 and 2019 in the region, or approximately 20% per decade since monitoring began.

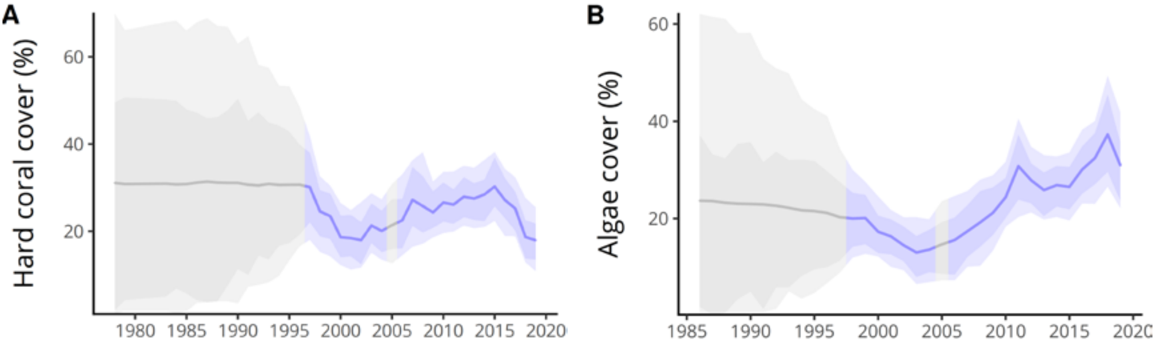


Figure 4.5. Estimated regional average cover of live hard coral (A) and algae (B) for the ROPME Sea Area. The solid line represents the estimated mean and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods during which no field data were available.

Comparisons of the average hard coral cover between five-year periods (2005-09, 2010-14, 2015-19) indicate that despite the uncertainty in individual yearly estimates, there is a high degree of confidence (~82%) in long-term declines and that the greatest decline occurred in the last five years (2015-19) (Tab. 4.3). Recovery in live coral cover was observed between 2005-09 and 2010-14 (a near 20% increase in relative cover), but this was more than offset by a 26.9% decline in the subsequent 2015-19 period. Changes in hard coral cover at the regional scale may not be representative of changes within the Outer ROPME Sea Area owing to a scarcity of data and the different ecology of the reefs in this subregion[2,4].

Table 4.3. Probability and magnitude of mean absolute and relative change in the percent cover of live hard coral in the ROPME Sea Area 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	80	2.9	18.2
2010-14 - 2015-19	96	-6.1	-26.9
2005-09 - 2015-19	82	-3.2	-14.4

[6] Riegl B, Johnston M, Purkis S, Howells E, Burt J, Steiner S, Sheppard C, Bauman A (2018) Population collapse dynamics in Acropora downingi, an Arabian/Persian Gulf ecosystem‐engineering coral, linked to rising temperature. Global Change Biology 24:2447–2462 https://doi.org/10.1111/gcb.14114

[7] Burt JA, Paparella F, Al-Mansoori N, Al-Mansoori A, Al-Jailani H (2019) Causes and consequences of the 2017 coral bleaching event in the southern Persian/Arabian Gulf. Coral Reefs 38:567-589 https://doi.org/10.1007/s00338-019-01767-y

The average cover of algae across the region has been increasing since the early 2000s, from a low of 13% in 2003 to a peak of 37.3% in 2018 (Fig. 4.5B), presumably reflecting algal overgrowth on dead coral skeletons following the summer 2017 coral bleaching event in the Inner ROPME Sea Area subregion. Increases in algal growth were observed in all periods compared (Tab. 4.4), with average algal cover more than doubling (~115%) between the 2005-09 and 2015-19 periods.

Table 4.4. **Probability and magnitude of mean absolute and relative change in the percent cover of algae in the ROPME Sea Area 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	8.3	68.5
2010-14 - 2015-19	92	5.1	28.2
2005-09 - 2015-19	100	13.4	115.4

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

In the ROPME Sea Area, coral bleaching is the primary cause of coral loss, although considerable localized degradation and loss has also occurred as a result of coastal development[3,5,6]. The substantial declines in coral cover recorded between 1997 and 2002 coincide with the occurrence of two back-to-back coral bleaching events in 1996 and again in 1998 that affected reefs across the Inner ROPME Sea Area (which contains 74% of regional coral reef habitat; Table 4.1)[5]. Similarly, the dramatic decline in coral cover between 2015 and 2019 coincides with the 2017 coral bleaching event[6], when sea surface temperatures were the highest ever recorded in the Inner ROPME Sea Area, as well as a bleaching event in the Middle ROPME Sea Area in 2015. Coral bleaching is rare for the Outer ROPME Sea Area, as monsoonal upwelling cools temperatures during the late summer[2]. The cause of the long-term increase in cover of algae on regional reefs is unclear, as it counterintuitively matches increasing trends in coral cover over time (Fig. 4.5A). This may simply reflect a transition from categories previously classified as 'dead coral' being later classified as algae due to overgrowth as regional reefs transitioned after the impact of the 1996/1998 coral bleaching events.

- Changes in resilience of coral reefs within the ROPME Sea Area

The ROPME Sea Area contains the most thermally tolerant corals in the world, but they live at the limits of their physiological tolerance and can be pushed over the edge during extreme thermal anomalies[5]. The average cover of live coral declined from 30.1 % to 18.0% in the wake of the 1996 and 1998 coral bleaching events, which resulted in loss of 40% of the corals across the region. However, reefs showed capacity to recover, with coral cover returning to pre-bleaching levels a decade later in 2015, despite the Inner ROPME Sea Area being the hottest sea in the world during each of these years and the documented occurrence of minor to moderate coral bleaching events in 2007, 2010, 2011 and 2012 that had limited impact on region-wide coral cover (Fig. 4.5A)[5,6]. However, this recovery was reset by the extreme coral bleaching event in 2017, when reef bottom temperatures of 37.7 °C were recorded[6] causing a second major decline in which 40% of the living coral in the region was lost by 2019 (Fig. 4.5A).

4. Subregional trends in the cover of live hard coral and algae in ROPME Sea Area

Within the ROPME Sea Area, trends in hard coral cover among the subregions vary (Fig. 4.6), reflecting heterogeneity in the type, magnitude and frequency of disturbance as well as recovery dynamics, indicating a need for continued region-wide monitoring. Subregion 1 (The Inner ROPME Sea Area) showed trends that mirror the larger ROPME Sea Area, reflecting the heavy weighting of this subregion in the regional-scale analyses (77% of regional reef area). In contrast, coral cover declined by nearly half between 2005 and 2010 in the Sea of Oman (subregion 2), reflecting the localized impacts from super-cyclone Gonu (2007) and cyclone Phet (2010) as well as a large-scale algal bloom (2008/9)[2,4], although recovery began thereafter. Coral cover has remained stable in the Outer ROPME Sea Area (subregion 3), likely reflecting low disturbance in this relatively unpopulated area (although limited temporal sampling makes trend analysis difficult).

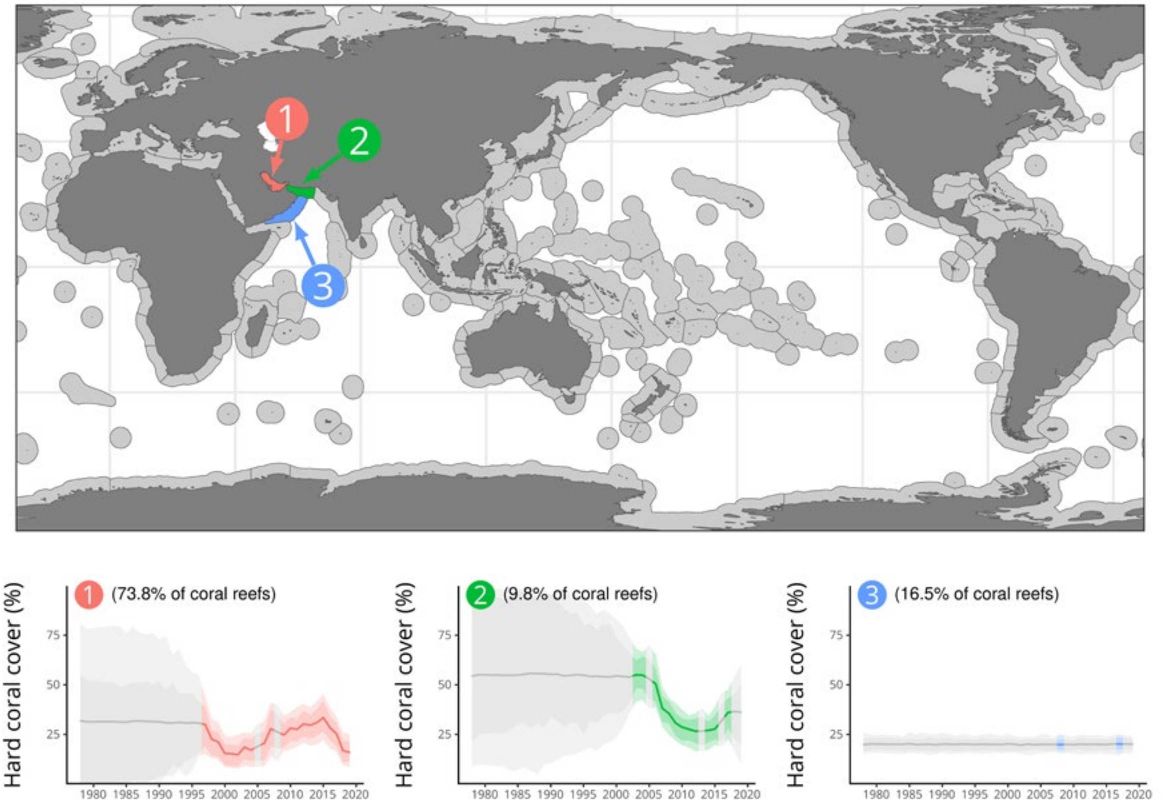


Figure 4.6. Estimated average cover of live hard coral within each subregion comprising the ROPME Sea Area. The solid line represents the estimated mean and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods during which no field data were available. The proportion of all coral reefs in the ROPME Sea Area within each subregion is indicated by the % of coral reefs.

In general, it appears that the cover of algae has increased regionally (Fig. 4.7). A trend towards increasing cover of algae has clearly occurred in the Inner ROPME Sea Area and the Sea of Oman, suggesting a phase shift in reef communities in the wake of disturbances on these reefs, with the cover of algae increasing by more than two to three times what it was in the early 2000s (in subregions 1 & 2, respectively). Insufficient temporal monitoring data were available for analyses of long-term trends in the Outer ROPME Sea Area (subregion 3), but it is well known that algal density varies seasonally (high cover in late summer following monsoon upwelling, low cover in spring)[2], suggesting that the timing of surveys can influence monitoring results.

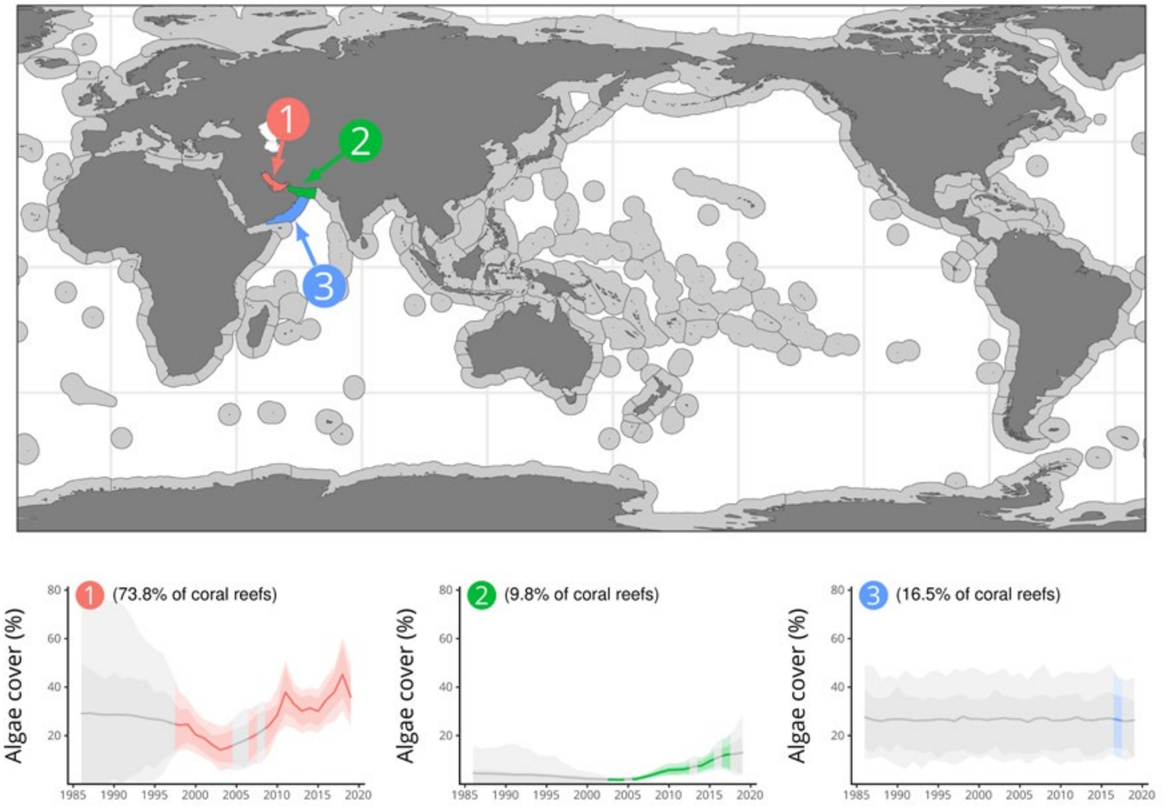


Figure 4.7. Estimated average cover of algae within each subregion comprising the ROPME Sea Area. The solid line represents the estimated mean and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods during which no field data were available. The proportion of all coral reefs in the ROPME Sea Area within each subregion is indicated by the % of coral reefs.

Box 2.

Ocean Acidification

Alexander A. Venn, Andreas Andersson, Sylvie Tambutté

The world's oceans have taken up more than a third of the CO_2 produced by human activities, altering seawater carbonate chemistry in a process termed 'Ocean Acidification'[1]. These chemical changes, involving decreases in seawater pH, carbonate ion concentration [CO_3^{2}] and the saturation state of calcium carbonate minerals (Ω), have been unequivocally documented at long-term monitoring stations since the 1980s[2].

Ocean acidification is predicted to continue unabated in coming decades, posing a major threat to coral reefs in both shallow tropical seas and deep cold water habitats[3]. Synthesis of multiple experimental studies shows that ocean acidification interacts with ocean warming to impair the capacity of most corals and many other marine calcifiers to deposit their $CaCO_3$ skeletons[4,5]. Corals may be particularly vulnerable in their juvenile stages[6], potentially diminishing the capacity of reefs to restock and recover after disturbances. In addition, ocean acidification has been shown to increase $CaCO_3$ sediment dissolution and bioerosion on coral reefs[7,8], which may weaken the three-dimensional framework and increase the vulnerability of coral reefs to physical and mechanical erosion.

Observations from reefs exposed to naturally low pH conditions show a cessation of reef growth at certain thresholds, and indicate that ocean acidification changes community composition and decreases reef biodiversity[9]. Field studies suggest that modern-day net reef calcification has decreased over the last few decades[10] and may already be significantly

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lower than during pre-industrial times[11]. Overall, the direct and indirect effects of ocean acidification could have far-reaching implications for the roles and functions of coral reef ecosystems such as the provision of habitat, protection from shoreline erosion, and provision of nutrition to human communities[12].

There are local actions that can ensure the health of coral reefs and maximize their resilience to ocean acidification and other environmental stressors[13]. Water quality management can assist in reducing the effects of global acidification at the reef scale as inputs of organic matter and eutrophication from anthropogenic sources can be important drivers of local acidification of reef waters exacerbating the long-term effects of rising atmospheric CO_2[14,15]. In addition, fisheries management can limit destructive practices that directly damage reef structure, which ultimately promotes reef growth[16]. Other actions focus on assisting the acclimatization and adaptation potential of coral reefs by using corals of different strains, species, environmental history and geographical origin to build reef resilience against climate change and ocean acidification[17]. All of these actions are potentially valuable, but relatively restricted to local scales. Protection of coral reefs from the threat of ocean acidification on global and long time scales ultimately depends on significant and rapid reductions in emissions of CO_2.

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Chapter 5.

Status and trends of coral reefs of the Western Indian Ocean region

Authors: David Obura, Mishal Gudka, Sean Porter, Rose Abae, Pierre-André Adam, Aly Bachiry Adouhouri, Céline Agathe-Miternique, Said Ahamada, Mmadi Ahamada, Soifa Ahmed, Nassir Amiyo, Paul Anstey, Kike Ballesteros, Jim Beets, Charlotte Berkström,, Hawthorne Beyer, Lionel Bigot, Chico Birrell, Emeline Bouvelle, Eric Brown, Christophe Cadet, Nicole Caudana, Bruce Cauvin, Pascale Chabanet, Julie Church, Jérôme Clotagatide, Isabel Marques da Silva, Juliette Damien, Emily Darling, Solomon Davida, Marine Dedeken, Willy Domitin, Sirilo Dulunaqio, Patrick Durville, Linda Eggertsen, Eylem Elma, Ben Fleay, Margaret Fox, Sarah Freed, Jan Freiwald, Alan Friedlander, Albert Gamoe, Rémi Garnier, Paul Giannasi, Whitney Goodell, Charlotte Gough, Nick Graham, Alison Green, Gabriel Grimsditch, Imogen Hamer, Dominique Hibon, Arielle Inès Hoamby, Ove Hoegh-Guldberg, Colin Jackson, Stacy Jupiter, Hassan Kalombo, Juliet Karisa, Siriya Karissa, Jillo Katello, Joseph Kilonzo, Ulrike Kloiber, John David Komakoma, Roberto Jean-Luc Komeno, Abigail Leadbeater, Mikaël Legras, Clément Lelabousse, Mariliana Leotta, Tom Leven, Jean Maharavo, Jairos Mahenge, Louise Malaise, Marine Malen-Francoise, Sangeeta Mangubhai, Zamil Mannfou, Lola Massé, Phanor Montoya Maya, Adfaon Mchinda, Nassur Ahamada Mdroimana, Modesta Medard, Mouchtadi Mmadi, Fiona Moejes, Misbahou Mohamed, Mohammed S. Mohammed, Djaffar Mouhidine, Rachad Mourid, Peter Musembi, Josephine Mutiso, Edward Mwamuye, Jelvas Mwaura, Odile Naim, Yashika Nand, January Ndagala, Jean-Benoit Nicet, Judith Nyunja, Pádraig O'Grady, Bernard Ogwoka, Jennifer Olbers, Mike Olendo, Lorna Parry, Marcos A.M. Pereira, Karine Pothin, Fouad Abdou Rabi, Volanirina Ramahery, Ravaka Ranaivoson, Manuel Gonzalez Rivero, David Rowat, Tévamie Rungassamy, Faissoil Ahmed Said, Michael H. Schleyer, Naomi Scholten, Chloe Shute, Erwan Sola, Emmanuel Tessier, Ali Makame Ussi, Maunoa Vesarikaro, Effy Vessaz, Jeanne Wagner, Marylène Wagner, Andra Whiteside, Julien Wickel, Shaun Wilson, Jacques van Wyk, Saleh A.S. Yahya.

1. Geographic information and context

Key numbers:

- Total area of coral reefs: 15,180 km^2
- Proportion of the world's coral reefs: 5.85%
- Number of countries with coral reefs: 10
- Number of Marine Ecoregions of the World (MEOW) ecoregions: 10

The Western Indian Ocean (WIO) region comprises almost 6% (about 15,180 km^2) of the total global area of coral reefs, and the region is a globally important hotspot for coral reef biodiversity. The WIO includes sovereign states along the eastern and southern African mainland (Somalia, Kenya, Tanzania, Mozambique, South Africa), island states (Mauritius, Madagascar, Comoros, Seychelles), as well as overseas territories (Reunion, France). The human population has grown considerably during the last century, with the states named now supporting ca. 220 million people, of which some 69 million live within 100 km of the coastline. Coral reef ecosystems underpin the economies of the countries in the region, particularly through the fisheries and tourism sectors, and provide livelihood opportunities and income for local communities estimated at US$ 8.4 billion annually. WIO coral reefs are estimated to have an asset value of U$ 18.1 billion[1].

The GCRMN WIO region is a distinct biogeographic province comprised of 10 marine ecoregions[2], which have been combined into five subregions for this analysis (Tab. 5.1, Fig. 5.1).

Table 5.1. The subregions comprising the Western Indian Ocean region, the area of reef they support, and the constituent Marine Ecoregions of the World (MEOW)[2].

Subregion	Reef Area (km^2)*	Proportion of Reef Area within the WIO Region (%)	Constituent Marine Ecoregions of the World
1	6,441	42.43	93: Central Somali Coast 94: Northern Monsoon Current Coast 95: East African Coral Coast
2	1,935	12.75	96: Seychelles
3	1,076	7.09	97: Cargados Carajos/Tromelin Island 98: Mascarene Islands
4	5,442	35.85	99: Southeast Madagascar 100: Western and Northern Madagascar
5	285	1.88	101: Bight of Sofala/Swamp Coast 102: Delagoa

*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

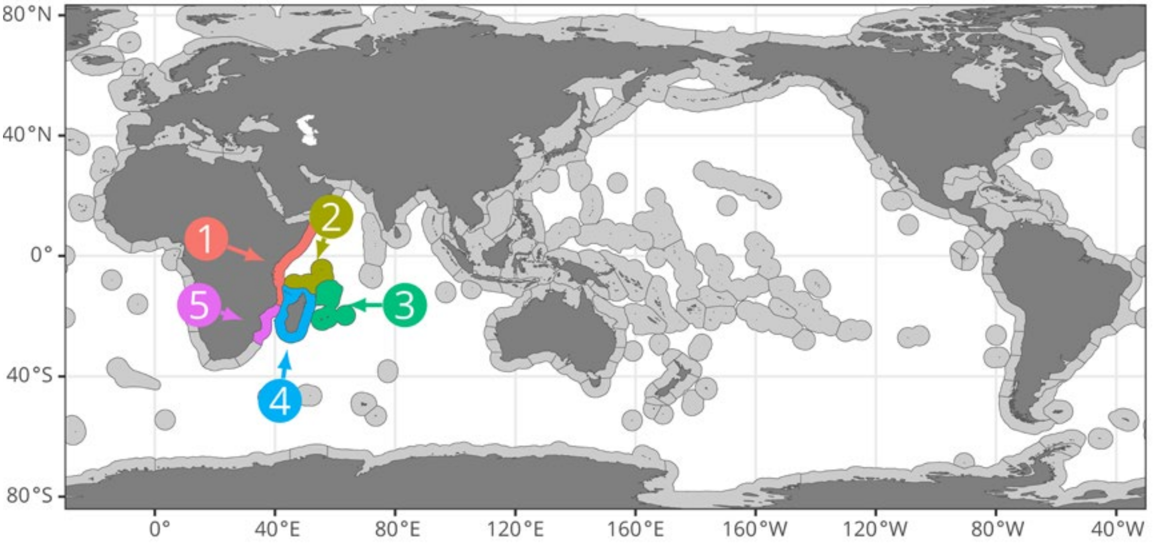

Figure 5.1. Map of each subregion comprising the Western Indian Ocean region. The number ascribed to each subregion corresponds with that in Table 5.1.

[1] Obura D, Gudka M, Rabi FA, et al (2017) Coral reef status report for the Western Indian Ocean. Global Coral Reef Monitoring Network (GCRMN)/International Coral Reef Initiative (ICRI)

[2] 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

2. Summary of data contributed to this report

Key numbers:

- Number of countries from which monitoring data were used: 9 (of 10)
- Number of sites: 915
- Number of observations: 25,570
- Longest time series: 26 years

General features:

Monitoring sites were spread across all five subregions, with a greater number of sites in Kenya, Tanzania and the Mascarene Islands (Tab. 5.2). Over half of all sites were surveyed in one-off assessments, while 6% of sites had been surveyed over periods exceeding 15 years (Fig. 5.2, Fig. 5.3A). The number of long-term monitoring sites was similar in subregions 1, 2, 3 and 4, but only one long term monitoring site occurred in subregion 5 (Tab. 5.2). The data contributed to this analysis spanned approximately 30 years, with the earliest data being collected in 1985 (Fig. 5.3B). Relatively few surveys were collected during the 1980s and 1990s, but a sharp increase in the number of surveys occurred in 1998-99 in response to the first global mass coral bleaching event, with this level of monitoring effort persisting until now (Fig. 5.3B). Line-intercept transects were the most frequently used survey method (27%), although point-intercept transects (21%) and photo-quadrats (7%) were also commonly used (Fig. 5.4). Unfortunately, the method used to conduct a large proportion (44%) of surveys was not described (Fig. 5.4). Data contributed for the WIO region and incorporated into the global dataset were provided at a summary level for each site, and additional data sources included from publications. Full details are reported in Obura et al. (2017).

Table 5.2. Summary statistics describing data contributed from the Western Indian Ocean 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.

Western Indian Ocean 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	25,570	2.64	915	7.52	64	10.88
1	5,893	0.61	378	3.11	16	2.72
2	882	0.09	172	1.41	21	3.57
3	3,330	0.34	39	0.32	14	2.38
4	13,790	1.42	243	2	12	2.04
5	1,675	0.17	83	0.68	1	0.17

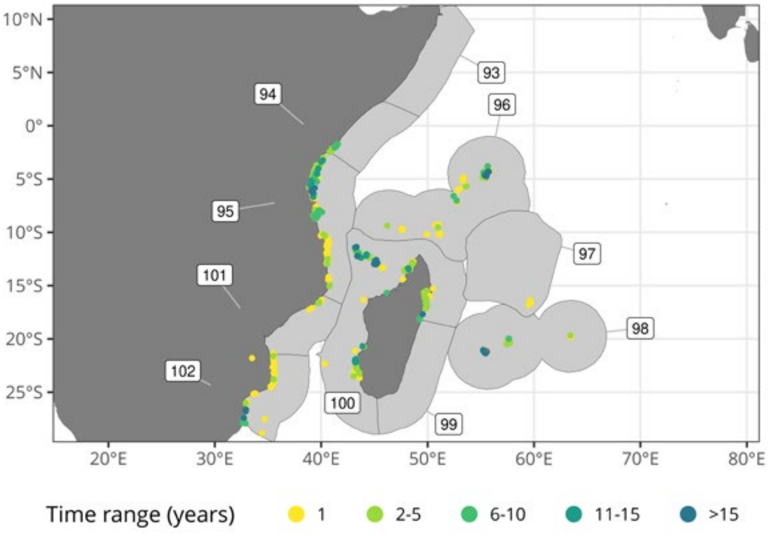

Figure 5.2. The distribution and duration of monitoring at sites across the Western Indian Ocean region. The colours of dots represent the time span between the first survey and the most recent survey at each site. Numbers refer to the MEOW ecoregions listed in Table 5.1.

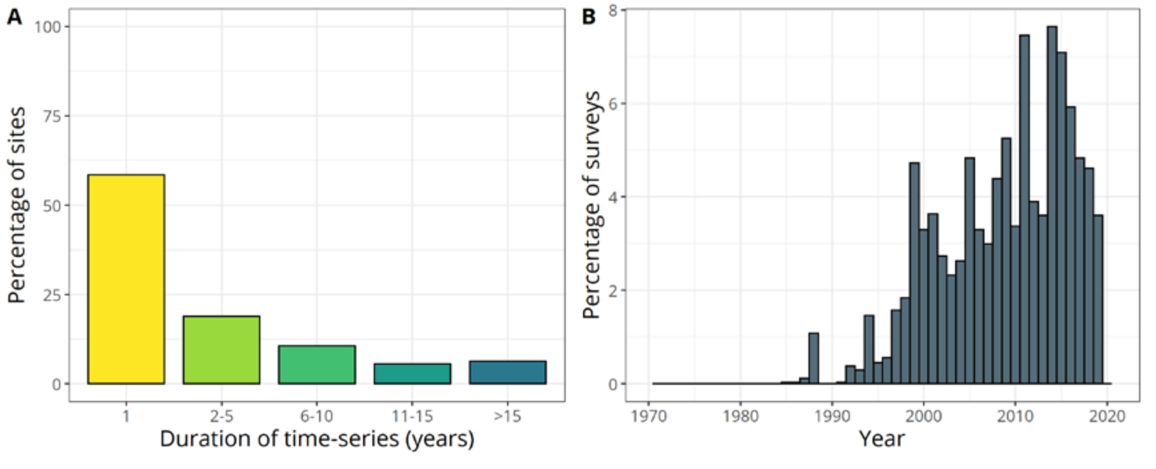

Figure 5.3. The proportion of sites in the Western Indian Ocean region within each category describing the time span between the first and most recent surveys (A), and the proportion of the total number of surveys conducted in each year (B). The total number of surveys was 2,642.

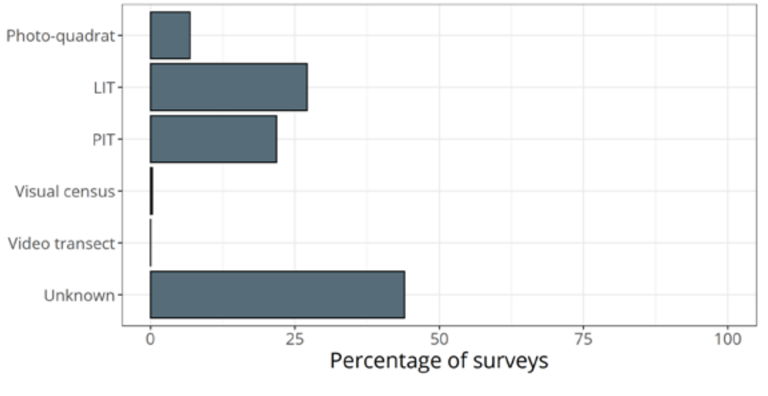

Figure 5.4. The proportion of the total number of surveys conducted in the Western Indian Ocean region using each survey method. PIT: Point Intercept Transect; LIT: Line Intercept Transect.

3. Status of coral reefs in the Western Indian Ocean region

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

Between 1985 and 1997, the estimated average cover of live hard coral was moderate and showed a gradual increasing trend from 26.2% to 28.8%, although there is considerable uncertainty in early estimates due to the paucity of data from this time (Fig. 5.5A). Following the El Niño and consequent global bleaching event of 1998, coral cover declined to 26.5% in 1999 and remained at similar levels until 2003. From 2004, reefs showed recovery, with an increasing trend in coral cover that peaked at 32.3% in 2012. In 2013 and 2017 two sharp declines were observed, reaching 29.4% in 2018-19. While data contributed to this analysis showed that current coral cover is higher than during the 1980s and 1990s, other published data not shared for this analysis show greater coral cover in the 1980s and 1990s (up to 40%), 45-70% coral mortality in 1998 and a failure to return to pre-existing levels[3,4].

The obvious declines in coral cover in this time-series clearly illustrate the impacts of the two major coral bleaching events (1998 and 2016) on the region (Fig. 5.5A). However, promisingly, it also highlights the capacity for reefs to recover after bleaching, if there is enough time between major disturbances. Other bleaching events have been documented in the region, but their signal in the regional dataset is obscured by different coral cover trajectories across the region.

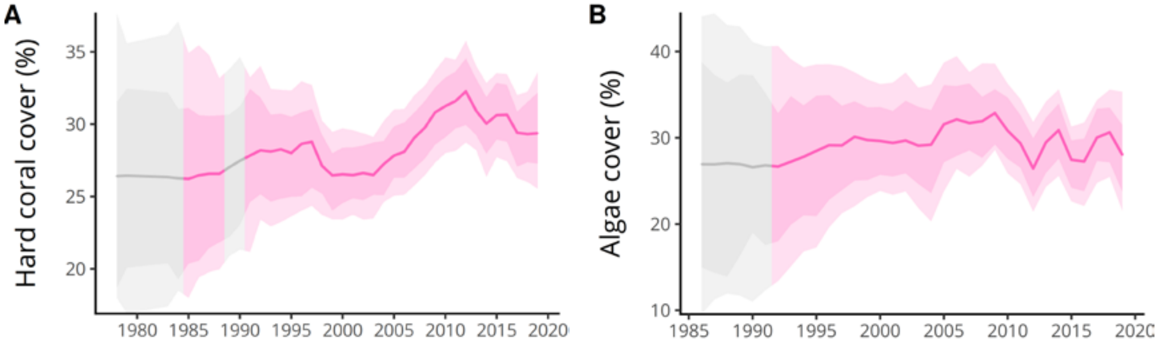

Figure 5.5. Estimated regional average cover of live hard coral (A) and algae (B) for the Western Indian Ocean region. The solid line represents the estimated mean and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods during which no field data were available.

Comparisons of average hard coral cover between three five-year periods (2005-09, 2010-14, 2015-19) indicated that despite the uncertainty in individual yearly estimates, there was a reasonable probability (~84%) that hard coral cover has declined between 2010-14 and 2015-19 (Tab. 5.3). On average, the decline in the absolute cover of live hard coral between 2010-14 and 2015-19 was 1.4%, which represents a loss of 6.2% of the coral in the region. However, the decline between 2010-14 and 2015-19 was offset by an equally likely (~88%) and similar (1.3%) increase in hard coral cover between 2005-09 and 2010-14 (Tab. 5.3), which resulted from an uninterrupted period of recovery from a low baseline. The net result is little change in average coral cover at a regional scale during the last 15 years. The paucity of data prior to 2005 (globally) prevents this analysis for prior years.

[3] McClanahan T, Muthiga N, Mangi S (2001) Coral and algal changes after the 1998 coral bleaching: interaction with reef management and herbivores on Kenyan reefs. Coral Reefs 19:380–391. https://doi.org/10.1007/s003380000133

[4] Ateweberhan M, McClanahan TR, Graham NAJ, Sheppard CRC (2011) Episodic heterogeneous decline and recovery of coral cover in the Indian Ocean. Coral Reefs 30:739–752. https://doi.org/10.1007/s00338-011-0775-x

Table 5.3. Probability and magnitude of mean absolute and relative change in the percent cover of live hard coral in the Western Indian Ocean 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	88	1.3	6.6
2010-14 - 2015-19	84	-1.4	-6.2
2005-09 - 2015-19	52	-0.1	-0.2

The trend in algal cover over the last 27 years is less clear than that of hard coral cover (Fig. 5.5B). While uncertainty in early estimates is substantial because fewer data were available and there were inconsistencies in monitoring and classifying different types of algae (including macroalgae and turf assemblages), the cover of algae on WIO reefs generally increased from 26.7% in 1992, when the first algal cover data were collected, to a peak of 32.9% in 2009 (Fig. 5.5B). However, after 2009, the cover of algae fluctuated considerably (Fig. 5.5B), yet there was no evidence (53%) of an overall change between 2010-14 and 2015-19 (Tab. 5.4). Similarly, there was little overall difference in the average cover of algae across the WIO region when comparing the earliest estimate (26.7% in 1992) with the most recent estimate (28% in 2019). The cover of algae has remained moderately high compared with other GCRMN regions that have similar hard coral cover to the WIO.

Table 5.4. Probability and magnitude of mean absolute and relative change in the percent cover of algae in the Western Indian Ocean 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	91	-3.2	-13.4
2010-14 - 2015-19	53	0.3	2.0
2005-09 - 2015-19	88	-2.9	-12.1

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

Within the WIO region, widespread decline in live coral cover following global bleaching events occurred in 1998 and 2016[5,6]. Less significant bleaching events occurred in 1983, 2005, 2007 and 2010, but with varying bleaching severity and mortality among subregions, and no impacts visible at the regional level. These periods of thermal stress have interacted strongly with fishing and various local environmental stressors[7,1], producing complex patterns of decline and partial recovery.

All but one of the long-term monitoring sites (i.e. sites monitored over periods > 15 years, Tab. 5.2) considered here were established since the 1998 coral bleaching event. As a consequence, none of these sites experienced a 20% decline in relative coral cover between the first and last survey, which made it difficult to examine patterns of disturbance and recovery and potential changes to the resilience of coral reefs in the region (see analysis in other regional chapters). The longest time series (1993-2014) was collected from a high latitude reef in South Africa which has not been impacted by the regional bleaching events and has shown an increase in hard coral over time[8]. The 2017 GCRMN WIO report found that coral cover declined in 1998 by 25%[1], corresponding to earlier findings[5,4]. Citizen science surveys conducted

[5] Goreau T, McClanahan T, Hayes R, Strong A (2000) Conservation of Coral Reefs after the 1998 Global Bleaching Event. Conservation Biology 14:5–15. https://doi.org/10.1046/j.1523-1739.2000.00011.x

[6] Gudka M, Obura D, Mbugua J, et al (2020) Participatory reporting of the 2016 bleaching event in the Western Indian Ocean. Coral Reefs 39:1–11. https://doi.org/10.1007/s00338-019-01851-3

[7] Maina J, Venus V, McClanahan T, Ateweberhan M (2008). Modelling susceptibility of coral reefs to environmental stress using remote sensing data and GIS models. Ecological Modelling 212:180-199. https://doi.org/10.1016/j.ecolmodel.2007.10.033.

[8] Porter SN, Schleyer MH (2017) Long-term dynamics of a high-latitude coral reef community at Sodwana Bay, South Africa. Coral Reefs 14. https://doi.org/10.1007/s00338-016-1531-z

after the coral bleaching event in 2016 found 20% of sites showed high to extreme mortality exceeding 50% of corals[6], which corresponded with the decline in coral cover from 30.7% in 2016 to 29.4% in 2017 shown here (Fig. 5.5A). It is likely that, had data from long term monitoring sites established prior to 1998 been contributed to these analyses, they would show a decline in coral reef health and failure to recover back to pre-1998 levels of hard coral cover, rather than the apparent improvement shown in Figure 5.5A.

- Changes in resilience of coral reefs within the Western Indian Ocean region

Recent studies on other pressures and key processes driving coral reef health in the WIO include studies of coral reproduction[9,10], coral disease[11], fish and fishery dynamics[12,13], genetic connectivity[14] and transport by currents[15,16]. These factors will influence the resilience and response of coral reefs to climate threats[17], particularly as several subregions within the WIO are projected to have among the most favourable climates for coral survival compared with other subregions here, and globally[18]. To date, some reefs have shown reasonable recovery in the 18-year period between the two major bleaching events in 1998 and 2016, notably in the Seychelles[19], which is evident in the upward trend between 2000 and 2010 in Figure 5.6. There is a clear signal of shifting coral community structure, with loss of susceptible coral species and loss of diversity[20], though some acclimation and/or adaptation of corals to warming may have occurred following multiple bleaching events, as shown in Mayotte[21]. This provides some hope that with adequate measures to minimise local threats, reefs in climatically favourable subregions may have a chance to keep up with warming conditions[22]. However, the increasing frequency and intensity of heat stress globally[23] and intensification of other pressures locally may overwhelm such capacities for adaptation unless strong actions are taken to reduce all threats.

[9] Mangubhai S (2009) Reproductive ecology of the scleractinian corals Echinopora gemmacea and Leptoria phrygia (Faviidae) on equatorial reefs in Kenya. Invertebrate Reproduction and Development 53:67–79

[10] Sola E, Marques da Silva I, Glassom D (2016) Reproductive synchrony in a diverse Acropora assemblage, Vamizi Island, Mozambique - Sola - 2016 - Marine Ecology - Wiley Online Library. Marine Ecology 37:1373–1385

[11] Séré MG, Chabanet P, Turquet J, et al (2015) Identification and prevalence of coral diseases on three Western Indian Ocean coral reefs. Diseases of Aquatic Organisms 114:249–261. https://doi.org/10.3354/dao02865

[12] Samoilys MA, Halford A, Osuka K (2019) Disentangling drivers of the abundance of coral reef fishes in the Western Indian Ocean. Ecol Evol 9:4149–4167. https://doi.org/10.1002/ece3.5044

[13] Le Manach F, Gough C, Harris A, et al (2012) Unreported fishing, hungry people and political turmoil the recipe for a food security crisis in Madagascar? Marine Policy 36:218–225. https://doi.org/10.1016/j.marpol.2011.05.007

[14] van der Ven RM, Flot J-F, Buitrago-López C, Kochzius M (2020) Population genetics of the brooding coral Seriatopora hystrix reveals patterns of strong genetic differentiation in the Western Indian Ocean. Heredity 1–15. https://doi.org/10.1038/s41437-020-00379-5

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[17] Obura D (2005). East Africa - Summary. In: Souter D, Linden O (eds) Coral reef Degradation in the Indian Ocean Status Report 2005. University of Kalmar, Sweden. pp 25-31.

[18] UNEP 2020. Projections of future coral bleaching conditions using IPCC CMIP6 models: climate policy implications, management applications, and Regional Seas summaries. United Nations Environment Programme, Nairobi, Kenya

[19] Theresine P, Mason-Parker C, Bijoux J (2017) Seychelles. In: Obura DO, Gudka M, et al. (eds) Status of coral reefs in the Western Indian Ocean. GCRMN/CORDIO, Mombasa, Kenya, pp 109–121

[20] McClanahan, T.R., Ateweberhan, M., Darling, E.S., Graham, N.A. and Muthiga, N.A., 2014. Biogeography and change among regional coral communities across the Western Indian Ocean. PloS one, 9(4), p.e93385

[21] Obura DO, Bigot L, Benzoni F (2018) Coral responses to a repeat bleaching event in Mayotte in 2010. PeerJ 6:e5305. https://doi.org/10.7717/peerj.5305

[22] McClanahan TR, Muthiga NA (2017) Environmental variability indicates a climate-adaptive center under threat in northern Mozambique coral reefs. Ecosphere 8:e01812. https://doi.org/10.1002/ecs2.1812

[23] Hughes T, Anderson K, Connolly S, Heron S, Kerry J, Lough J, Baird A, Baum J, Berumen M, Bridge T, Claar D, Eakin M, Gilmour J, Graham N, Harrison H, Hobbs J, Hoey A, Hoogenboom M, Lowe R, McCulloch M, Pandolphi J, Pratchett M, Schoepf V, Torda G, Wilson S (2018). Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. Science 359: 80-83. DOI: 10.1126/science.aan8048

4. Subregional trends in the cover of live hard coral and algae within the Western Indian Ocean region

Within the WIO region, the trends in hard coral cover among the five different subregions varied, indicating heterogeneity in exposure to disturbances which affected recovery patterns of reefs among subregions (Figs. 6 & 7). Subregions 2 (Seychelles) and 3 (Mascarene Islands) showed general and steady declines, while subregion 1 (N Mozambique - Somalia) showed temporal changes most consistent with the broader regional-scale trend. Subregion 5 (Delagoa) showed a steady and gradual increase in hard coral cover post-1998 and subregion 4 (Madagascar and Comoros) showed increased coral cover until 2012 and then subsequent decline.

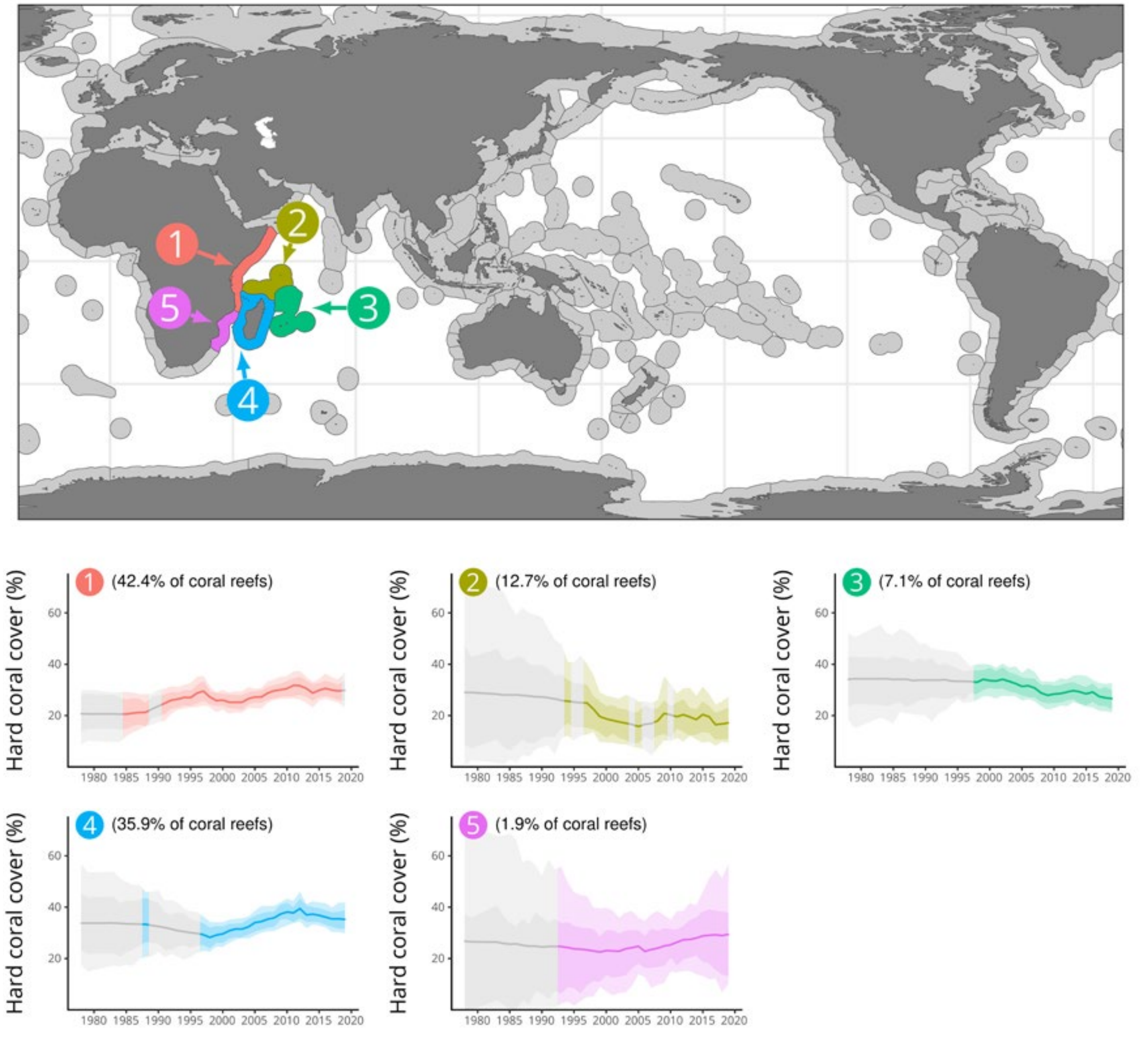

Figure 5.6. Estimated average cover of live hard coral within each subregion comprising the Western Indian Ocean region. The solid line represents the estimated mean and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods during which no field data were available. The proportion of all coral reefs in the Western Indian Ocean region within each subregion is indicated by the % of coral reefs.

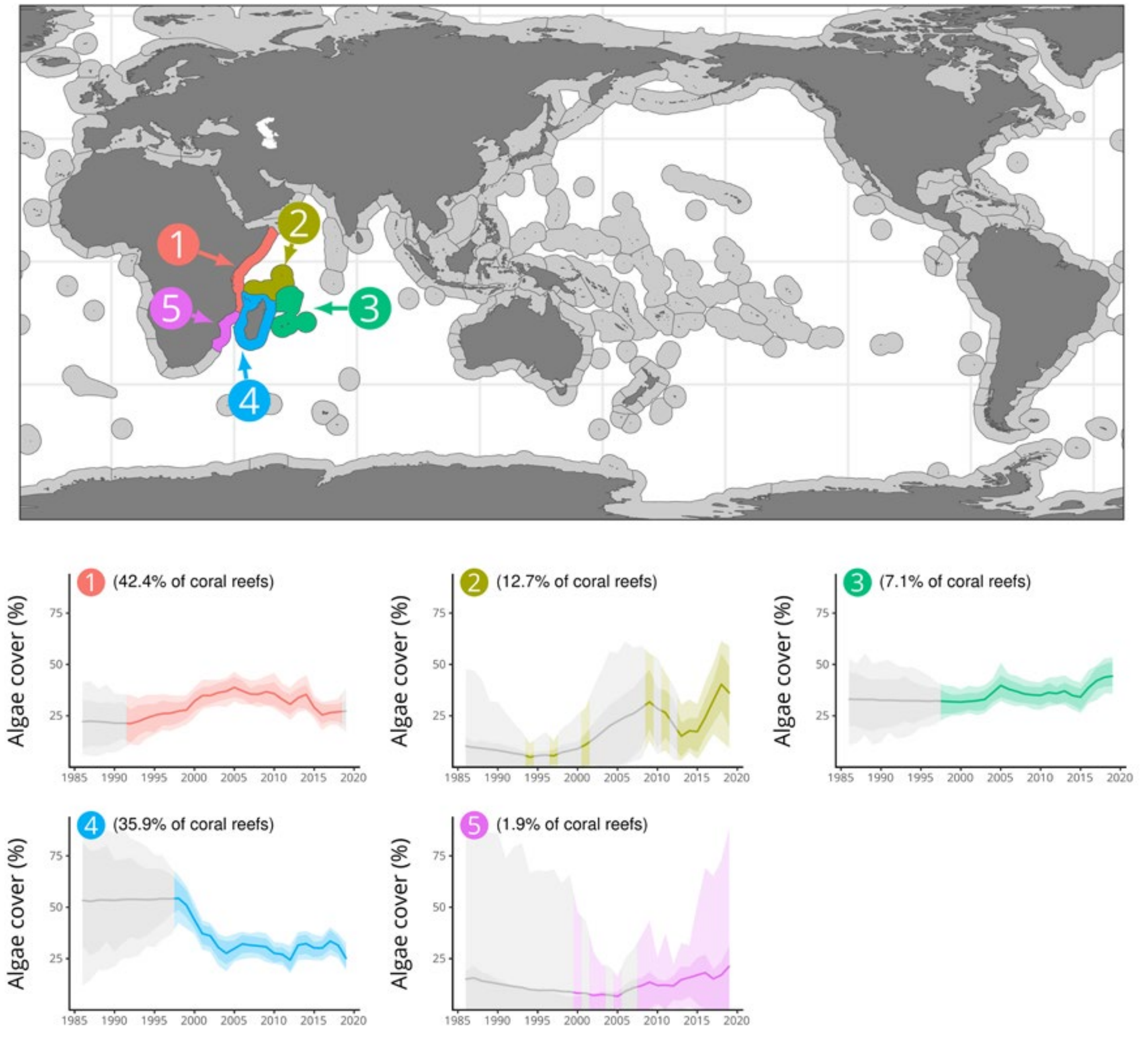

Figure 5.7. Estimated average cover of algae within each subregion comprising the Western Indian Ocean region. The solid line represents the estimated mean and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods during which no field data were available. The proportion of all coral reefs in the Western Indian Ocean region within each subregion is indicated by the % of coral reefs.

Box 3.

The IUCN Red Lists of corals and coral reef ecosystems

David Obura and Mishal Gudka, CORDIO East Africa and IUCN Coral Specialist Group

The IUCN Red List of species was established over 50 years ago[1], and assesses the risk of extinction of species. Reef-building corals were first assessed in 2008, when one-third of species were listed as Threatened with extinction[2]. The assessment is being updated through the IUCN Coral Specialist Group (https://www.coralspecialistgroup.org/), which is currently assessing over 950 species compared with 854 assessed in 2008. The assessment has used a new fully-online process for assessment due to cost constraints, and the COVID-19 pandemic. Close to 100 participants have been involved, using online tools to remotely compile the new species assessments. Results will be completed during 2022.

The Red List of ecosystems (RLE, www.iucnrle.org) was developed in the last decade, applying similar principles and approaches to assess the risk of collapse of ecosystems[3,4]. Coral reefs in the Western Indian Ocean (WIO) and in 11 nested ecoregions were assessed by comparing GCRMN data describing the current covers of hard coral and fleshy algae, parrotfish and grouper abundance with estimated baselines of 50 years ago. Projected SSTs generated by UNEP[5] were also used to assess risk of collapse in 50 years time. The results, in which 10 nested ecoregions were assessed as Vulnerable and Critically Endangered, indicated higher threat levels than those indicated in this report, primarily because of the inclusion of fish abundance data and direct assessment of the worsening climate threat in the next 50 years.

Both species and ecosystem Red Lists used data aggregated and reported through the GCRMN, delivering under goals 2 (informing policy and decisions) and 3 (promote greater utilization of coral reef data) of the GCRMN Implementation and Governance Plan. For the

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1 Mace GM, Collar NJ, Gaston KJ, Hilton Taylor C, Akçakaya HR, Leader Williams N, Milner Gulland EJ, Stuart SN (2008) Quantification of Extinction Risk: IUCN's System for Classifying Threatened Species. Conserv Biol 22:1424–1442

2 Carpenter KE, Abrar M, Aeby G, Aronson RB, Banks S, Bruckner A, Chiriboga A, Cortés J, Delbeek JC, Devantier L, Edgar GJ, Edwards AJ, Fenner D, Guzmán HM, Hoeksema BW, Hodgson G, Johan O, Licuanan WY, Livingstone SR, Lovell ER, Moore JA, Obura DO, Ochavillo D, Polidoro BA, Precht WF, Quibilan MC, Reboton C, Richards ZT, Rogers AD, Sanciangco J, Sheppard A, Sheppard C, Smith J, Stuart S, Turak E, Veron JEN, Wallace C, Weil E, Wood E (2008) One-third of reef-building corals face elevated extinction risk from climate change and local impacts. Science 321:560–563

3 Keith DA, Rodriguez JP, Rodriguez-Clark KM, Nicholson E, Aapala K, Alonso A, Asmussen M, Bachman S, Basset A, Barrow EG, Benson JS, Bishop MJ, Bonifacio R, Brooks TM, Burgman MA, Comer P, Comín FA, Essl F, Faber-Langendoen D, Fairweather PG, Holdaway RJ, JENNINGS M, Kingsford RT, Lester RE, Nally RM, McCarthy MA, Moat J, Oliveira-Miranda MA, Pisanu P, Poulin B, Regan TJ, Riecken U, Spalding MD, Zambrano-Martínez S (2013) Scientific Foundations for an IUCN Red List of Ecosystems. PLoS ONE 8:e62111

4 Rodriguez JP, Keith DA, Rodriguez-Clark KM, Murray NJ, Nicholson E, Regan TJ, Miller RM, Barrow EG, Bland LM, Boe K, Brooks TM, Oliveira-Miranda MA, Spalding M, Wit P (2015) A practical guide to the application of the IUCN Red List of Ecosystems criteria. Philos Trans R Soc B Biol Sci 370:20140003–20140003

5 van Hooidonk R, Maynard J, Tamelander J, Gove J, Ahmadia G, Raymundo L, Williams G, Heron SF, Planes S (2016) Local-scale projections of coral reef futures and implications of the Paris Agreement. Sci Rep 1–8

global Red List of coral species analysis, the regional and subregional results presented in this report provided estimates of percent decline in coral cover (for most species for a period of 30 years), which were then mapped against individual species distributions. For the regional RLE analysis, the GCRMN network in the WIO updated and re-analyzed its primary data, developing a method that can be replicated in all other GCRMN regions.

The Red List of species is the premier biodiversity metric informing global conventions and United Nations processes. Both CORDIO, through the IUCN RLE Partnership, and the International Coral Reef Initiative have promoted the use of the RLE as a primary indicator in the Global Biodiversity Framework of the Convention on Biological Diversity (CBD). The IUCN RLE Partnership aims to replicate the regional coral reef RLE across all GCRMN regions in the next 2-3 years, based on the global coverage of data in this GCRMN report. This will strengthen the provision of standardized biodiversity metrics in the CBD and other convention processes, including for the Sustainable Development Goals, providing more nuanced and policy-relevant indicators of the status of coral reefs globally, and their provision of services to people.

Chapter 6.

Status and trends of coral reefs of the South Asia region

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1. Geographic information and context

Key numbers:

- Total area of coral reefs: 10,949 km^2
- Proportion of the world's coral reefs: 4.22%
- Number of countries with coral reefs: 7
- Number of Marine Ecoregions of the World (MEOW) ecoregions: 6

Regional Context:

The South Asia region is one of the smaller GCRMN regions in terms of area of coral reefs, accounting for only 4.2 % (10,949 km^2) of global area of coral reefs. These reefs are distributed among six sovereign countries (Bangladesh, India, Maldives, Myanmar, Pakistan and Sri Lanka) and the Chagos Archipelago. Much of the reef area is concentrated along the more than 2,000 km long Lakshadweep-Maldives-Chagos Ridge, which accounts for around 75% of the total reef area in the region. Other significant reef systems are found in the Gulf of Mannar, and around parts of Sri Lanka. Reef development is poor along mainland India, Pakistan and Bangladesh.

Despite its relatively small area, South Asia contains a wide variety of coral reef habitats that vary significantly in reef structure, biodiversity, proximity to continents, and anthropogenic impacts. Many reefs face severe human pressure from overfishing and destructive fishing, coastal development, land-based agricultural runoff, and increased sedimentation. In general, reefs around atolls and offshore islands are subject to less anthropogenic pressure and remain in better condition than those around the South Asian mainland and coastal islands. Climate change has increased vulnerability of both coral reefs and coastal communities to the impacts of higher temperatures and extreme weather events. Sea level rise is a major threat to island communities in the Maldives and Lakshadweep Islands.

Coastal communities throughout the region are directly dependent on reef resources. Coral reefs play a significant role in national economies, and in supporting livelihoods through fisheries and tourism, particularly in Maldives, India and Sri Lanka. Marine fishery resources are the main source of protein for coastal communities, accounting for over 66% of protein consumed in Sri Lanka and over 90% in Lakshadweep and Maldives.

South Asia is characterized by a high population and high population densities. The total population of the region exceeds 1.8 billion, with densities ranging from 244 people per km^2 in Pakistan to more than 1,100 people per km^2 in Maldives and Bangladesh. Despite the small number of countries, there is significant cultural, social and economic variation among states and local communities. With the exception of Maldives, poverty is widespread, especially among coastal populations. Gross Domestic Product ranges from USD15,463 in Maldives to USD1,349 in Pakistan.

The South Asia region includes six distinct ecoregions under the Marine Ecoregions of the World (MEOW) classification[1] (Tab. 6.1, Fig. 6.1) grouped into four subregions. Data from each ecoregion is reported here but does not include data from Pakistan and Bangladesh.

Table 6.1. The subregions comprising the South Asia region, the area of reef they support, and the constituent Marine Ecoregions of the World (MEOW)[1].

Subregion	Reef Area (km^2)*	Proportion of Reef Area within the South Asia Region(%)	Constituent Marine Ecoregions of the World
1	2,731	24.94	106: Chagos
2	6,372	58.2	105: Maldives
3	1,032	9.43	103: Western India 104: South India and Sri Lanka
4	813	7.43	107: Eastern India 108: Northern Bay of Bengal

*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

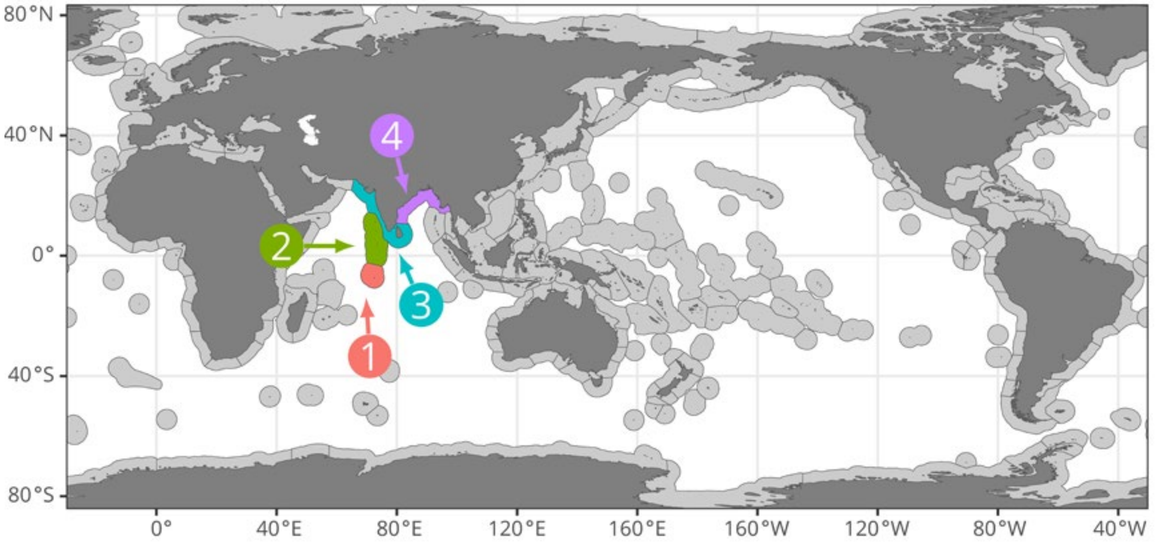

Figure 6.1. Map of each subregion comprising the South Asia region. The number ascribed to each subregion corresponds with that in Table 6.1.

[1] 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

2. Summary of data contributed to this report

Key numbers:

- Number of countries from which monitoring data were used: 5 (of 7)
- Number of sites: 389
- Number of observations: 48,891
- Longest time series: 20 years

General features:

The status and trends of coral reefs in South Asia are presented below and are based on almost 49,000 observations from 389 sites distributed across five countries and territories within the South Asia region (Tab. 6.2). These data were collected primarily using transect-based methods (Fig. 6.4).

Coral reef research is relatively new in South Asia with significant constraints in capacity. This is reflected in the limited long-term monitoring data available for the region (Fig. 6.2, Fig. 6.3A). The distribution of monitoring effort over time has primarily been in response to major disturbance events. Only a small amount of monitoring data collected prior to 1998 were contributed to this analysis, with the earliest data collected from the Chagos Archipelago in 1978 (Fig. 6.3B). Widespread monitoring began in response to the 1998 global coral bleaching event, which had a significant impact on coral reefs in the region. Additional increases in the number of surveys occurred around 2005 related to the Indian Ocean tsunami. Survey intensity has continued to increase with a peak around the 2016 mass bleaching event (Fig. 6.3B). The greatest number of surveys were conducted in subregion 3 (Western India, South India, and Sri Lanka) followed by subregions 1 (Chagos) and 2 (Maldives). Few data were reported for subregion 4 (Eastern India, Northern Bay of Bengal).

Long-term monitoring data (>15 years between the first survey and the most recent survey) were reported from only nine sites, all of which were located in the Maldives (Tab. 6.2, Fig. 6.2 and 3A). The lack of long-term monitoring data is a major shortcoming in the region. More than 60% of the sites included in this analysis were surveyed in only one year (Fig. 6.3A). The South Asia region has also suffered from the lack of a coordinated data management program both nationally and regionally, resulting in poor reporting of data. The volume of data contributed to this analysis from the region may significantly under-represent the data that have been collected within the region historically.

Table 6.2. **Summary statistics describing data contributed from the South Asia 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.**

South Asia 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	48,891	5.04	389	3.2	9	1.53
1	5,920	0.61	160	1.32	0	0
2	5,561	0.57	136	1.12	9	1.53
3	37,315	3.85	89	0.73	0	0
4	95	0.01	4	0.03	0	0

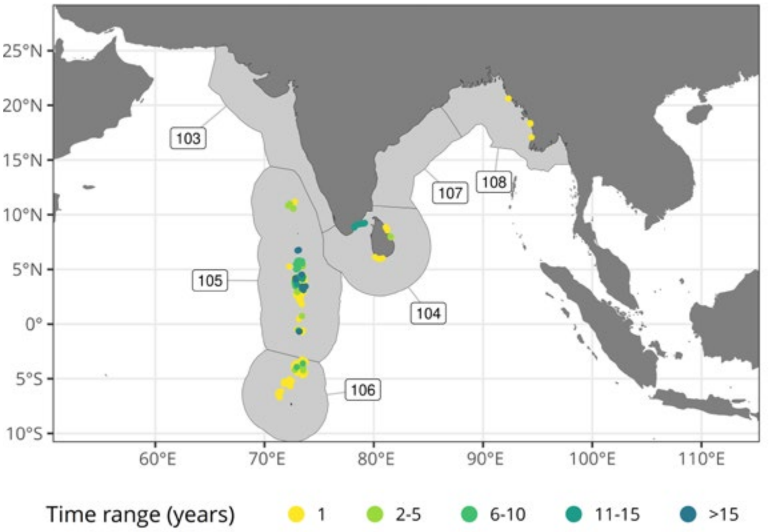

Figure 6.2. The distribution and duration of monitoring at sites across the South Asia region. The colours of dots represent the time span between the first survey and the most recent survey at each site. Numbers refer to the MEOW ecoregions listed in Table 6.1.

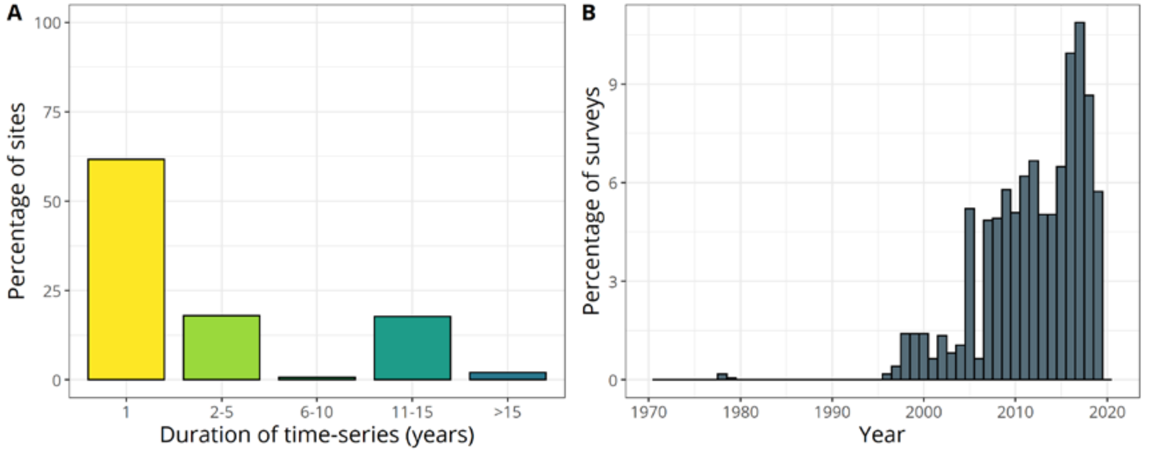

Figure 6.3. The proportion of sites in the South Asia region within each category describing the time span between the first and most recent surveys (A), and the proportion of the total number of surveys conducted in each year (B).The total number of surveys is 1,635.

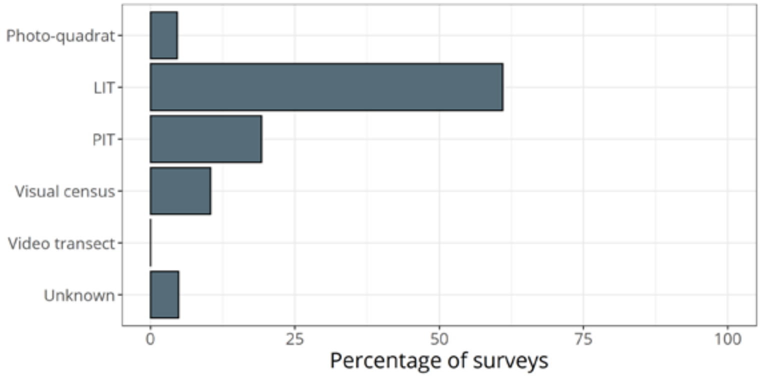

Figure 6.4. The proportion of the total number of surveys conducted in the South Asia region using each survey method. PIT: Point Intercept Transect; LIT: Line Intercept Transect.

3. Status of coral reefs in the South Asia region

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

Overall, there was a declining trend in live hard coral cover in the region, most significantly as a result of El Niño-related coral bleaching events in 1998 and 2016 (Fig. 6.5A). Although reefs showed significant recovery between 1998 and 2010, extensive bleaching-induced mortality in 2016 and localized coral bleaching events from 2017-2019 have continued to cause declines in live hard coral cover. Although there was considerable uncertainty owing to the scarcity of data, the estimated average cover of live hard coral prior to 1998 was relatively high and stable, ranging between 38.0% and 46.4% (Fig. 6.5A). However, about 70% of the living hard coral was lost as a result of extensive coral mortality caused by the 1998 coral bleaching event, reducing the average live hard coral cover in the region to around 11.8% by 1999 (Fig. 6.5A). Some recovery was observed over the next decade as live hard coral cover increased to 39.4% by 2010 and remained relatively stable until 2016. The mass coral bleaching event in 2016 had severe impacts on reefs in the region, killing more than 42% of the living hard coral and reducing the cover of live coral to 26.3%.

The average cover of algae remained relatively low and stable at about 10% until 2008, after which there was a progressive increase to 14% by 2018 (Fig. 6.5B). While a decline in live coral cover, such as that seen during the 1998 coral bleaching event, would be expected to result in an increase in algal cover, this is not evident in the early data, although short term increases in algal cover immediately after major bleaching events may be overridden by the noticeable recovery of reefs between 1998 and 2010 (Fig. 6.5A). However, since 2015, there was an upward trend in algal cover, which corresponds with a decline in live coral cover due to coral bleaching. The increased monitoring and reporting of data was a likely contributor to this trend being more visible.

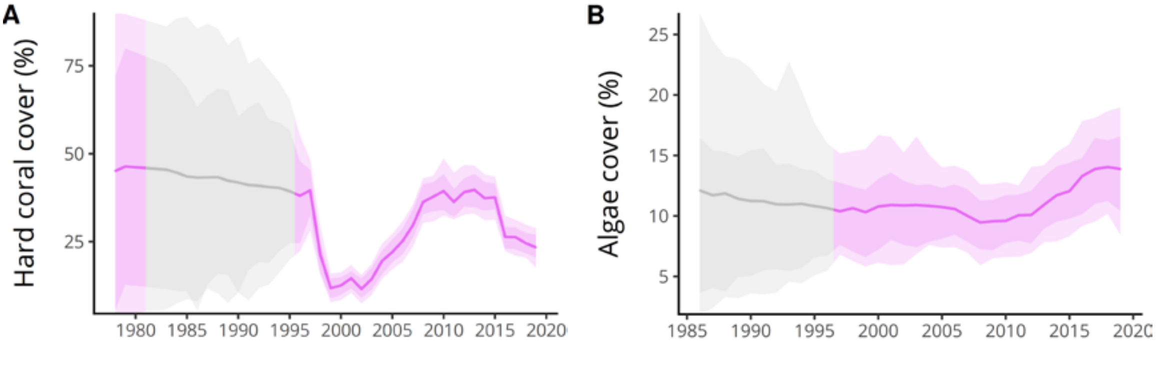

Figure 6.5. Estimated regional average cover of live hard coral (A) and algae (B) for the South Asia region. The solid line represents the estimated mean and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods during which no field data were available.

When comparing the average live hard coral cover between five-year periods (2005-09, 2010-14, 2015-19), there was strong evidence (94.3%) that coral cover increased between 2005-09 and 2010-14 (4.3% on average) as reefs continued to recover from the 1998 mass coral bleaching event, but that these gains were erased by a decline in average live hard coral cover between 2010-14 and 2015-19 (Tab. 6.3). As a result, the hard coral cover declined between 2005-09 and 2015-19 by an average of 8.7%, which represented an overall loss of 34% of the living coral from the region during this period.

Table 6.3. Probability and magnitude of mean absolute and relative change in the percent cover of live hard coral in the South Asia 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	94	4.3	21.2
2010-14 - 2015-19	100	-12.9	-45.2
2005-09 - 2015-19	100	-8.7	-34.0

Similar comparison of the average cover of algae between five-year periods (2005-09, 2010-14, 2015-29) showed weak evidence (79% probability) of an increase in algal cover between 2005-09 and 2010-14, but much stronger evidence (95% probability) of a larger increase between 2010-14 and 2015-19 (Tab. 6.4). These results strongly indicate (99% probability) that there was more algae on South Asian coral reefs in 2015-19 compared with 2005-09. On average, there was 51% more algae, with almost two-thirds of this increase occurring between 2010-14 and 2015-19 (Tab. 6.4).

Table 6.4. Probability and magnitude of mean absolute and relative change in the percent cover of algae in the South Asia 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	79	1.1	14.8
2010-14 - 2015-19	95	2.8	32.8
2005-09 - 2015-19	99	3.9	50.7

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

Coral bleaching has been the major driver of coral loss in the South Asia region. The first major coral bleaching event occurred in 1998 resulting in extensive loss of live coral cover across the region (Fig. 6.5A). Some shallow reefs in Maldives, Lakshadweep and Sri Lanka suffered coral mortality exceeding 90%, with *Acropora* and *Echinopora* being the most susceptible coral genera. Smaller-scale coral bleaching was observed in 2010 (Fig. 6.5A) that had more localized impacts with significantly less coral mortality compared to the 1998 bleaching event. A second major bleaching event occurred in 2016 (Fig. 6.5A), although the coral mortality associated with the 2016 event was less than that in 1998, partly because there was less coral, but also because there were more bleaching resistant species within the coral community. A smaller bleaching event in 2019 resulted in localized yet severe coral mortality in some areas, particularly along parts of the east coast of Sri Lanka.

In addition, coastal fringing reefs along mainland India, Bangladesh, Pakistan, and Sri Lanka continue to suffer from anthropogenic stresses such as overfishing, destructive fishing, coastal development, pollution and sedimentation. Some reefs have shown little to no recovery since the 1998 coral bleaching event due to chronic stress, while more healthy reefs continue to experience loss of coral cover, fish biomass and diversity as a result of human impacts. Reefs around offshore island groups such as the atolls along the Lakshadweep-Maldives-Chagos Ridge have significantly less anthropogenic pressure. Many of these reefs have restricted access or have been declared marine protected areas (MPAs), with the largest being the Chagos MPA. Coral bleaching remains the primary threat to these reefs.

- Changes in resilience of coral reefs within the GCRMN South Asia region

Repetitive coral bleaching events and natural disturbances may have changed long-term disturbance-recovery patterns to the point that many reefs are not recovering completely from one disturbance before experiencing another. Smaller, localized bleaching events may have more significant impacts if they follow a larger bleaching event as a result of a short window of recovery for reefs. The problem is more acute on coastal reefs that are subjected to high levels of anthropogenic stress, and where long-term pressure has decreased resilience to natural and climate-related disturbances. Reef recovery is highly variable with better recovery on atolls along the Lakshadweep-Maldives-Chagos Ridge. Nearshore reefs that experience higher rates of overfishing and pollution have shown low to no recovery since the 1998 coral bleaching event. In Sri Lanka, the erosion of reef structures from waves associated with seasonal storms has led to the loss of stable hard substrate, inhibiting recruitment and reef recovery. As a result, there has been a continual decline in hard coral cover across many sites. Of the 30 sampling units in the South Asia region 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%, 28 (93%) had not recovered to at least 90% of their pre-disturbance hard coral cover (Tab. 6.5). Among these sampling units, the average decline in hard coral cover between the first survey and the most recent survey was almost 20.8%, representing a loss of 55.1% of the existing hard coral. The average maximum absolute decline in hard coral cover was 27.2%, representing a loss of 65.6% of the hard coral within these sampling units (Tab. 6.5).

Table 6.5. 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
30	28	93.33	27.22	65.62	20.80	55.06

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

There was significant variation in the trends in live hard coral cover in different subregions within the South Asia region (Fig. 6.6). Trends in subregions 1 (Chagos) and 2 (Maldives) were primarily responsible for the overall regional trend in South Asia on account of supporting more than 80% of the coral reefs in the region. These subregions showed a significant decrease in live coral cover after the 1998 coral bleaching event, followed by a period of recovery until 2015 before another decline in live coral cover after the 2016 coral bleaching event. The estimated live coral cover for subregion 3 (Western India, South India, and Sri Lanka) showed a gradual decline from 2000 to 2015, and a significant decline following the 2016 coral bleaching event (Fig. 6.6). Unfortunately, the analysis does not capture the impact of the 1998 coral bleaching event and any subsequent reef recovery because the earliest data contributed from this subregion were collected in 2003. However, previous GCRMN reports and published literature indicate that the subregion exhibited similar patterns to subregions 1 and 2, albeit with less recovery in some reef areas. Data from subregion 4 (Eastern India and the Northern Bay of Bengal) were provided for only three years making it difficult to accurately describe the trends in live hard coral cover on coral reefs in this subregion. However, analysis of those few data suggested relatively stable live hard coral cover, without evidence of significant mortality from mass coral bleaching events.

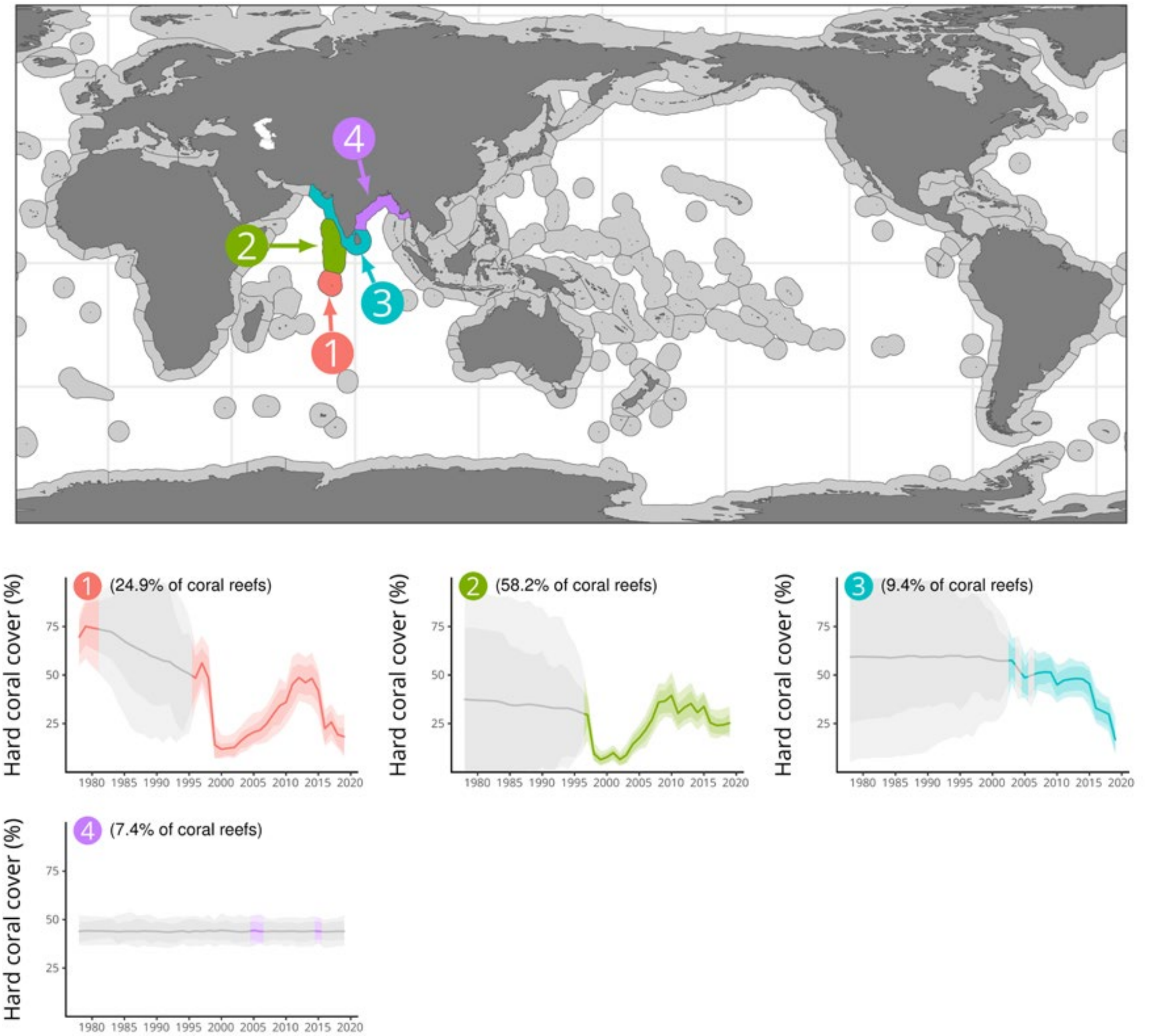

Figure 6.6. Estimated average cover of live hard coral within each subregion comprising the South Asia region. The solid line represents the estimated mean and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods during which no field data were available. The proportion of all coral reefs in the South Asia region within each subregion is indicated by the % of coral reefs.

Similar to hard coral cover, trends in the percent cover of algae varied among different subregions (Fig. 6.7). For subregions 1 and 2, the increase in the average algal cover corresponds to the decrease in live hard coral cover following the 1998 and 2016 coral bleaching events. Subregion 3 showed an increase in algal cover by nearly 50% after the 2016 coral bleaching event but, owing to a lack of data, it was not possible to assess changes in algal cover following the 1998 coral bleaching event. The data contributed from subregion 4 suggest a substantial increase in average cover of algae. While it was difficult to determine the reason for this increase because data were reported from only four sites in three years, it is unlikely to have been caused by a mass coral mortality event as overall live hard coral cover has remained stable through the same period.

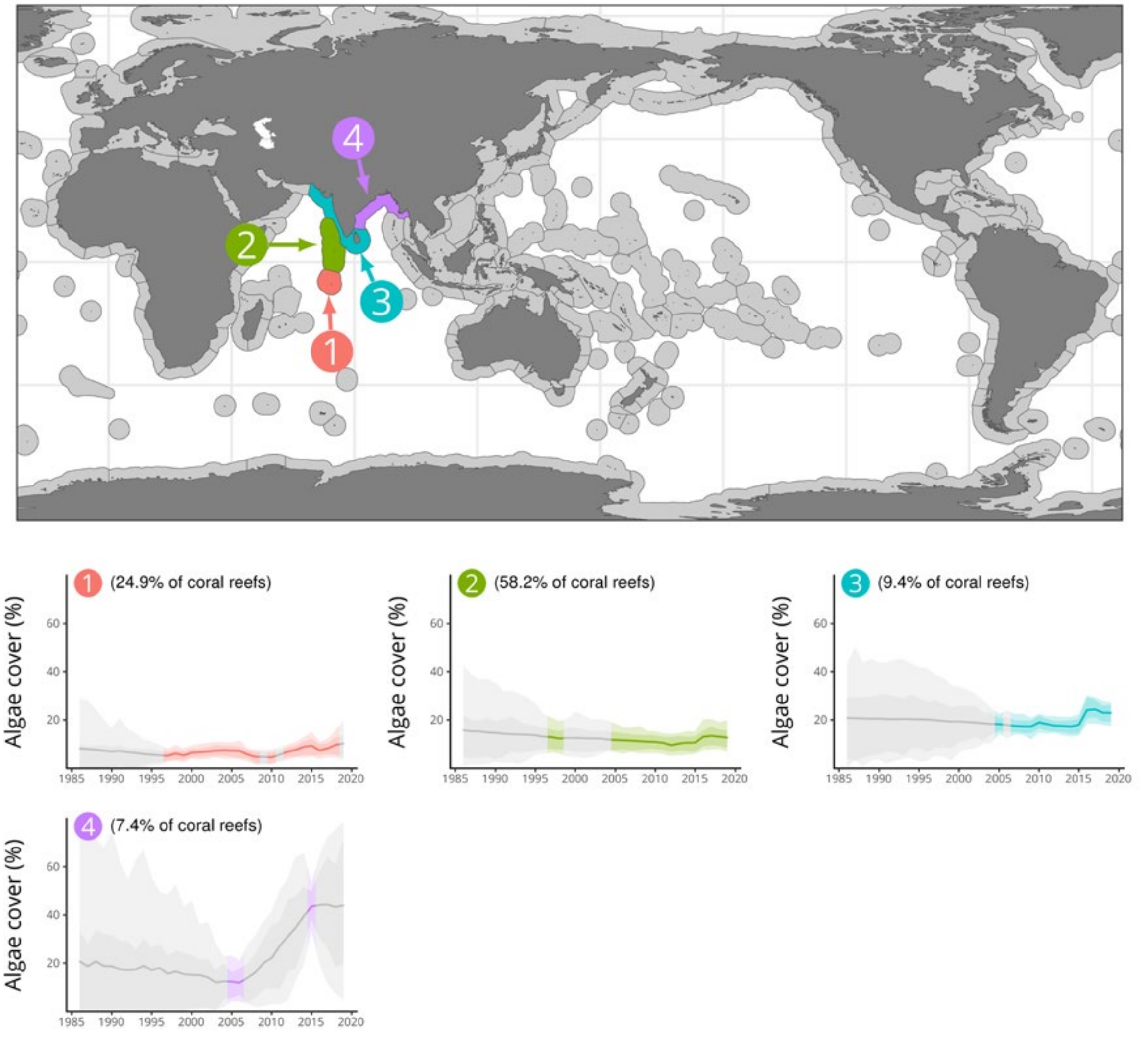

Figure 6.7. Estimated average cover of algae within each subregion comprising the South Asia region. The solid line represents the estimated mean and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods during which no field data were available. The proportion of all coral reefs in the South Asia region within each subregion is indicated by the % of coral reefs.

Analysis of both live hard coral and algae within subregions highlights the issues associated with limited data from the South Asia region. Most of the data reported are from subregions 1 and 2, with very few data contributed from subregions 3 and 4. A more coordinated approach to data management including regular reporting is required to identify long-term trends and better predict resilience of coral reefs to the impacts of climate change including coral bleaching.

Chapter 7.

Status and trends of coral reefs of the East Asian Seas region

Collaborators: Emily Yong, David J.W. Lane, Desimawati Hj Metali, Matthew Glue, Marianne Teoh, Ouk Vibol, Giyanto, Tri Aryono Hadi, Muhammad Abrar, Rikoh Manogar Siringoringo, Ni Wayan Purnama Sari, Suharsono, Augy Syahailatuha, Affendi Yang Amri, Zarinah Waheed, Zau Lunn, Carli, F. M., Carroll, B. P., Salai Mon Nyi Nyi Lin, Soe Tint Aung, Porfirio M. Aliño, Cleto L. Nañola, Jr, Maria Vanessa Baria-Rodriguez, Michael Atrigenio, Vincent Hilomen, Laura David, Wilfredo Y. Licuanan, Tai Chong Toh, Danwei Huang, Yong Kit Samuel Chan, Chin Soon Lionel Ng, Karenne Tun, Loke Ming Chou, Thamasak Yeemin, Makamas Sutthacheep, Nguyen Van Long, Vo Si Tuan, Huang Hui, Jiansheng Lian, Put Ang, Jr., Apple Chui Pui Yi, Chao-Yang Kuo, Ming-Jay Ho, Chien-Hsun Chen, Hernyi Justin Hsieh, Ming-Shiou Jeng, Tung-Yun Fan, Chang-Feng Dai, Keryea Soong, Chaoluan Allen Chen, Tadashi Kimura, Takeshi Nakamura, Heung-sik Park, Sun Wook Kim, Abigail Alling, Hawthorne Beyer, Andy Cameron, Kitty Currier, Thomas Dallison, Orla Doherty, Henry Duffy, Dan Exton, Jan Freiwald, Manuel Gonzalez Rivero, Ove Hoegh-Guldberg, Carol Milner, Lorna Parry, Daniel Steadman, Chelsea Waters.

1. Geographic information and context

Key numbers:

- Total area of coral reefs: 78,272 km^2
- Proportion of the world's coral reefs: 30.15%
- Number of countries with coral reefs: 14
- Number of Marine Ecoregions of the World (MEOW) ecoregions: 24

Regional Context:

The coral reefs of the East Asian Seas (EAS) region, which comprises the countries of Northeast and Southeast Asia, are distributed over a wide geographic area within the Indian and Pacific Oceans. The region supports the largest area of coral reefs of all the GCRMN regions, accounting for over 30% (78,272 km^2) of the world's total. The region is also home to two of the world's largest archipelagic states—Indonesia with more than 17,000 islands and the Philippines with over 7,000 islands.

Overlapping with the Coral Triangle, an area recognized as the global epicentre of marine biodiversity, the EAS region boasts the world's greatest diversity of reef-building corals with nearly 600 species, six of the world's seven marine turtle species and more than 2,000 reef fish species. It also includes some of the most important spawning grounds for commercially important tuna species, supporting the largest tuna fisheries in the world.

There are significant differences in the magnitude of direct (e.g. protein consumption) and indirect (e.g. seafood exports) dependence on coral reef resources within the EAS region, with coastal populations in many Southeast Asian countries being considerably more dependent than Northeast Asian countries. This has led to significant impacts on the marine environment in the region, driven by overfishing and expansion of coastal aquaculture, and exacerbated by land use changes that contribute to siltation and eutrophication to the marine environment. Adding to these impacts is the emerging threat posed by marine litter, particularly marine plastics and microplastics, with the region estimated to generate as much as half the world's marine plastic litter. Climate-related impacts on the marine environment are also increasingly recognized as a major concern, particularly for archipelagic states with large coastline to land area ratios where impacts can potentially be magnified across a wider area.

Table 7.1. The subregions comprising the East Asian Seas region, the area of reef they support, and the constituent Marine Ecoregions of the World (MEOW)

Subregion	Reef Area (km^2)*	Proportion of Total Reef Area Within the East Asia Region(%)	Constituent Marine Ecoregions of the World
1	32,567	41.6	126: Palawan/North Borneo 127: Eastern Philippines 128: Sulawesi Sea/Makassar Strait
2	20,568	26.3	129: Halmahera 130: Papua 131: Banda Sea 133: Northeast Sulawesi 138: Gulf of Papua 139: Arafura Sea
3	6,497	8.3	115: Gulf of Thailand 116: Southern Vietnam 117: Sunda Shelf/Java Sea 118: Malacca Strait
4	4,279	5.5	119: Southern Java 132: Lesser Sunda
5	6,192	7.9	109: Andaman and Nicobar Islands 110: Andaman Sea Coral Coast 111: Western Sumatra
6	5,600	7.2	112: Gulf of Tonkin 113: Southern China 114: South China Sea Oceanic Islands
7	2,569	3.3	051: Central Kuroshio Current 052: East China Sea 121: South Kuroshio

*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

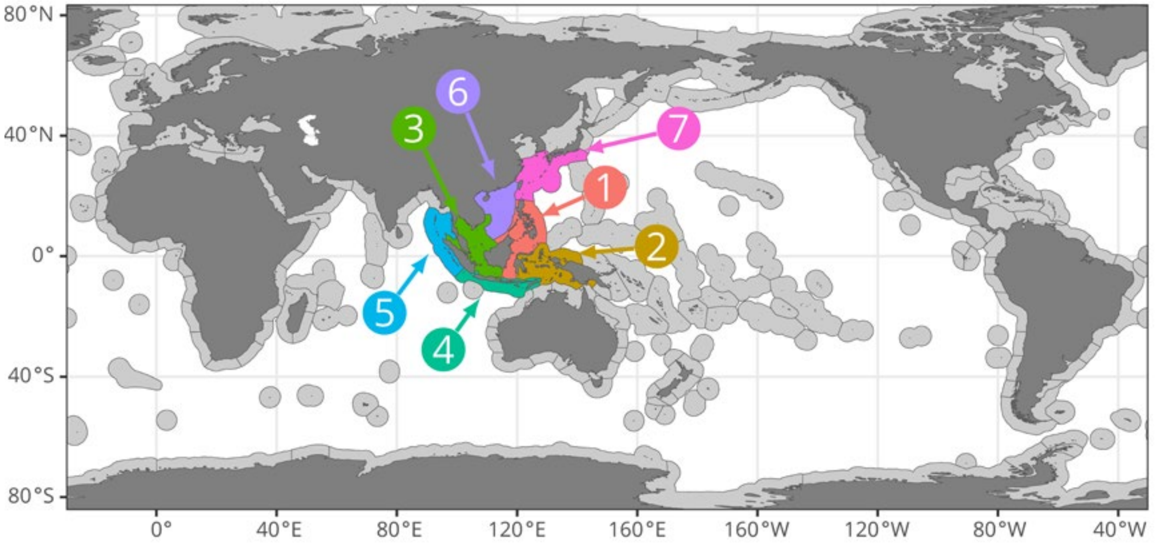

Figure 7.1. Map of each subregion comprising the East Asian Seas region. The number ascribed to each subregion corresponds with that in Table 7.1.

2. Summary of data contributed to this report

Key numbers:

- Number of countries from which monitoring data were used: 11 (of 14)
- Number of sites: 2,570
- Number of observations: 80,382
- Longest time series: 26 years

General features:

More than 80,000 records collected across 2,570 sites were contributed from the EAS region, representing 8.3% of the overall global dataset (Tab. 7.2). The greatest proportion of these records were collected within subregions 2 (28%) and 3 (30%). Fewer observations were collected from subregions 1, 4, 5, 6 and 7 (Tab. 7.2). The vast majority of sites (82%) have been surveyed only once (Fig. 7.2, Fig. 7.3A). Slightly more than 10% of sites have records that were collected over periods exceeding a decade, with about 4% of these exceeding 15 years (Fig. 7.2, Fig. 7.3A). Across the entire EAS region there were 158 long-term monitoring sites (>15 years), of which 142 (90%) occurred within subregion 7. A small number of long-term monitoring sites were monitored in subregions 2 (6) and 3 (10). Subregions 1, 4, 5 and 6 did not have any sites from which long-term monitoring data were collected (Tab. 7.1, Fig. 7.3A). A range of methods were used to collect the data, with visual census and point intercept transects being the most common (Fig. 7.4).

Table 7.2. Summary statistics describing data contributed from the East Asian Seas 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.

East Asian Seas 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	80,382	8.29	2,570	21.13	158	26.87
1	11,235	1.16	171	1.41	0	0
2	22,445	2.31	503	4.14	6	1.02
3	24,264	2.5	635	5.22	10	1.7
4	5,964	0.62	310	2.55	0	0
5	8,020	0.83	319	2.62	0	0
6	1,109	0.11	19	0.16	0	0
7	7,345	0.76	613	5.04	142	24.15

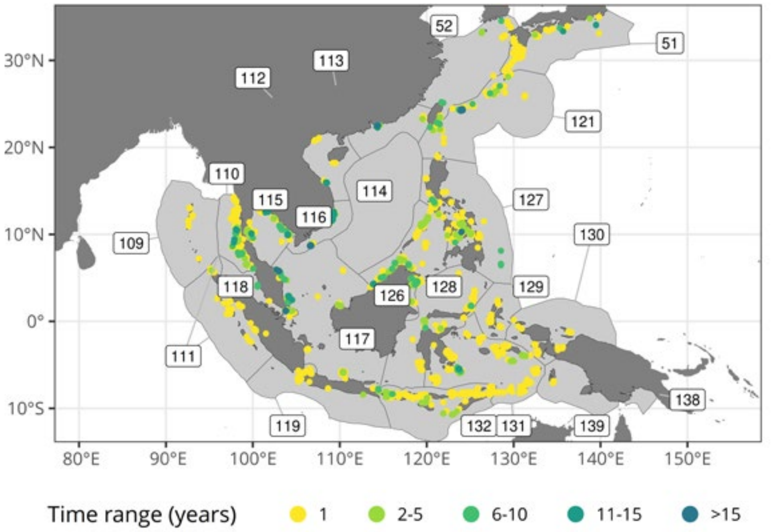

Figure 7.2. The distribution and duration of monitoring at sites across the East Asian Seas region. The colours of dots represent the time span between the first survey and the most recent survey at each site. Numbers refer to the MEOW ecoregions listed in Table 7.1.

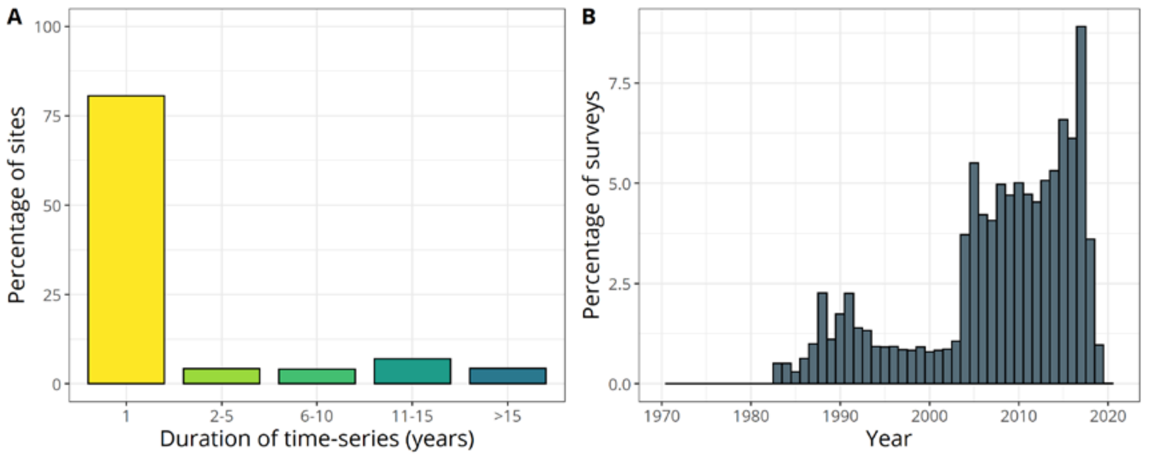

Figure 7.3. The proportion of sites in the East Asian Seas region within each category describing the time span between the first and most recent surveys (A), and the proportion of the total number of surveys conducted in each year (B). The total number of surveys was 9,785.

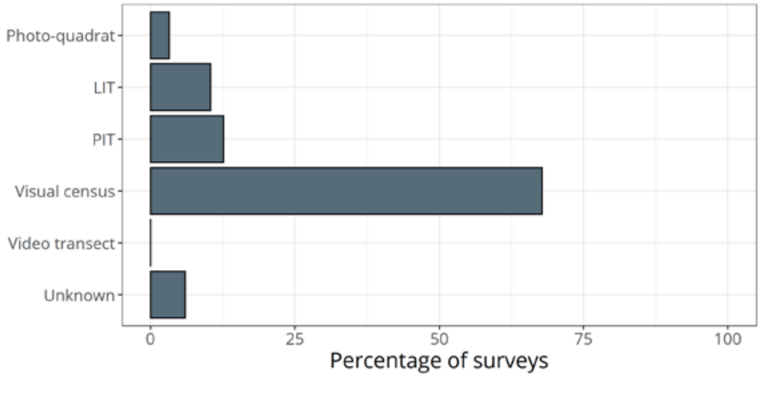

Figure 7.4. The proportion of the total number of surveys conducted in the East Asian Seas region using each survey method. PIT: Point Intercept Transect; LIT: Line Intercept Transect.

3. Status of coral reefs in the East Asian Seas region

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

The estimated average live hard coral cover in the EAS region in 2019 (36.8%) was slightly greater than in 1983 (32.8%) when the first records contributed to this analysis were collected (Fig. 7.5A). However, hard coral cover varied during the intervening 37 years. Between 1983 and 1999, live coral cover remained relatively stable with only minor fluctuations ranging between 31.5% (1987) and 33.7% (1998). During the subsequent decade between 1999 and 2009, hard coral cover increased from 32.9% to 40.8%, but then declined abruptly to 35% by 2012, as a result of the 2010 mass coral bleaching event. Coral cover showed small signs of recovery over the next three years reaching 35.8% in 2015, but declined to 33.9% in 2017 likely due to the 2016 mass coral bleaching event. Since then, coral cover has recovered to around 36.8% (Fig. 7.5A).

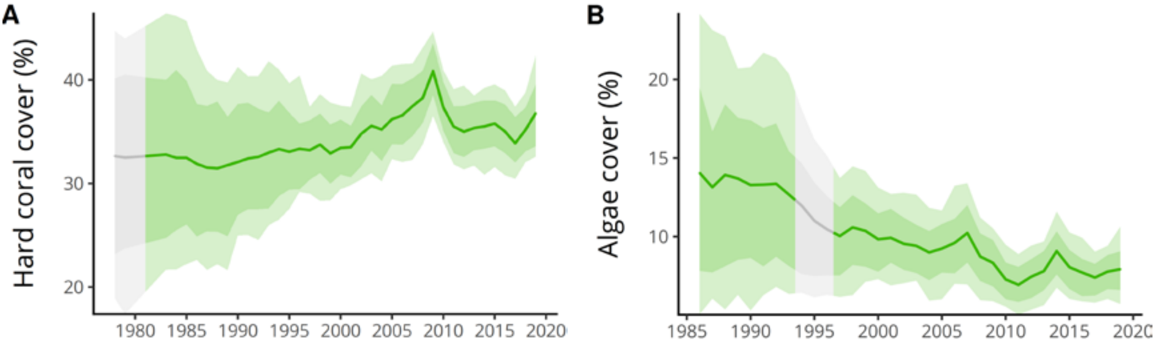

Figure 7.5. Estimated regional average cover of live hard coral (A) and algae (B) for the East Asian Seas region. The solid line represents the estimated mean and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods during which no field data were available.

While coral cover has increased slightly over the last 37 years, during the last decade, coral cover has declined slightly. Comparison of the average hard coral cover between five-year periods (2005-09, 2010-14, 2015-19) indicates that despite the uncertainty in individual yearly estimates, there is strong evidence (96% probability) that average coral cover has declined during the last decade (Tab. 7.3). On average, this decline equates to a loss of almost 11% of the hard coral, of which more than 90% occurred between 2005-09 and 2010-15 (Tab. 7.3).

Table 7.3. Probability and magnitude of mean absolute and relative change in the percent cover of live hard coral in the East Asian Seas region among 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	96	-2.7	-10.5
2010-14 - 2015-19	54	-0.2	-0.8
2005-09 - 2015-19	96	-2.8	-10.9

The first records of the cover of algae were collected in 1986 when average cover was 14.1% (Fig. 7.5B). During the subsequent 26 years, the average cover of algae across the region has generally declined, reaching a minimum of 6.9% in 2011. Since 2011, the cover of algae has fluctuated between 7.4% (2017) and 9.1% (2014), but has remained relatively low. Early estimates of algal cover, particularly prior to

1997, were accompanied by large uncertainties because of a scarcity of data. Comparison of average algal cover between the three five-year periods comprising the last 15 years provides weak evidence (86% probability) of a small decline (1.1%) in absolute algal cover on coral reefs in the EAS (Tab. 7.4).

Table 7.4. Probability and magnitude of mean absolute and relative change in the percent cover of algae in the East Asian Seas 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	87	-0.9	-11.0
2010-14 - 2015-19	59	-0.1	-0.2
2005-09 - 2015-19	86	-1.1	-11.7

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

Analysis of trends in the condition of coral reefs in the EAS region was limited by the availability of historical data, as well as the distribution of survey sites across the region. Monitoring efforts tended to concentrate on easily accessible or well-known reefs, as many coral reefs, particularly in the large archipelagic states which have most of the coral reefs in the region, are hidden or inaccessible to researchers and NGOs, and potentially could have been destroyed or degraded before being monitored.

While there was an overall slight increase in regional coral cover between 1983 and 2019, the initial baseline coral cover was relatively low compared with historical and anecdotal accounts of coral cover in the region, suggesting that the earliest data provided reflected an already altered state of coral reefs in the region. Notwithstanding, the declines recorded in 2012 and 2016 are likely to be associated with the 2010 and 2016 mass coral bleaching events, which resulted in a relative decline in coral cover in the order of 11% during the last decade.

- Changes in resilience of coral reefs within the East Asian Seas region

To identify changes in the resilience of coral reefs in the EAS region, patterns of disturbance and recovery were examined within sampling units 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%. Of the 55 such sampling units in the EAS region, 25 did not recover to at least 90% of their pre-disturbance hard coral cover (Tab. 7.5). Among those sampling units, the average decline in hard coral cover between the first and most recent surveys was 1.7%, representing a loss of 4.7% of the existing hard coral. The average maximum decline in absolute hard coral cover was 18.9%, representing a loss of 69.3% of the hard coral within these sampling units.

Table 7.5. 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
55	25	45.5	18.9	69.3	1.7	4.7

4. Subregional trends in the cover of live hard coral and algae within the East Asian Seas region

Within the EAS region, the trends in hard coral cover among the different subregions varied, indicating some heterogeneity in exposure to disturbance and subsequent recovery (Fig. 7.6). Average hard coral cover in subregions 1, 2, 3, 4 and 7 show considerable fluctuations, while subregion 5 shows a progressive increase in coral cover and subregion 6 remained stable throughout, although there is considerable uncertainty associated with the modelled estimate.

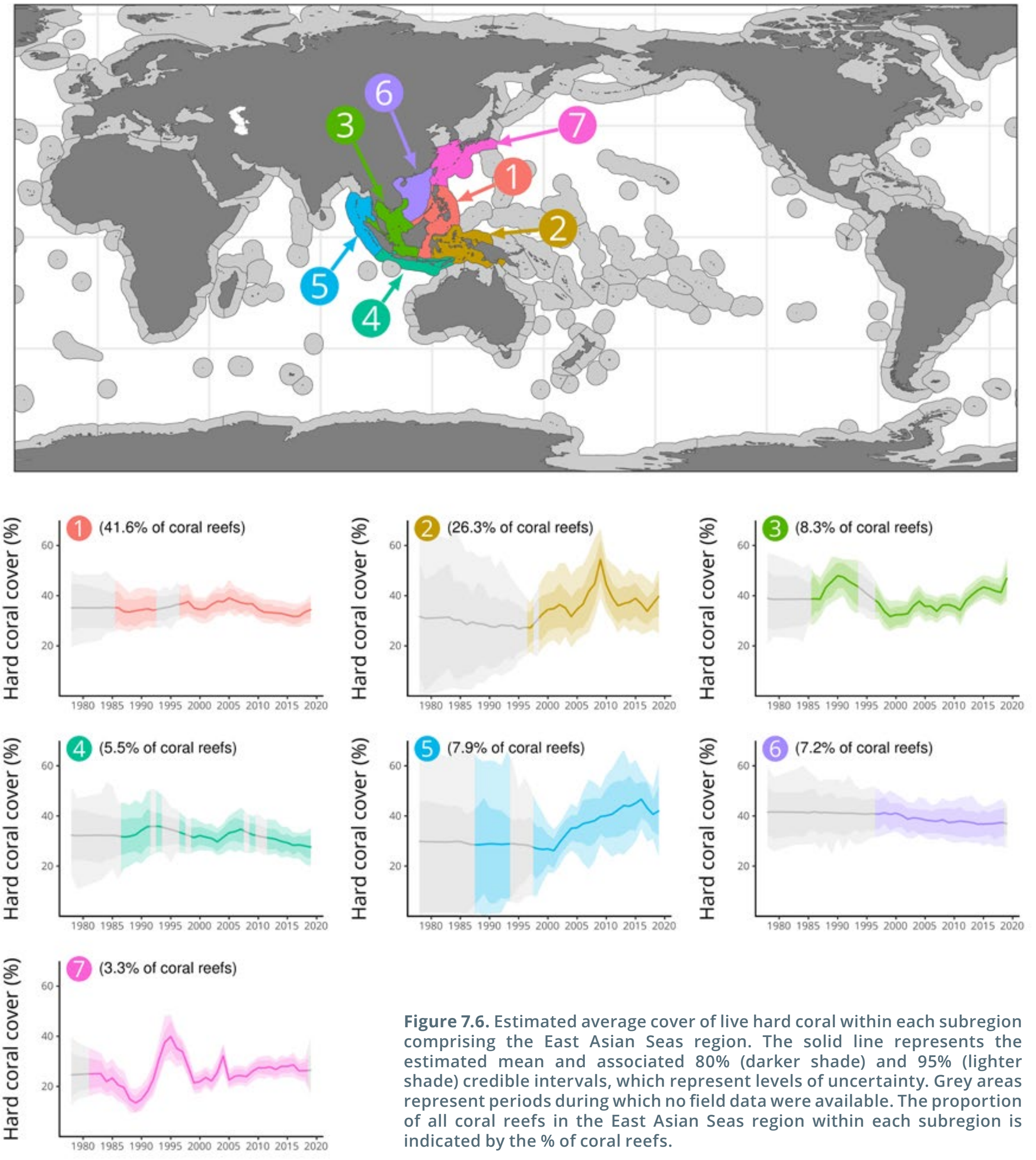

Figure 7.6. Estimated average cover of live hard coral within each subregion comprising the East Asian Seas region. The solid line represents the estimated mean and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods during which no field data were available. The proportion of all coral reefs in the East Asian Seas region within each subregion is indicated by the % of coral reefs.

In general, the cover of algae has decreased regionally (Fig. 7.7). Substantial decreases in algal cover were evident in subregions 1 and 3, while subregions 4 and 5 showed a progressive decline. Algal cover in subregions 2, 6 and 7 remained relatively constant throughout.

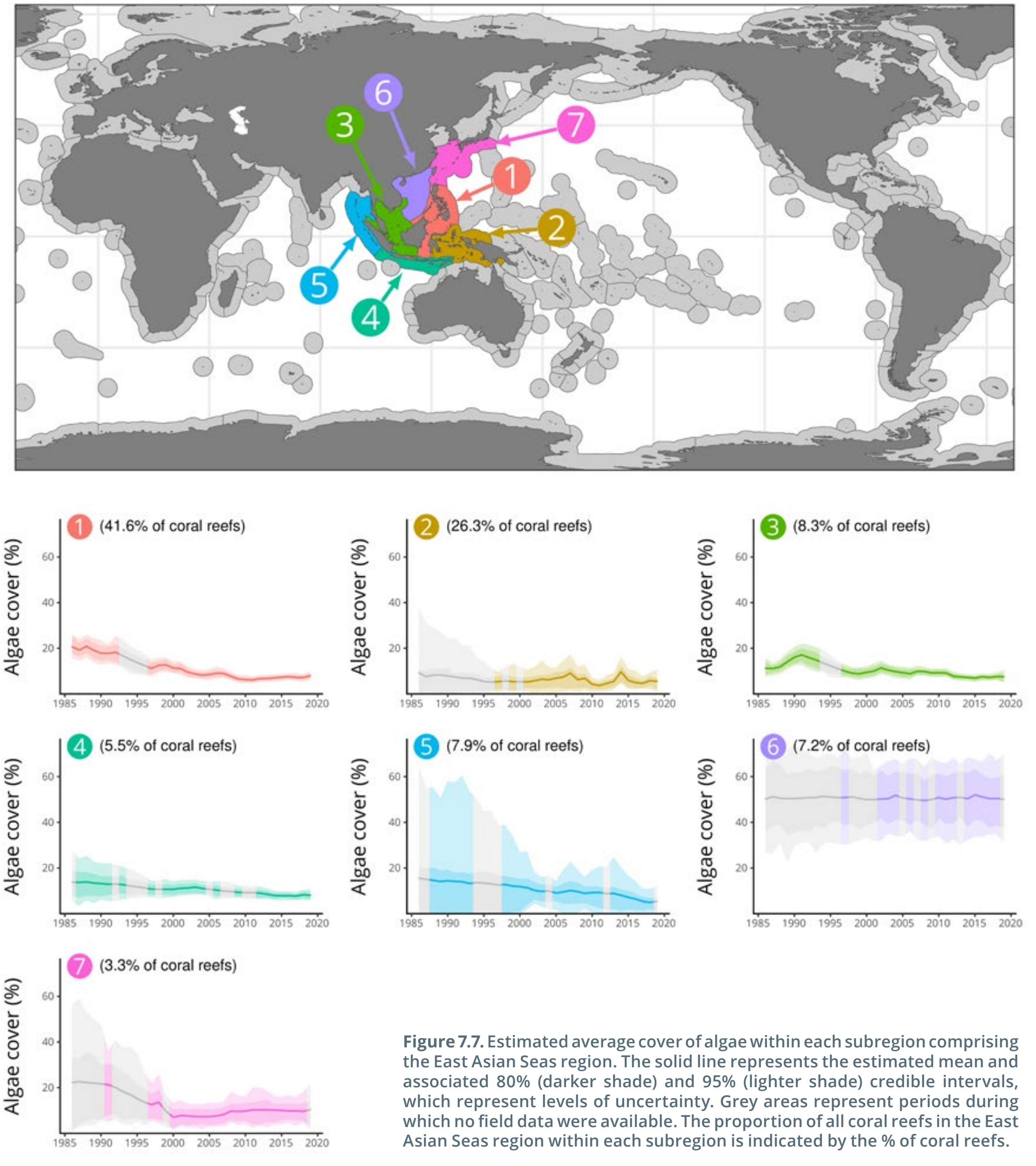

Figure 7.7. Estimated average cover of algae within each subregion comprising the East Asian Seas region. The solid line represents the estimated mean and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods during which no field data were available. The proportion of all coral reefs in the East Asian Seas region within each subregion is indicated by the % of coral reefs.

Box 4.

Biodiversity in coral reef ecosystems

Jérémy Wicquart, David Obura, David Souter

What is biodiversity?

The concept of biodiversity encompasses the variety of life on Earth, extending from the varying genetic make-up of different individuals of a species, to the number of different species, to the differing communities and ecosystems. Hence, in coral reefs, which are among the most diverse ecosystems on the planet, biodiversity is expressed in myriad geomorphological structures, the vast number of species of colourful fish, coral and other invertebrates, and in the genetic variation that enables some individuals to tolerate disturbances, such as marine heat waves, better than others.

Distribution of reef-building coral species richness

Coral reefs are geological structures resulting from the accumulation of calcium carbonate produced by numerous organisms, but mainly by hard corals. Zooxanthellate (i.e. those possessing the symbiotic algae zooxanthellae) hard corals, of which some 850 species found on shallow tropical reefs and are distributed from the Mediterranean Sea to southern Australia (Fig. 1), but those building large scale calcium carbonate reef structures are limited to the tropics. The centre of reef-building coral species richness is in the 'Coral Triangle', an area including Philippines, Indonesia and Papua New Guinea (Fig. 1). The species richness of reef-building corals is driven mainly by historical tectonic movements and the availability of shallow-water habitat, more than by the latitude or longitude[1].

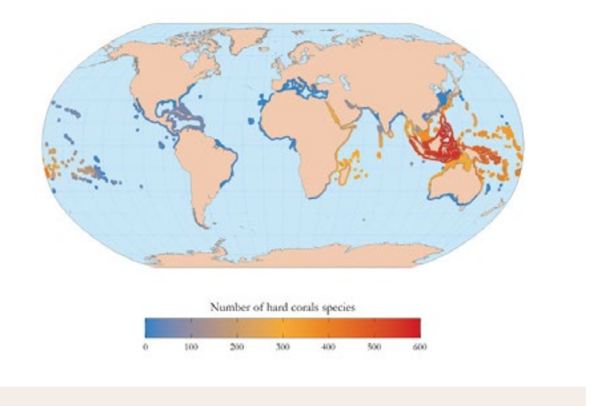

Figure 1. Map of reef-building coral species richness based on data from the International Union for Conservation of Nature[2].

[1] Bellwood, D. R., & Hughes, T. P. (2001). Regional-Scale Assembly Rules and Biodiversity of Coral Reefs. Science, 292(1532). doi:10.1126/science.1058635

[2] Reef-forming Coral. The IUCN Red List of Threatened Species. Version 2015. (2015). Retrieved 17 July 2019, from https://www.iucnredlist.org/resources/spatial-data-download

Estimates of total species richness on a coral reef

Patterns of species richness of other major coral reef taxa such as fish, snails or lobsters, are similar to that of reef-building corals[3]. When considering all taxa (excluding unicellular organisms and fungi but including undiscovered species), estimates of the total species richness of coral reefs average about 830,000 species, and range between 550,000 to 1,330,000 species[4]. Based on these estimates, these authors conclude that approximately 32% of all named marine species occur on coral reefs and that 74% of coral reef species remain undiscovered. The majority of species on coral reefs are small cryptic species, living within the huge number of microhabitats created by the reef-building corals, sponges or gorgonians that are the foundation of coral reefs and give them their complex three-dimensional structure. Unlike the macrofauna, these small cryptic species are difficult to sample, explaining partly why the estimates of total coral reef species richness range so widely[5]. Nevertheless, the growing use of recent molecular tools makes it possible to improve our knowledge of coral reefs species richness.

Biodiversity and its importance

In recent decades, a growing emphasis has been placed on functional diversity (another facet of biodiversity), which is a measure of the breadth of different services organisms provide to the ecosystem. Within an ecosystem, each species performs a set of functions, such as nutrient cycling, herbivory or carbon storage. If species performing key functions within the ecosystem disappear, the integrity of the ecosystem can be affected, resulting in declines in condition and potentially local extinctions of other species through cascading effects[6]. In turn, this may cause the loss of other functions. A good example of this phenomenon is the large-scale phase-shift that occurred in Jamaican coral reefs[7]. Following decades of overfishing, the biomass of herbivorous fish declined markedly. Between 1982 and 1984, disease reduced the density of another important herbivorous species, the sea urchin *Diadema antillarum*, to 1% of its original density. Without herbivorous fish and sea urchins, algae proliferated, outcompeting reef-building corals for space and causing a phase-shift whereby reefs are now dominated by algae instead of reef-building corals. This extreme example shows that, far from being a simple inventory, biodiversity plays a key role in the stability of ecosystems.

[3] Roberts, C. M., McClean, C. J., Veron, J. E. N., Hawkins, J. P., Allen, G. R., McAllister, D. E., ... Werner, T. B. (2002). Marine Biodiversity Hotspots and Conservation Priorities for Tropical Reefs. Science. doi:10.1126/science.1067728

[4] Fisher, R., O'Leary, R. A., Low-Choy, S., Mengersen, K., Knowlton, N., Brainard, R. E., & Caley, M. J. (2015). Species richness on coral reefs and the pursuit of convergent global estimates. Current Biology, 25(4), 500–505. doi:10.1016/j.cub.2014.12.022

[5] Knowlton, N., Brainard, R. E., Fisher, R., Moews, M., Plaisance, L., & Caley, M. J. (2010). Coral Reef Biodiversity. In A. D. McIntyre (Ed.), Life in the World's Oceans - Diversity, Distribution and Abundance (pp. 65–77). Wiley-Blackwell.

[6] Kaneryd, L., Borrvall, C., Berg, S., Curtsdotter, A., Eklöf, A., Hauzy, C., ... Ebenman, B. (2012). Species-rich ecosystems are vulnerable to cascading extinctions in an increasingly variable world. Ecology and Evolution, 2(4), 858–874. doi:10.1002/ece3.218

[7] Hughes, T. P. (1994). Catastrophes, Phase Shifts, and Large-Scale Degradation of a Caribbean Coral Reef. Science, 265(5178), 1547–1551.

Chapter 8.

Status and trends of coral reefs of the Australia region

Collaborators: Dave Abdo, Debbie Bass, Hawthorne Beyer, Scott Burgess, Dani Ceccarelli, Alistair Cheal, Caroline Christie, Greg Coleman, Ellen D'Cruz, Mike Emslie, Richard Evans, Jan Freiwald, Andrew Halford, James Gilmour, Manuel Gonzalez Rivero, Jordan Goetze, Ove Hoegh-Guldberg, Thomas Holmes, Kerryn Johns, Michelle Jonker, Alan Kendrick, Abbi MacDonald, Ian Miller, Stephen Neale, Kate Osborne, Will Oxley, Lorna Parry, William Robbins, Claire Ross, Nicole Ryan, Tane Sinclair-Taylor, Hugh Sweatman, Angus Thompson

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

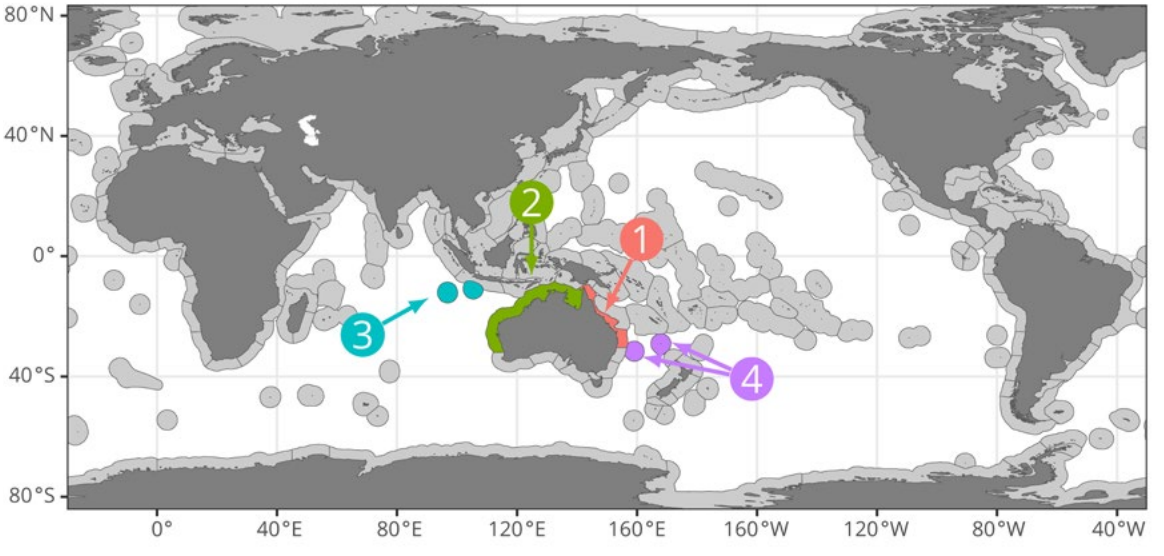

Figure 8.1. Map of each subregion comprising the Australia region. The number ascribed to each subregion corresponds with that in Table 8.1.

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

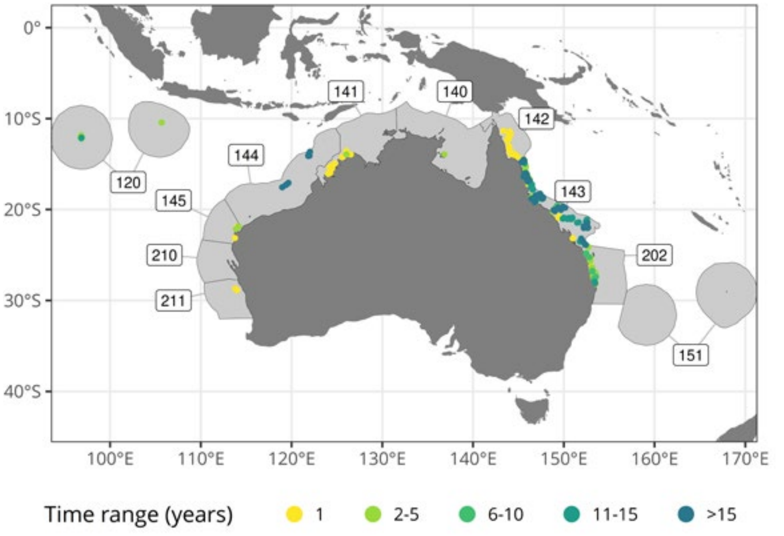

Figure 8.2. The distribution and duration of monitoring at sites across the Australia region. The colours of dots represent the time span between the first survey and the most recent survey at each site. Numbers refer to the MEOW ecoregions listed in Table 8.1.

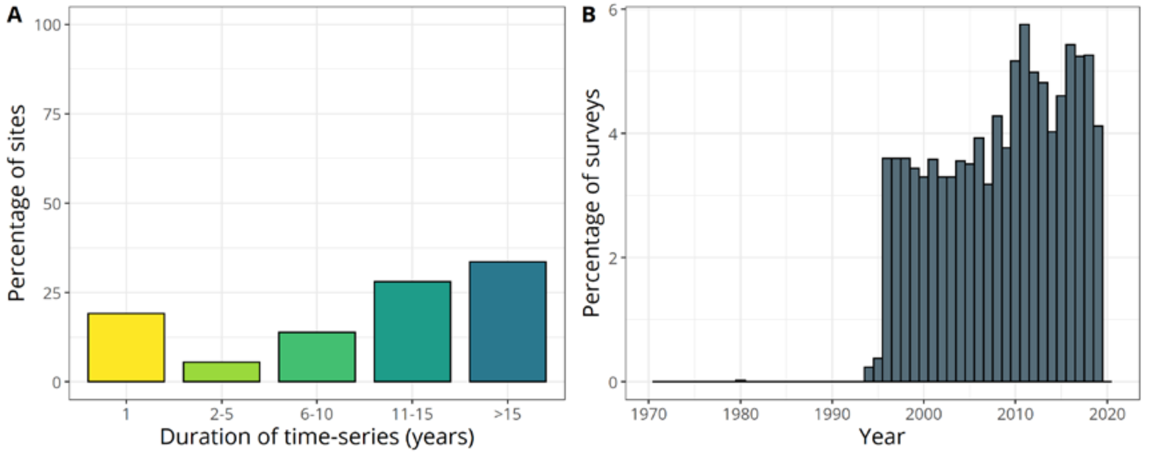

Figure 8.3. The proportion of sites in the Australia region within each category describing the time span between the first and most recent surveys (A), and the proportion of the total number of surveys conducted in each year (B). The total number of surveys was 3,804.

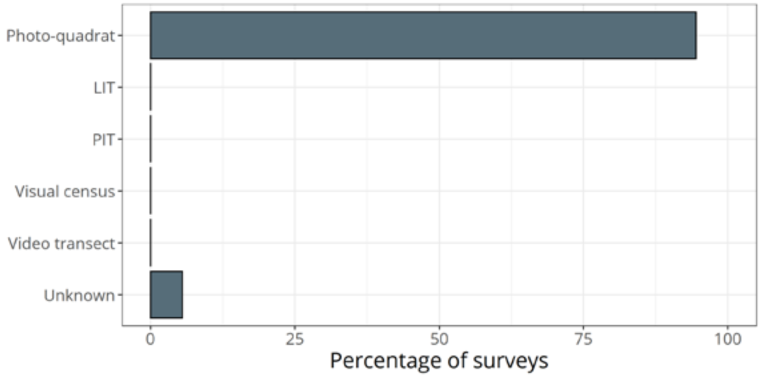

Figure 8.4. The proportion of the total number of surveys conducted in the Australia region using each survey method. PIT: Point Intercept Transect; LIT: Line Intercept Transect.

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).

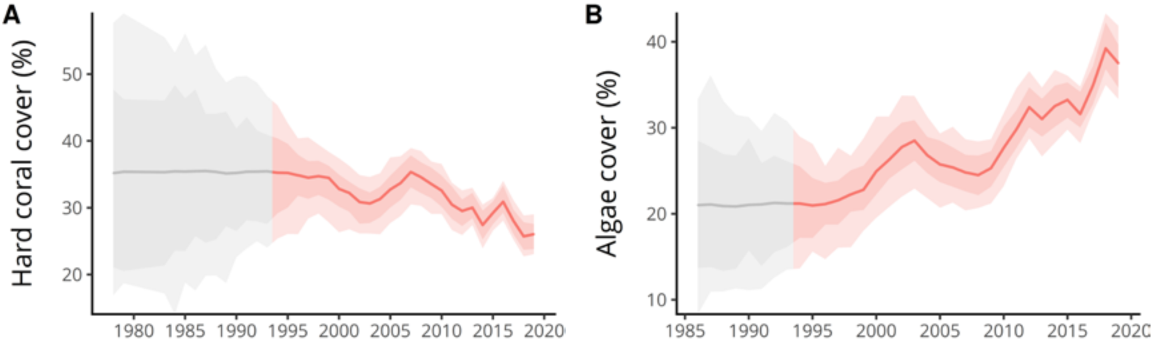

Figure 8.5. Estimated regional average cover of live hard coral (A) and algae (B) for the Australia region. The solid line represents the estimated mean and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods during 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.

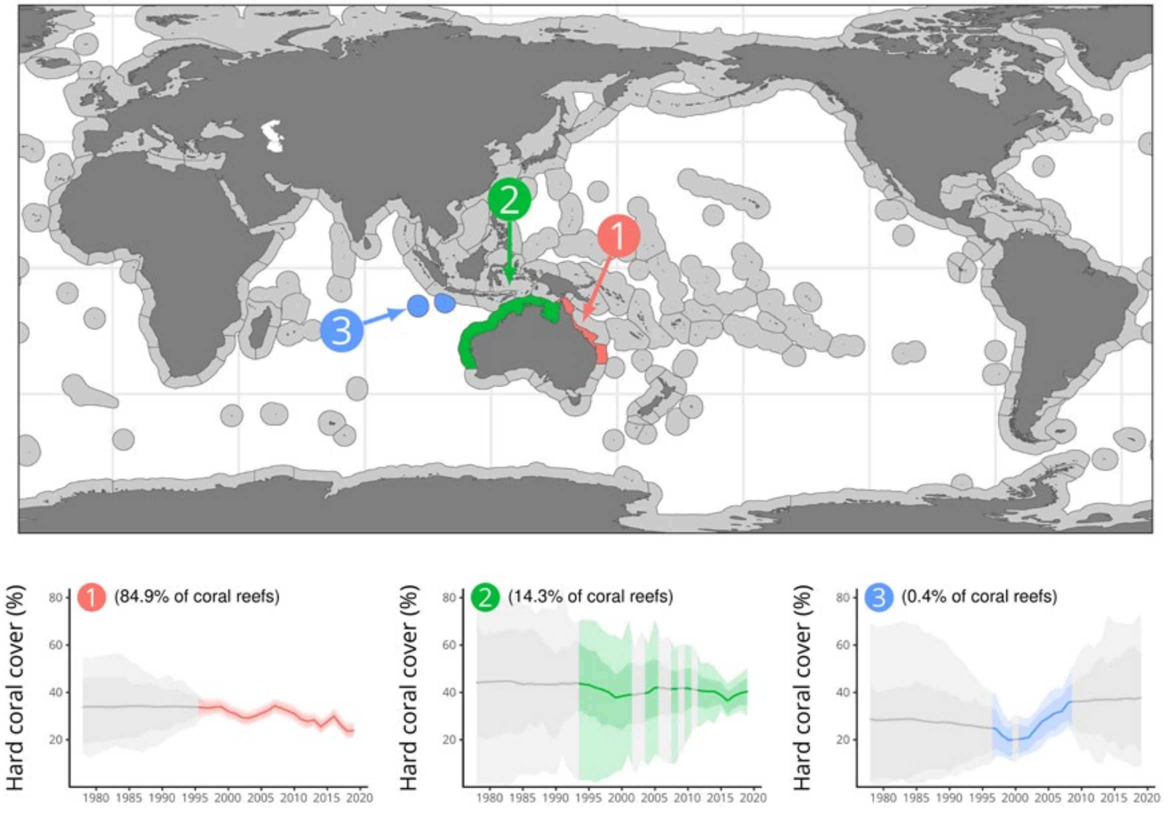

Figure 8.6. Estimated average cover of live hard coral within each subregion comprising the Australia region. The solid line represents the estimated mean and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods 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).

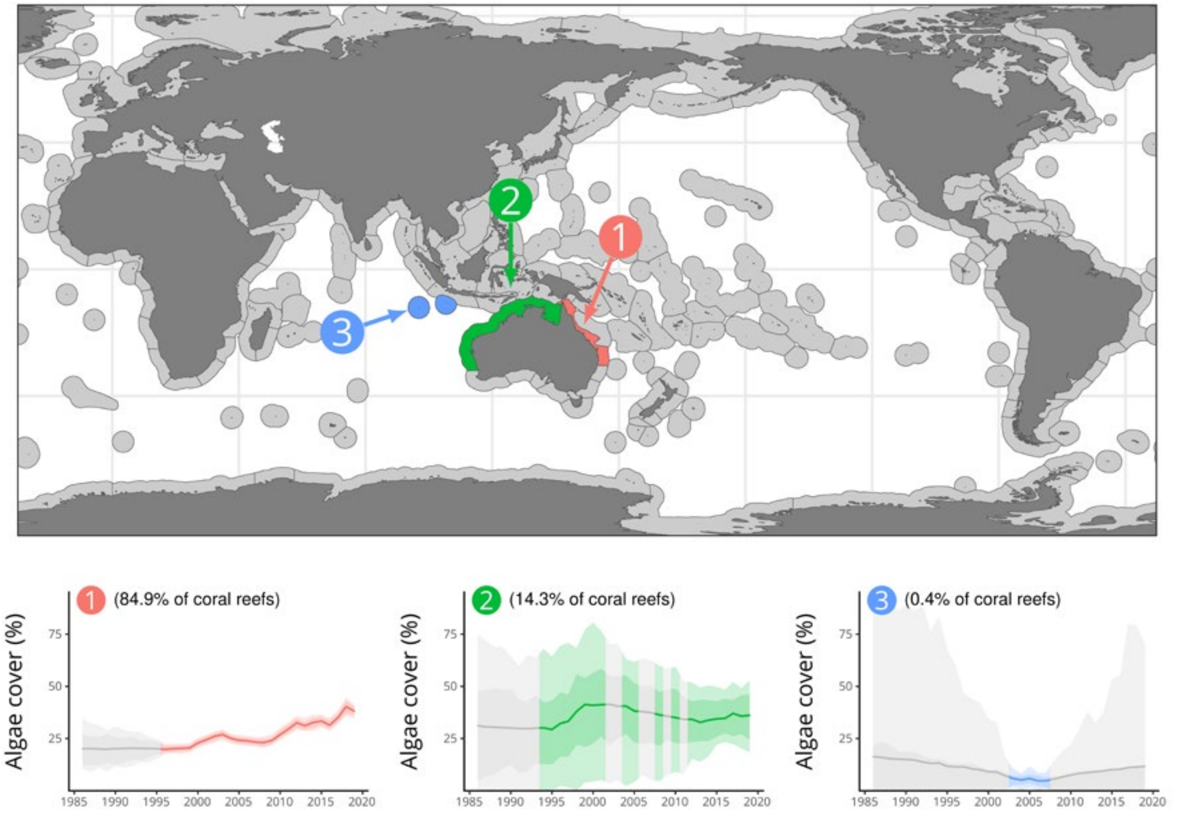

Figure 8.7. Estimated average cover of algae within each subregion comprising the Australia region. The solid line represents the estimated mean and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods during which 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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[1]Australian Institute of Marine Science
[2]Wildlife Conservation Society

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.

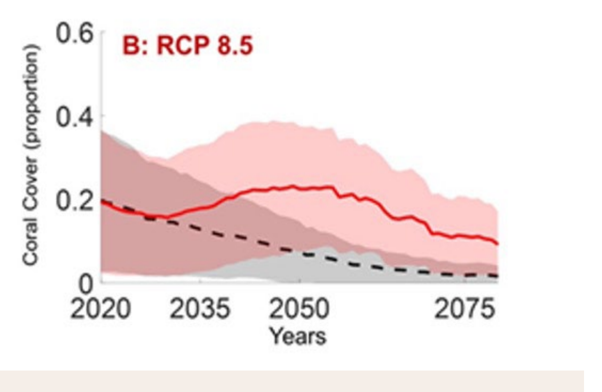


Figure 1: Combination of interventions deployed under RCP 8.5 conditions. They have an impact under RCP8.5 but perform much better under RCP 2.8.

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.

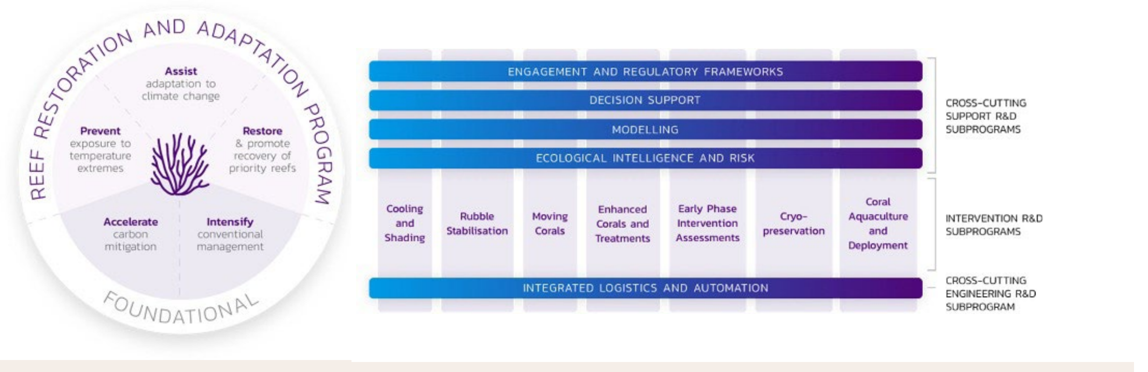


Figure 2. RRAP research and development program structure.

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.

Chapter 9.

Status and trends of coral reefs of the Pacific region

Collaborators: Lara Ainley, Abigail Alling, David Benavente, Hawthorne Beyer, Chico Birrell, Mary Bonin, Eric Brown, Rodney Camacho, Sara Cannon, Kitty Currier, Emily Darling, Orla Doherty, Simon Donner, Sirilo Dulunaqio, Janelle Eagle, Margaret Fox, Jan Freiwald, Antoine Gilbert, Manuel Gonzalez Rivero, Marine Gouezo, Nicolas Guillemot, Tom Heintz, Ove Hoegh-Guldberg, Eryn Hooper, Peter Houk, John Iguel, Arielle Inès Hoamby, Roberto Jean Luc Komeno, Sandrine Job, Johanna Johnson, Geoffrey Jones, Stacy Jupiter, Emma Kabua-Tibon, James Kora, Alice Lawrence, Florian Le Bail, Enelio Liufau, Sangeeta Mangubhai, Mark McCormick, Sheila McKenna, Carol Milner, Bradley Moore, Kirby Morejohn, Yashika Nand, Stephen Neale, Lorna Parry, Denise Perez, Serge Planes, Volanirina Ramahery, Ravaka Ranaivoson, Shannon Seeto, Maya Srinivasan, Heather Summers, Helen Sykes, Anthony Tenorio, Erica Towle, Maunoa Vesarikaro, Laurent Wantiez, Jane Waterhouse, David Welch, Andra Whiteside

(**Note:** This is the list of contacts, not the list of people to acknowledge. The full list of contributors to be acknowledged will be obtained from the various data sharing agreements.)

1. Geographic information and context

Key numbers:

- Total area of coral reefs: 69,424 km^2
- Proportion of the world's coral reefs: 26.73%
- Number of countries with coral reefs: 17
- Number of Marine Ecoregions of the World (MEOW) ecoregions: 24

General context:

The Pacific region is by far the largest of the GCRMN regions in terms of surface area and is unique in that the coral reefs occur mainly around oceanic islands. It includes more than 25,000 islands and supports almost 27% (about 69,424 km^2) of the total global area of coral reefs. Spread across such a large area, these reefs vary considerably in terms of proximity to continents, reef structure, and biodiversity, as well as the frequency and intensity of natural disturbances.

Pacific islands and archipelagos include sovereign states as well as associated states or territories of continental countries. Coral reefs are an integral part of Pacific culture and provide a significant amount of dietary protein (25-100%). The human population has grown significantly during the last century, and islands of the Pacific Ocean now support around, 13.5 million people, of which 9 million live in Papua New Guinea. However, population density is not uniform within or between islands, ranging from 475 people per km^2 in Tuvalu, to 15 people per km^2 in Papua New Guinea and New Caledonia. There are also considerable economic disparities between Pacific nations and territories, with per capita Gross Domestic Product (GDP) ranging from USD1,035 in Tokelau to USD54,500 in Hawaii (United States of America), with populations more or less dependent on coral reefs.

The GCRMN Pacific region includes nine Marine Ecoregions of the World (MEOW) ecoregions[1] (Tab. 9.1, Fig. 9.1). Data from each ecoregion except Easter Island are reported here.

Table 9.1. The subregions comprising the Pacific region, the area of reef they support, and the constituent Marine Ecoregions of the World (MEOW)[1].

Subregion	Reef Area (km^2)*	Proportion of Reef Area within the Pacific Region (%)	Constituent Marine Ecoregions of the World
1	6,408	9.2	121: Mariana Islands 122: Ogasawara Islands 124: East Caroline Islands 125: West Caroline Islands
2	20,144	29.0	134: Bismarck Sea 135: Solomon Archipelago 136: Solomon Sea 137: Southeast Papua New Guinea
3	21,172	30.5	146: Kingdom of Tonga 147: Fiji Islands 148: Vanuatu 149: New Caledonia 150: Coral Sea
4	4,504	6.5	152: Hawaiian Islands
5	8,155	11.7	153: Marshall Islands 154: Gilbert/Ellis Island
6	2,315	3.3	155: Line Islands 156: Phoenix/Tokelau/Northern Cook Islands/Wallis 157: Samoa Islands
7	6,726	9.7	158: Tuamotu 162: Marquesas Islands 159: Rapa-Pitcairn 160: Southern Cook/Austral Islands 161: Society 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

[1] 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

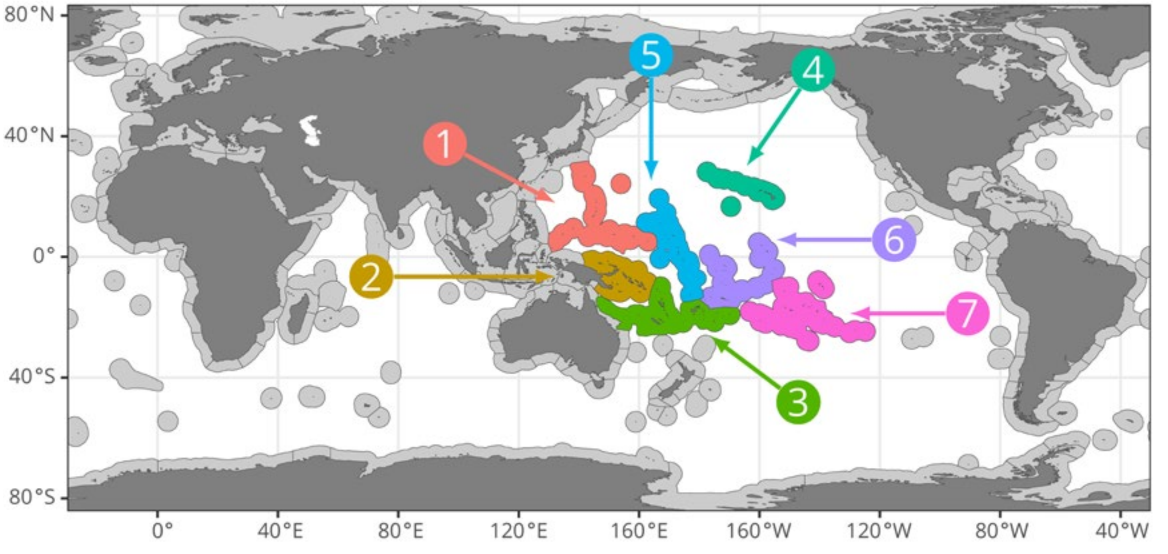


Figure 9.1. Map of each subregion comprising the Pacific region. The number ascribed to each subregion corresponds with that in Table 9.1.

2. Summary of data contributed to this report

Key numbers:

- Number of countries from which monitoring data were used: 15 (of 17)
- Number of sites: 4,050
- Number of observations: 438,803
- Longest time series: 29 years

General features:

The status of, and trends in, coral reefs presented below are based on almost 440,000 observations collected since 1987 from 4,050 sites in 15 different countries within the Pacific region (Tab. 9.2). These data were collected primarily using photo-quadrat or transect-based methods (Fig. 9.4), and comprise 45% of the global dataset that underpins this GCRMN *Status of Coral Reefs of the World: 2020* report.

The distribution of monitoring effort across the Pacific region reflects the commitment to monitoring by national governments, organisations and programs. The most surveyed subregions within the Pacific were subregions 1 (Mariana Islands, Ogasawara Islands, East and West Caroline Islands) and 6 (Line Islands, Phoenix/Tokelau/Northern Cook Islands/Wallis, Samoa Islands), which are included in the NOAA Coral Reef Monitoring Program. Monitoring in subregions 3 (Kingdom of Tonga, Fiji Islands, Vanuatu, New Caledonia, Coral Sea) and 7 (Tuamotu, Marquesas Islands, Rapa-Pitcairn, Southern Cook/Austral Islands, Society Islands) was conducted primarily as part of long-term programs supported by France and based in New Caledonia and French Polynesia.

Long-term monitoring (>15 years between the first survey and the most recent survey) has occurred at 50 sites within the Pacific region, with the longest time series recorded from any site being 29 years

(Tab. 9.2, Fig. 9.2 and 9.3A). The vast majority of long-term monitoring sites occurred either within subregion 3 (25) or 7 (14) and were part of long-term programs supported by France (Tab. 9.2).

The distribution of monitoring effort over time was driven primarily by responses to disturbance events. Only a small amount of monitoring occurred between 1987, when the earliest data contributed to this report were collected, and 1998. However, considerable increases in monitoring effort were evident in response to mass coral bleaching events in 1998, 2010 and 2015, although this has not been maintained in recent years (Fig. 9.3B).

Table 9.2. Summary statistics describing data contributed from the Pacific 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.

Pacific 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	438,803	45.26	4,050	33.31	50	8.5
1	105,783	10.91	1,080	8.88	0	0
2	56,057	5.78	74	0.61	8	1.36
3	49,841	5.14	377	3.1	25	4.25
4	66,288	6.84	1,002	8.24	0	0
5	16,617	1.71	219	1.8	0	0
6	109,204	11.26	1,149	9.45	3	0.51
7	35,013	3.61	149	1.23	14	2.38

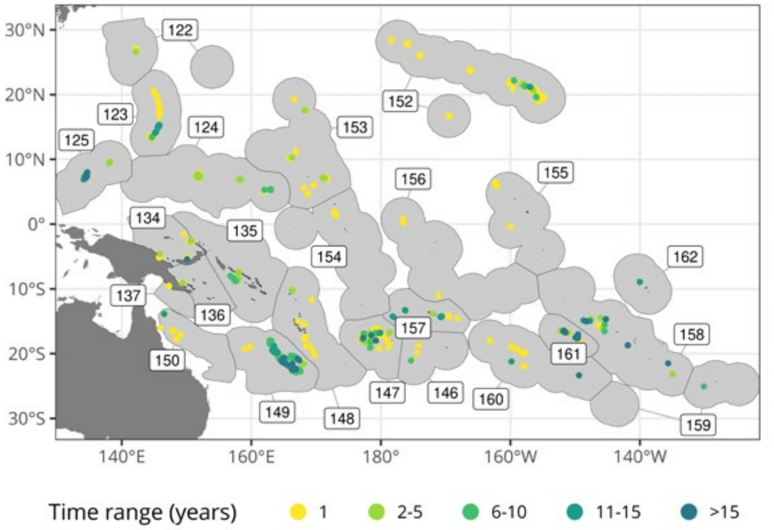


Figure 9.2. The distribution and duration of monitoring at sites across the Pacific region. The colours of dots represent the time span between the first survey and the most recent survey at each site. Numbers refer to the MEOW ecoregions listed in Table 9.1.

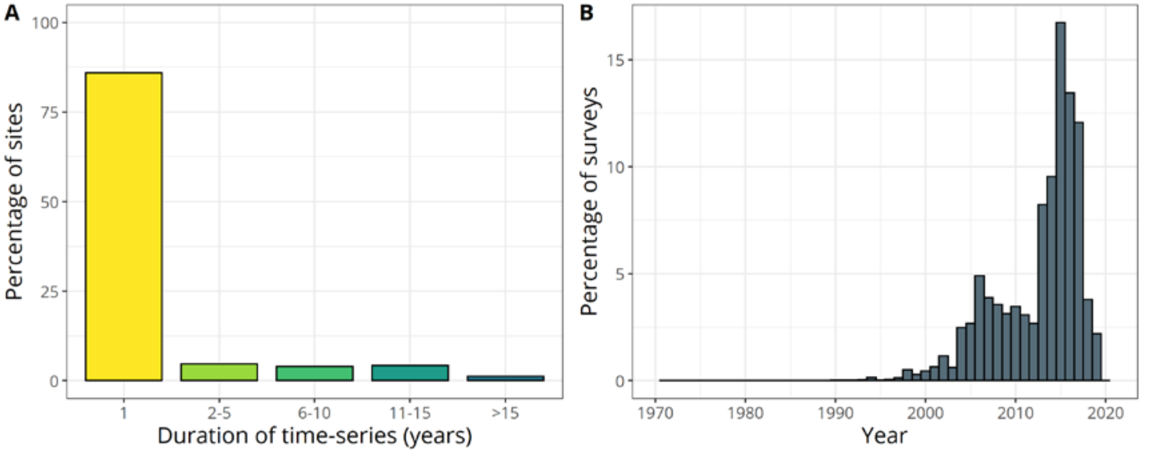


Figure 9.3. The proportion of sites in the Pacific region within each category describing the time span between the first and most recent surveys (A), and the proportion of the total number of surveys conducted in each year (B). The total number of surveys was 7,585.

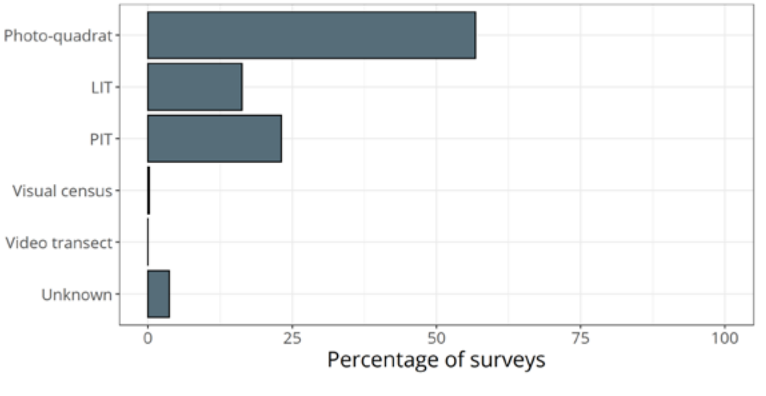


Figure 9.4. The proportion of the total number of surveys conducted in the Pacific region using each survey method. PIT: Point Intercept Transect; LIT: Line Intercept Transect.

3. Status of coral reefs in the Pacific region

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

Prior to 1998, the estimated average cover of live hard coral was relatively high and stable, ranging between 37.0% and 37.7% (Fig. 9.5A). Since 1998, there has been a general decline in coral cover to 31.3% in 2019. Although the overall trend declined, periods of recovery occurred between 2009 and 2011 and, more recently, between 2017 and 2019, with average coral cover increasing by 1.1% and 1.7% respectively. The impacts of the 1998 El Niño in the Pacific event were evident in a 2.3% decline in average coral cover between 1999 and 2001. El Niño events in 2015 and 2016 caused considerable coral mortality which was apparent in the 2.7% decline in average coral cover across the region between 2015 and 2017. This suggests that successive El Niño events have had greater impacts, which will need to be considered in future monitoring.

The trend in the average cover of algae over the last 35 years was the opposite of hard coral cover, with relatively low (~15%) but stable cover between 1987 and 1999, followed by a progressive increase during the last two decades, peaking in 2018 at 20.8% (Fig. 9.5B).

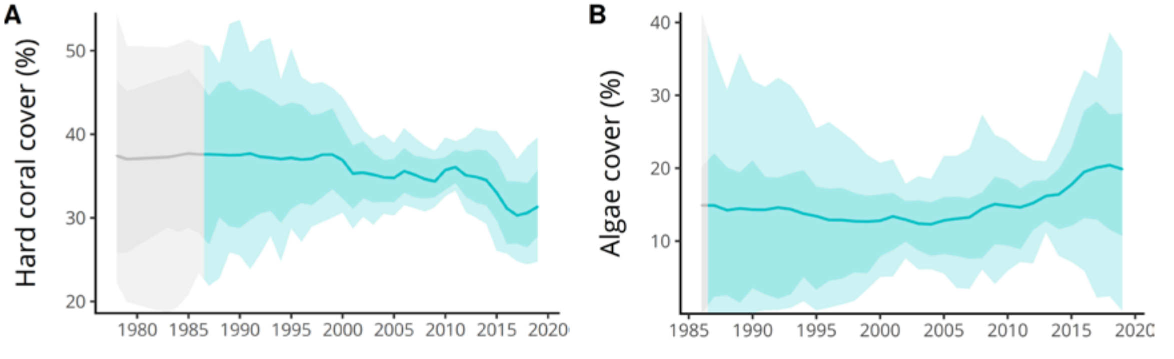


Figure 9.5. Estimated regional average cover of live hard coral (A) and algae (B) for the Pacific region. The solid line represents the estimated mean and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods during which no field data were available.

Comparison of the average hard coral cover between the three five-year periods comprising the last 15 years (2005-09, 2010-14, 2015-19, Tab. 9.3) indicated that there was a high degree of confidence (93%) in the long-term decline, despite the uncertainty in individual yearly estimates. Further, the vast majority (90%) of this decline occurred between 2010-14 and 2015-19, suggesting that the rate of decline in hard coral cover has accelerated during the last five years (Tab.3).

Table 9.3. Probability and magnitude of mean absolute and relative change in the percent cover of live hard coral in the Pacific 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	61	-0.4	-1.3
2010-14 - 2015-19	95	-3.9	-15.8
2005-09 -2015-19	93	-4.3	-16.8

Comparison of the average algal cover between the three five-year periods comprising the last 15 years (2005-09, 2010-14, 2015-19) suggested a moderate probability (87%) of a long-term increase in the average cover of algae on Pacific reefs in the order of 5.9% (87.5% relative increase), and that the majority of this increase has occurred between 2010-14 and 2015-19 (Tab. 9.4).

Table 9.4. Probability and magnitude of mean absolute and relative change in the percent cover of algae in the Pacific 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	84	1.9	27.5
2010-14 - 2015-19	82	4.1	42.6
2005-09 -2015-19	87	5.9	87.5

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

In the Pacific region, coral bleaching has been the main cause of coral loss. The decline in average hard coral cover across the Pacific region began in 1998, corresponding with the first global mass coral bleaching event, and more recent declines were attributable to global-scale coral bleaching events in 2014, 2015 and 2016 (Fig. 9.5A). The frequency of these successive bleaching events provided limited opportunity for corals to recover between events, which accelerated the rate of coral loss, particularly between 2015 and 2017.

Coral bleaching has also occurred at smaller scales at several locations within the Pacific during the last two decades, notably in 2002-03 in the Phoenix Islands and Kiribati, in 2004-05 in the Gilbert Islands, Kiribati and Tuvalu, and in 2009-10 in the Gilbert, Phoenix and Line Islands. However, because these coral bleaching events were relatively localized, they did not have a large influence on the average coral cover at the scale of the entire Pacific region.

- Changes in resilience of coral reefs within the Pacific region

Increases in the frequency of disturbances to Pacific coral reefs may have changed long-term disturbance-recovery patterns to a point that many reefs are not recovering completely between one disturbance and the next. The result is a stepwise decline in hard coral cover. In the Pacific region, there were 120 sampling units 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% (Tab. 9.5). At more than half (69) of these sampling units, the hard coral cover did not recover to at least 90% of their pre-disturbance level. On average, hard coral cover declined by 7% between the first survey and the most recent survey at these sites, representing a loss of 21.4% of the existing hard coral. The average maximum decline in absolute hard coral cover was 24.7%, representing a loss of 73.3% of the hard coral at these sampling units (Tab. 9.5).

Table 9.5. 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
120	69	57.5	24.7	73.3	7.0	21.4

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

Within the Pacific region, the trends in hard coral cover among the different subregions varied, indicating some heterogeneity in exposure to disturbance and subsequent recovery, and highlighting the need to survey all subregions (Fig. 9.6). Subregions 1, 3, 5 and 6 all show declines in average hard coral cover that are consistent with the overall trend of the Pacific region, while subregion 2 (PNG, Solomon Islands, New Caledonia, Vanuatu, and Fiji) and 4 (Hawaii) were stable, and subregion 7 (French Polynesia) increased until 2010 after which it exhibited a substantial decline in average hard coral cover during the last decade. Although impossible to determine from the available data, there was evidence that the impact of bleaching varied among coral families.

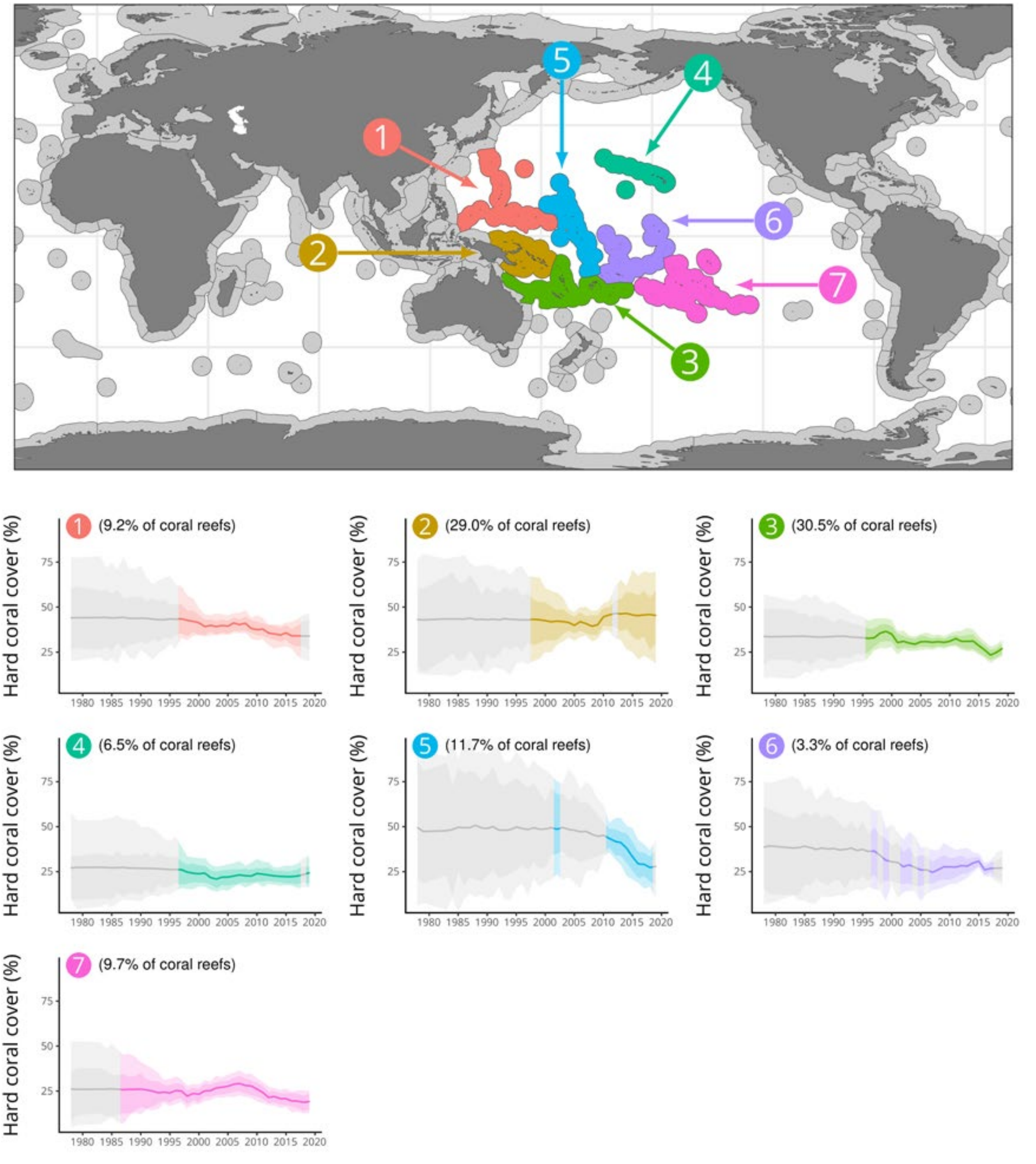


Figure 9.6. Estimated average cover of live hard coral within each subregion comprising the Pacific region. The solid line represents the estimated mean and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods during which no field data were available. The proportion of all coral reefs in the Pacific region within each subregion is indicated by the % of coral reefs.

Similar to hard coral cover, trends in the percent cover of algae varied among different subregions (Fig. 9.7). The average cover of algae remained reasonably stable within subregions 2, 3 and 7, but in subregion 4, the cover of algae had clearly increased, and in subregions 1 and 5, it had doubled in the last 10-15 years. While the substantial increase in the number of surveys conducted in the last 10-15 years may have overemphasised more recent trends, the overall increase in the cover of algae suggests a substantial shift from hard coral dominance towards algal dominance within these ecosystems.

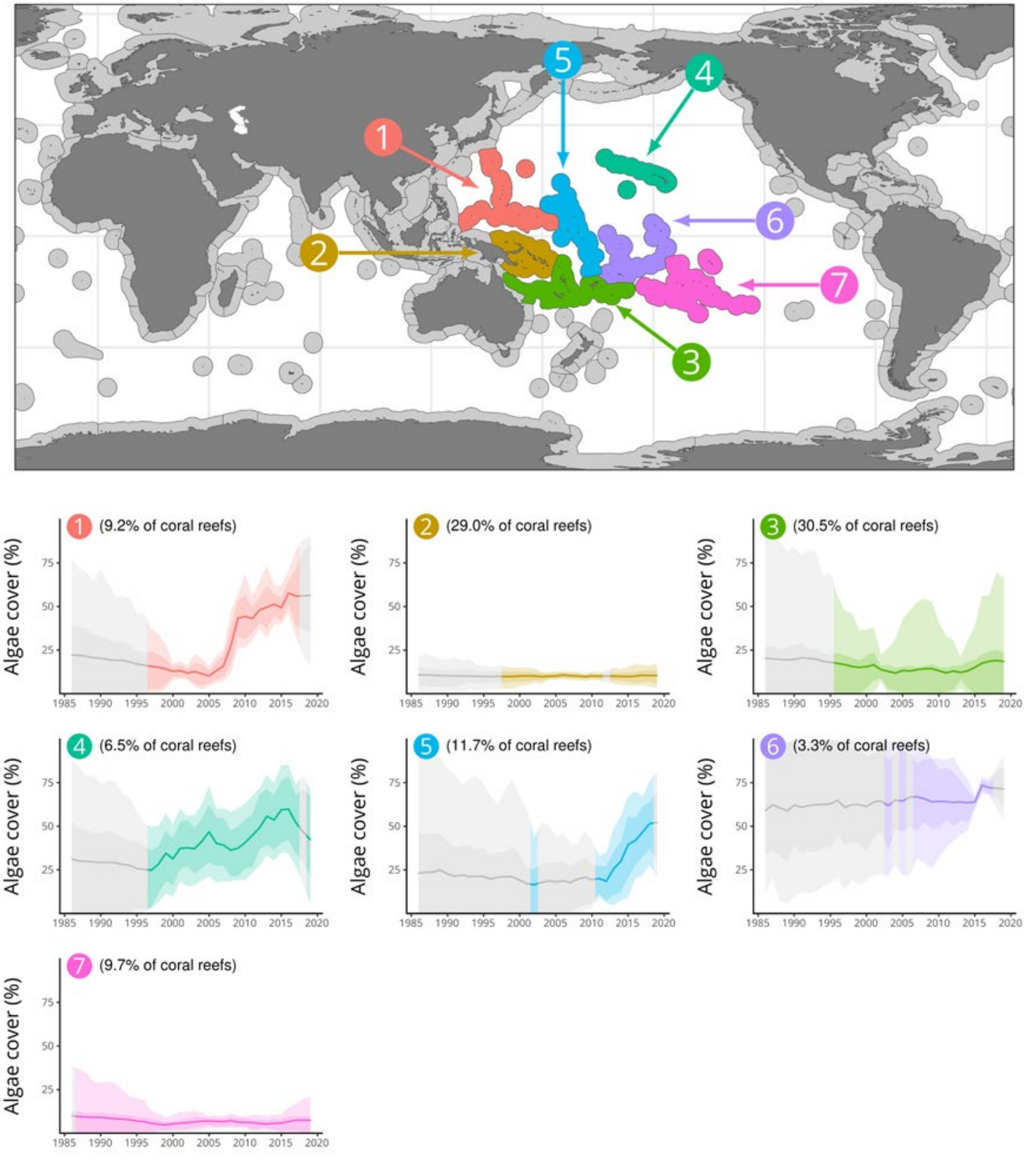


Figure 9.7. Estimated average cover of algae within each subregion comprising the Pacific region. The solid line represents the estimated mean and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods during which no field data were available. The proportion of all coral reefs in the Pacific region within each subregion is indicated by the % of coral reefs.

Box 7.

Mesophotic Coral Ecosystems are unique 'bright spots' of biodiversity

The thought of coral reefs conjures up visions of abundant bright and colourful organisms living in shallow, tropical, waters. While these sunlit waters support extensive coral growth and diversity, some hard coral species can be found at depths as great as 172 m in mesophotic coral ecosystems (MCEs)[1,2], but unlike reefs in the photic zone (<30 m), MCEs are poorly studied and conserved.

Hard corals rely on the products of photosynthesis by symbiotic zooxanthellae (*Symbiodiniaceae*) living within the tissues of the coral polyp to fuel up to 90% the coral's energy requirements for growth and reproduction[3]. As a consequence, the depths at which corals can survive is constrained by the exponential decrease in irradiance (<1% of surface light at 100 m depth), the change of the spectral composition of light (e.g. dominated by blue), the drop in seawater temperature[4], and low hydrodynamic and nutrient enrichment. In order to cope with these constraints, corals living in MCEs demonstrate several adaptations, including increasing zooxanthellae density, flattening skeleton morphology, shifting *Symbiodiniaceae* composition, reducing the number of polyps per surface area, increasing heterotrophy, decreasing tissue thickness and decreasing reproductive effort[5,6,7,8]. Research on MCEs reveals new knowledge of the biological and evolutionary mechanisms employed by corals to withstand such marginal environmental conditions, and provides insights regarding the adaptive capacity of corals.

Historically, interest in MCEs centred on their potential as refuges. The Deep Reef Refugia

1 Rouzé, H., Galand, P.E., Medina, M. et al. Symbiotic associations of the deepest recorded photosynthetic scleractinian coral (172 m depth). ISME J 15, 1564–1568 (2021). https://doi.org/10.1038/s41396-020-00857-y

2 Baker EK, Puglise KA, Harris PT (2016) Mesophotic coral ecosystems – a lifeboat for coral reefs?. The United Nations Environment Programme and GRID-Arendal, Nairobi and Arendal

3 Muscatine L (1990) The role of symbiotic algae in carbon and energy flux in reef corals. In: Dubinsky Z (ed) Coral reefs. Ecosystems of the world. vol 25. Elsevier, Amsterdam, pp 75–87

4 Rooney, J., Donham, E., Montgomery, A., Spalding, H., Parrish, F., Boland, R., Fenner, D., Gove, J., Vetter, O. (2010). Mesophotic coral ecosystems in the Hawaiian Archipelago. Coral Reefs 29: 361-367. https://doi.org/10.1007/s00338-010-0596-3

5 Smith TB, Maté JL, Gyory J (2017) Thermal refuges and refugia for stony corals in the eastern tropical Pacific. In: Glynn WP, Manzello PD, Enochs CI (eds) Coral reefs of the eastern tropical Pacific: persistence and loss in a dynamic environment. Springer Netherlands, Dordrecht, pp 501–515

6 Bongaerts P, Frade PR, Hay KB et al (2015b) Deep down on a Caribbean reef: lower mesophotic depths harbor a specialized coral-endosymbiont community. Sci Rep 5:7652

7 Muir P, Wallace C, Bridge TC, Bongaerts P (2015) Diverse staghorn coral fauna on the mesophotic reefs of north-east Australia. PLoS ONE 10:e0117933

8 Lesser MP, Slattery M, Stat M et al (2010) Photoacclimatization by the coral Montastraea cavernosa in the mesophotic zone: light, food, and genetics. Ecology 91:990–1003

Hypothesis (DRRH) states that deep reefs may act as refuges against major disturbances (e.g., bleaching, pollution) and could provide a source of larvae to reseed decimated shallow reefs[9]. However, recent studies have shown that the vertical connectivity between deep and shallow reefs is far less than previously thought, and more complex, depending on species and geographic areas.

MCEs are generally divided into lower and upper zones, with a faunal break around 60 m. Upper MCEs support species of coral that can occur in both upper and lower MCEs, and are more likely to play a role as a potential refuge for shallow water coral reef species[10]. Lower MCEs support distinct assemblages of deep adapted corals and unique biodiversity (some of it undescribed and potentially endemic to this light-limited zone) that have inherent biological and conservation value. MCEs represent “bright spots” in the mesophotic zone, supporting unusually high coral cover and unique species diversity and assemblages at unexpected depths (e. g. Maui’s 'Au’au channel in Hawaii[11]), which, in turn, provide fish refuges, socio-ecological services for human populations .

Although some studies argue that MCEs are less affected than shallow-water reefs by the multitude of human and environmental pressures of the Anthropocene era, MCEs are exposed to threats such as oil spills and overfishing and require appropriate protection. Innovations in diving technology (e.g. closed-circuit rebreathers) and submersibles offer the possibility to better explore the world’s deepest coral reef ecosystems and enhance our scientific understanding of their extent, ecology and the importance of their contribution to coral reef functioning in order to prioritize management actions and conserve these unique ecosystems.

[9] Bongaerts P, Ridgway T, Sampayo EM, Hoegh-Guldberg O (2010) Assessing the ‘Deep Reef Refugia’ hypothesis: focus on Caribbean reefs. Coral Reefs 29:309–327

[10] Kahng S, Copus JM, Wagner D (2017) Mesophotic coral ecosystems. In: Rossi S, Bramanti L, Gori A, Orejas C (eds) Marine animal forests. Springer.

[11] Pyle RL, Boland R, Bolick H et al (2016) A comprehensive investigation of mesophotic coral ecosystems in the Hawaiian Archipelago. PeerJ 4:e2475

Box 8.

Recovery of hard coral cover: the case of Moorea

Jérémy Wicquart, Serge Planes

Ecosystems face a variety of disturbances that modify their structure and processes, sometimes dramatically. Forest fires that ravage hundreds of hectares are probably among the best known and most striking disturbances. Hence, there have been numerous studies of the capacity of forest ecosystems to recover, or to return to their pre-disturbance state. These studies have been central to research on the temporal dynamics of ecosystems.

On coral reef ecosystems, major disturbances include tropical storms, coral bleaching events and crown-of-thorns starfish (*Acanthaster* spp.) outbreaks. These disturbances impact the foundation species of reefs - the hard corals - either by breaking their skeleton or by partially or totally killing the colonies. This reduces the complex habitats they form and shelter they provide, which, in turn, can have cascading impacts on species that depend on hard corals, such as fish and invertebrates. Like forest ecologists, coral reef ecologists are working to determine how long it takes for coral reefs to recover to pre-disturbance states.

Coral reefs in Moorea in French Polynesia have been monitored since the late 1970s making this one of the world's longest monitoring time series. The history of coral reefs in Moorea has not always been peaceful and hard corals have been through several important disturbance events[1]. The last sequence of major disturbances involved the proliferation of the coral predator *Acanthaster* spp., between 2006 and 2010, and cyclone Oli in 2010, which decreased hard coral cover from 50% (Fig. 1A) to nearly 0% (Fig. 1B)[2]. Between 2010 and 2018, hard coral cover gradually recovered almost to pre-disturbance levels (Fig. 1D). This recovery resulted from the recruitment of young corals (Fig. 3C) by larval dispersion[3]. In some cases, recovery has also occurred through remnant coral, either by "re-sheeting" of dead skeletons from patch of tissue that survived (the "phoenix effect"[4]) or through the growth of a fragment from a broken colony (a process similar to cuttings).

[1] Lamy, T., Galzin, R., Kulbicki, M., Lison de Loma, T., & Claudet, J. (2016). Three decades of recurrent declines and recoveries in corals belie ongoing change in fish assemblages. Coral Reefs, 35(1), 293–302. doi:10.1007/s00338-015-1371-2

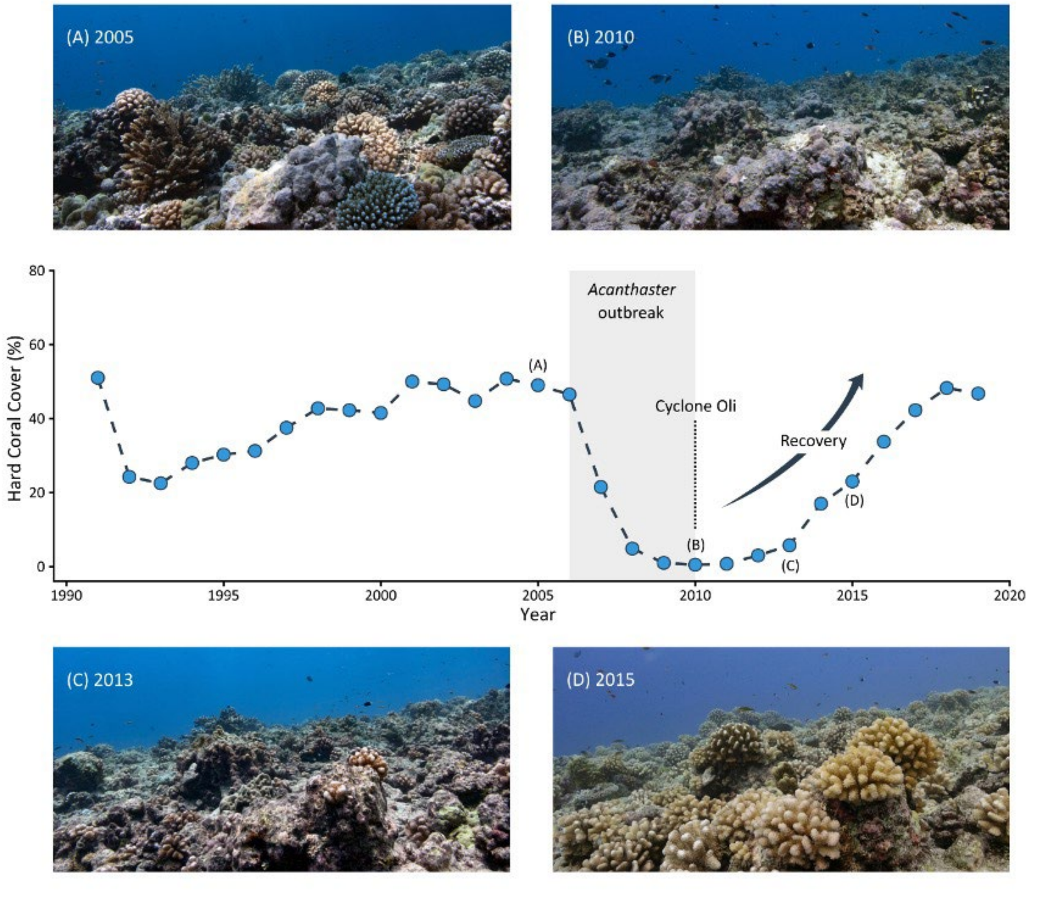
[2] Adjeroud, M., Kayal, M., Iborra-Cantonnet, C., Vercelloni, J., Bosserelle, P., Liao, V., ... Penin, L. (2018). Recovery of coral assemblages despite acute and recurrent disturbances on a South Central Pacific reef. Scientific Reports, 8(1), 1–8. doi:10.1038/s41598-018-27891-3

[3] Holbrook, S. J., Adam, T. C., Edmunds, P. J., Schmitt, R. J., Carpenter, R. C., Brooks, A. J., ... Briggs, C. J. (2018). Recruitment Drives Spatial Variation in Recovery Rates of Resilient Coral Reefs. Scientific Reports, 1–11. doi:10.1038/s41598-018-25414-8

[4] Roff, G., Bejarano, S., Bozec, Y.-M., Nugues, M., Steneck, R. S., & Mumby, P. J. (2014). Porites and the Phoenix effect: unprecedented recovery after a mass coral bleaching event at Rangiroa Atoll, French Polynesia. Marine Biology. doi:10.1007/s00227-014-2426-6

The good news is that hard coral cover can recover. However, coral reefs have adapted to recover in response to "natural" disturbance regimes, characterized by a given frequency and intensity range. If climate change modifies these disturbance regimes by increasing frequency and intensity of coral bleaching events, coral cover may no longer have the time to recover before they are subjected to subsequent disturbances. In order to limit the impacts of global climate change on coral reef ecosystems, greenhouse gas emissions must be reduced. In addition, to improve resistance and/or decrease recovery times from disturbances, local-scale chronic pressures, such as sedimentation, pollution and overfishing, must be mitigated[5].

Figure 1. Trends in live hard coral cover between 1990 and 2020 on the outer slope of the ATPP long-term monitoring site, in Moorea, French Polynesia. Blue points indicate mean values of hard coral cover between the different replicates. The photographs provide an illustration of the condition of the reef at the monitoring site (Photo credit: Yannick Chancerelle, CRIOBE).



5 Lam, V. Y. Y., Doropoulos, C., Bozec, Y. M., & Mumby, P. J. (2020). Resilience Concepts and Their Application to Coral Reefs. Frontiers in Ecology and Evolution, 8(March), 1–14. doi:10.3389/fevo.2020.00049

Chapter 10.

Status and trends of coral reefs of the Eastern Tropical Pacific

Collaborators: Héctor Reyes-Bonilla, Juan José Alvarado, Franz Smith, Jorge Cortés, Fernando Zapata, Fernando Rivera, Arturo Ayala-Bocos, Alan Friedlander, Juan Pablo Quimbayo, Damien Olivier, Priscila Martínez, Ana María Millán, Tatiana Araya, Andrea Arriaga, Manuel Olán, Alejandro Pérez-Matus, Evie Wieters

1. Geographic information and context

Key statistics:

- Total area of coral reefs: 780 km^2
- Proportion of the world's coral reefs: 0.30%
- Number of countries with coral reefs: 9
- Number of Marine Ecosystems of the World (MEOW) ecoregions: 13

Regional context:

The Eastern Tropical Pacific (ETP) comprises the ocean basin extending from the Gulf of California, México to Rapa Nui, Chile, and includes areas of the continental shelf and oceanic islands. The region is bounded by subtropical gyres of the North and South Pacific and the equatorial current system of the Eastern Pacific. An additional significant oceanographic feature of the region is the eastern Pacific warm pool, located along the Central American shelf[1]. The oceanographic dynamics of the region are strongly influenced by low-latitude trade winds, topography (i.e. shelf breaks), a shallow thermocline, and inter-annual climate variation associated with the El Niño-Southern Oscillation (ENSO).

These atmospheric and oceanographic conditions create a distinct environment for the development of coral reef habitats in the region, connectivity and diversity of coral species in the region[1,2]. Localised upwelling provides increased nutrients to shallow water environments, supporting enhanced local primary production. High rainfall in areas of Central America and northern South America reduces surface salinity and contributes to localised turbidity, nutrient loading, and sedimentation. The ETP is also characterised by low surface pH values, which lowers aragonite saturation values and has direct consequences for calcium carbonate mineralisation necessary for reef-building corals[3].

Inter-annual variation in oceanographic conditions associated with ENSO cycles can have dramatic effects on coral reef ecosystems in the ETP. In particular, the El Niño events of 1982-83 and 1997-98 caused extensive mortality of reef-building corals in the region. In many localities, there has been

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[1] Glynn, P.W., D. P. Manzello, and I. C. Enochs. 2017. Coral Reefs of the Eastern Tropical Pacific. Persistence and Loss in a Dynamic Environment. Springer.

[2] Cortés, J. (editor). 2003. Latin American coral reefs. Elsevier, Amsterdam.

[3] Manzello, D.P, J.A. Kleypas, D.A. Budd, C.M Eakin, P.W. Glynn and C. Langdon. 2008. Poorly cemented coral reefs of the eastern tropical Pacific: Possible insights into reef development in a high-CO2 world. Proceedings of the National Academy of Sciences 105: 10450-10455.

limited recovery of coral reef structure, indicating these events can have lasting impacts on reef ecosystems for decades[4],[5],[6].

These factors have combined to form a unique biogeographic situation in the ETP, where there is limited connectivity with the Western Pacific[7]. Subregional and localised oceanographic conditions and the presence of several offshore island archipelagos also contributes to considerable isolation for some coral assemblages within the region. There are an estimated 47 zooxanthellate scleractinian coral species present in the ETP region, of which 8 are considered endemic and the remainder are shared with the central/western Pacific.

Coastal human population density varies considerably across the ETP region, where artisanal fishing and tourism provide an important economic basis for many coastal communities. There has been a steady increase in the gross domestic product (GDP) per capita in key reef-bearing countries during the past two decades, where the average GDP has doubled or tripled in countries such as Chile, Ecuador, Panama and Costa Rica.

The ETP is comprised of 13 Marine Ecoregions of the World[8] (MEOW)(Tab. 10.1, Fig. 10.1), which were grouped into five subregions for the analyses underpinning this report (Tab. 10.1). Subregion 1 combines MEOW ecoregions in the vicinity of the Gulf of California. Subregion 2 is formed by the ecoregions extending along the coast of tropical Mexico and Central America. Subregion 3 includes the Panama Bight and coastal Colombia and Ecuador. Subregion 4 includes the offshore islands of Coco Island and the Galápagos Islands and subregion 5 includes the offshore islands of the Revillagigedo Archipelago and Clipperton Atoll, (Tab.1, Fig. 10.1). This designation captures major variations in north-south variation across the region as well as distinguishing coastal and offshore ecosystems.

Coral reef ecosystems of the ETP region are difficult to resolve using remote sensing technology and there is no comprehensive coral reef habitat map available for the region. This means the estimated area for coral reefs in the region presented in Table 10.1 may differ from the actual area of coral reefs supported by the region.

[4] Glynn, P.W. 1988. El Niño-Southern Oscillation 1982–1983: nearshore population, community and ecosystem responses. Annual Review of Ecology and Systematics 19: 129-160.

[5] Reyes-Bonilla H (2001) Effects of the 1997-1998 El Niño-Southern Oscillation on coral communities of the Gulf of California, Mexico. Bulletin of Marine Science 69:251–266.

[6] Glynn, P.W., B. Riegl, S. Purkis, J.M. Kerr and T.B. Smith. 2015. Coral reef recovery in the Galápagos Islands: the northernmost islands (Darwin and Wenman). Coral Reefs 34: 421-436.

[7] Baums IB, Boulay JN, Polato NR, Hellberg ME. 2012. No gene flow across the Eastern Pacific Barrier in the reef-building coral Porites lobata. Molecular Ecology 21:5418–5433

[8] 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 10.1. The subregions comprising the Eastern Tropical Pacific region, the area of reef they support, and the constituent Marine Ecoregions of the World (MEOW)

Subregion	Reef Area (km²)*	Proportion of Total Reef Area Within the ETP Region(%)	Constituent Marine Ecoregions of the World
1	19	2.4	060: Cortezian 061: Magdalena Transition
2	255	32.7	166: Mexican Tropical Pacific 167: Chiapas-Nicaragua 168: Nicoya
3	269	34.5	170: Panama Bight 171: Guayaquil
4	227	29.1	169: Cocos Islands 172: Northern Galapagos Islands 173: Eastern Galapagos Islands 174: Western Galapagos Islands
5	9	1.2	164: Revillagigedos 165: Clipperton

*UNEP-WCMC, WorldFish Centre, WRI, TNC (2018). Global distribution of coral reefs, compiled from multiple sources including the Millennium Coral Reef Mapping Project. Version 4.0. URL: http://data.unepwcmc.org/datasets/1

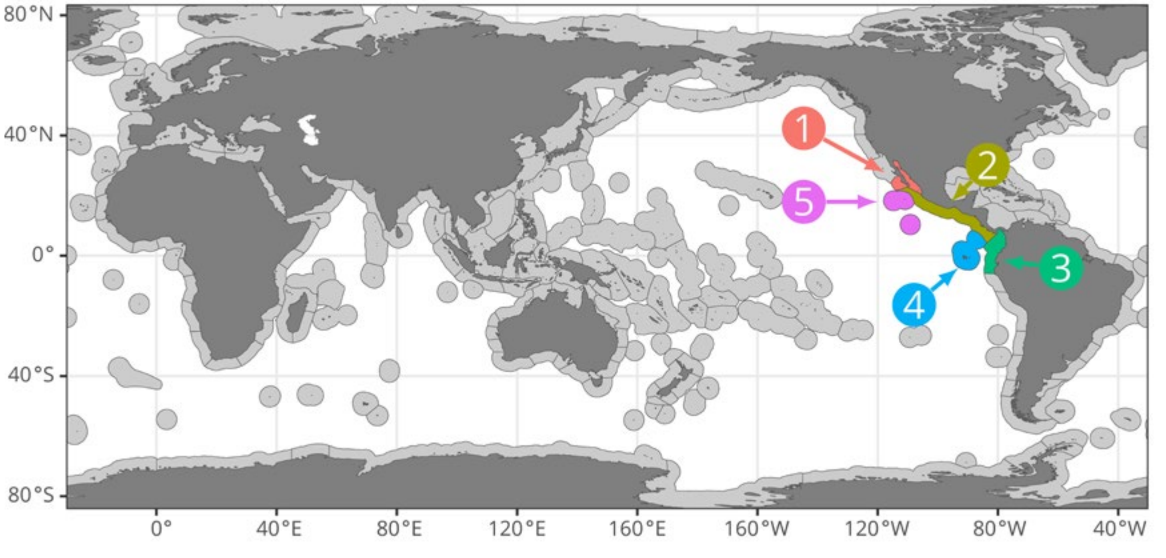

Figure 10.1. Map of each subregion comprising the Eastern Tropical Pacific region. The number ascribed to each subregion corresponds with that in Table 10.1.

2. Summary of data contributed to this report

Key numbers:

- Number of countries from which monitoring data were obtained: 8 (of 9)
- Number of sites: 352
- Number of observations: 10,627
- Longest time series: 18 years

General features:

Data were compiled for the region which extends from México to Ecuador and includes the offshore islands and archipelagos of Clipperton Atoll, Revillagigedos Islands Galápagos and Rapa Nui. The number of sites varied across territories in the region, with a total of 352 sites surveyed for the cover of coral and algae (Tab. 10.2, Fig. 10.2). The temporal resolution of the data also varied, with some time-series survey data dating back to ~18 years. The majority of sites were surveyed for shorter time periods (i.e. < 5 years, Fig. 10.3A). The number of surveys conducted increased substantially from 2005 (Fig. 10.3B). Compiled data were standardised to percent cover and taxonomic resolution was standardised to the lowest level possible (i.e. in most cases at the level of Genus or Family for corals and functional group for algae).

Table 10.2. Summary statistics describing data contributed from the Eastern Tropical Pacific 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.

Eastern Tropical Pacific 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	10,627	1.1	352	2.89	6	1.02
1	5,722	0.59	131	1.08	0	0
2	3,388	0.35	147	1.21	3	0.51
3	982	0.1	50	0.41	2	0.34
4	535	0.06	24	0.2	1	0.17
5	0	0	0	0	0	0

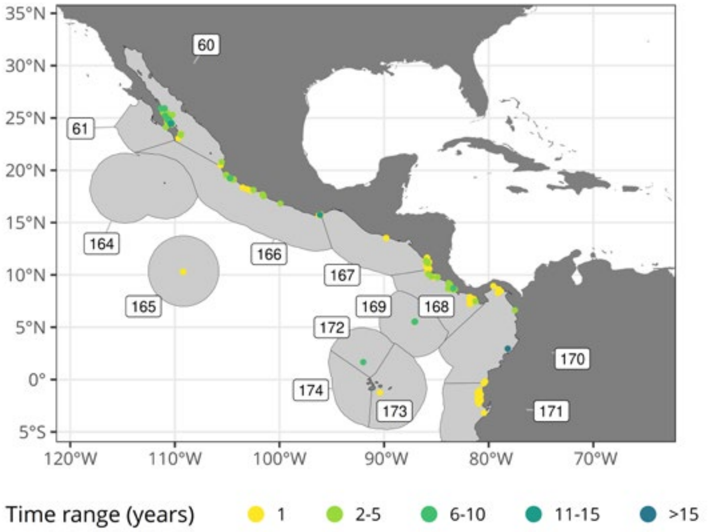

Figure 10.2. The distribution and duration of monitoring at sites across the Eastern Tropical Pacific region. The colours of dots represent the time span between the first survey and the most recent survey at each site. Numbers refer to the MEOW ecoregions listed in Table 10.1.

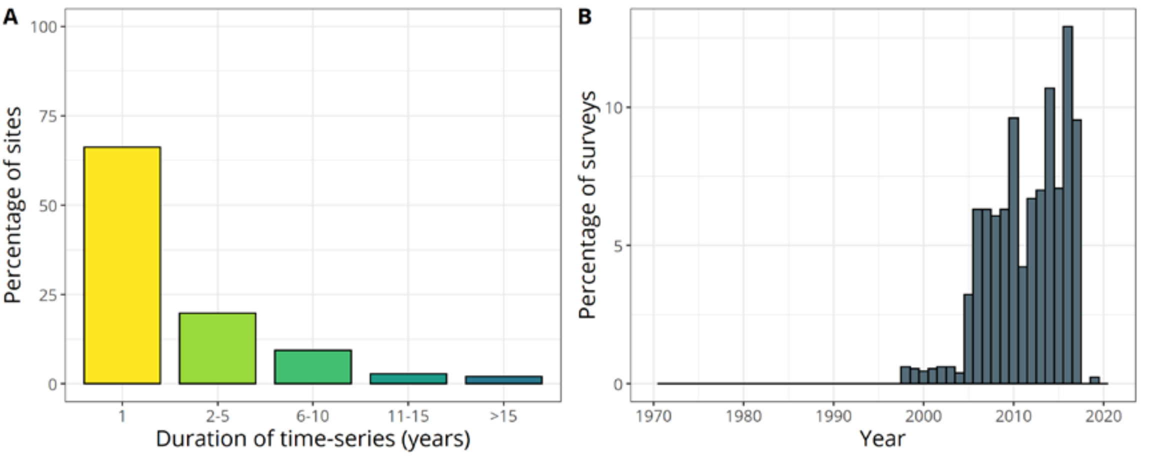

Figure 10.3. The proportion of sites in the Eastern Tropical Pacific region within each category describing the time span between the first and most recent surveys (A), and the proportion of the total number of surveys conducted in each year (B). The number of surveys was 1,277.

3. Status of coral reefs in the Eastern Tropical Pacific region

Regional trends in the cover of live hard coral and algae

The average cover of live hard coral on coral reefs in the ETP region has declined progressively from 34.6% in 1998 to 22.4% in 2016 (Fig. 10.4A). The only deviations from this downward trajectory during that time occurred in 2000 and 2010, when small increases in coral cover were recorded. Since 2016, the cover of hard coral has been maintained around 22.8%, although data from few surveys conducted in 2018 and 2019 were made available (Fig. 10.3B).

In contrast, the average cover of algae has increased across the region from 40.9% in 1998 to 49.1% in 2019 (Fig. 10.4B). The trend in the average cover of algae was characterised by a progressive increase between 2001 and 2007, followed by a slower decline until 2015. However, dramatic increases in the cover of algae were recorded in 2016 and 2017 associated with an unusual warm period across a large areas of the region.

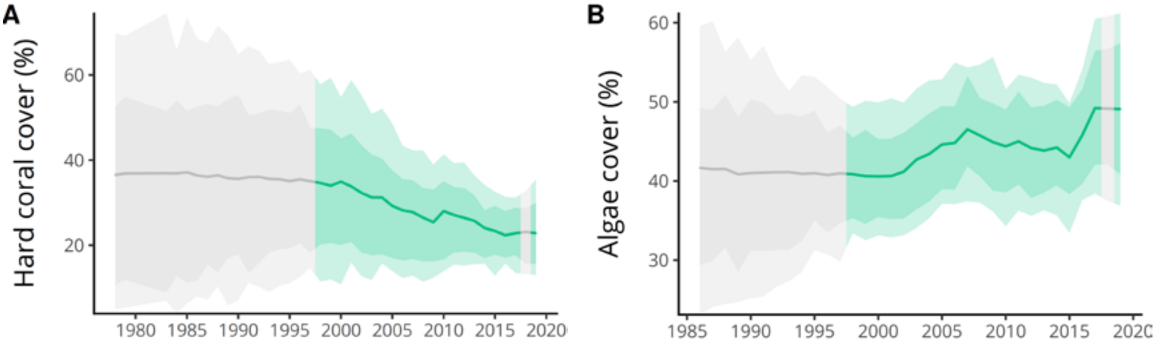

Figure 10.4. Estimated regional average cover of live hard coral (A) and algae (B) for the Eastern Tropical Pacific region. The solid line represents the estimated mean and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent 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) during the last 15 years shows a moderate probability (72%) of a decline in coral cover between 2005-09 and 2015-19. The decline in average coral cover was likely to be in the order of 4.4%, which equates to about 13.3% less coral on the reefs of the ETP (Tab. 10.3).

Table 10.3. Probability and magnitude of mean absolute and relative change in the percent cover of live hard coral in the Eastern Tropical Pacific 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	61	-1.9	-4.6
2010-14 - 2015-19	67	-2.5	-9.7
2005-09 - 2015-19	72	-4.4	-13.3

A similar comparison of the average cover of algae between the same five-year periods suggested a similar likelihood (72%) of an increase in algal cover between 2005-09 and 2015-19. However, the net increase was due to the high probability (83%) of an increase in algal cover in the order of 4.3 % between 2010-14 and 2015-19 after a small decline (1.2%) in algal cover between 2005-09 and 2010-14 (Tab. 10.4).

Table 10.4. Probability and magnitude of mean absolute and relative change in the percent cover of algae in the Eastern Tropical Pacific 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	68	-1.2	-4.2
2010-14 - 2015-19	83	4.3	21.2
2005-09 - 2015-19	74	3.1	15.3

- Changes in resilience of coral reefs within the Eastern Tropical Pacific region

To identify changes in the resilience of coral reefs in the ETP region, patterns of disturbance and recovery were examined within sampling units 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%. None of the 6 such sampling units in the ETP region recovered to at least 90% of their pre-disturbance hard coral cover (Tab. 10.5). Among those sampling units, the average decline in hard coral cover between the first survey and most recent surveys was 60.4%, which represents a loss of almost all (95.1%) the hard coral at these sites (Tab. 10.5).

Table 10.5. 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
6	6	100	63.5	96.7	60.4	95.1

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

Coastal development, eutrophication and poor land use practises in the region have also increased during the last two decades, suggesting that pressures from increased sedimentation and the alteration of coastal processes have also played a role in decreasing live coral cover and increasing algal cover. Pressure from local fisheries have also been implicated in the reduction of key coral reef grazers and predators important in controlling sea urchin populations.

The rapid population increases of invasive and noxious species has also affected coral reef ecosystems of the region. For example, blooms of noxious forms of *Caulerpa* spp., and outbreaks of crown-of-thorns starfish (*Acanthaster* spp.), and sea urchins (e.g. *Diadema* sp.) have had severe, localised impacts on reefs. The potential impacts of invasive species on coral reef processes is an emerging area of research for the area and highlights the interplay of human-derived and natural variability that determine the extent of impacts and potential actions to mitigate such impacts.

As the ETP can be strongly influenced by ENSO and other climatic events, these analyses suggest that coral reefs of the region may be more resilient to climate fluctuations than previously thought, although there has been a decline in live coral cover since the severe ENSO event of 1997-1998.

The ETP region is fortunate to have a number of large marine protected areas (MPAs), which predominantly occur around islands or in offshore areas (e.g. Coiba, Panama; Galápagos Islands) and protect coastal areas in the region. These large MPAs serve as important reference points to assess broader regional change and to better understand ecosystem recovery and resilience across coastal-offshore ecosystems.

4. Subregional trends in cover of live hard coral and algae within the Eastern Tropical Pacific region

Within the ETP region, there was a considerable degree of heterogeneity in the estimated trends in the covers of coral and algae (Fig. 10.5 & 6). For example, in the coastal subregions, there was a sharp decline following the 1997-98 ENSO event in subregion 1 and a more gradual decline across two decades in subregion 3. In contrast, little change occurred in the average cover of hard coral in subregion 2. In contrast, offshore subregions (4 & 5) showed a moderate increase in average coral cover since 2010 (Fig. 10.5), although few data were available for subregion 5 and it is difficult to generalise across the entire subregion.

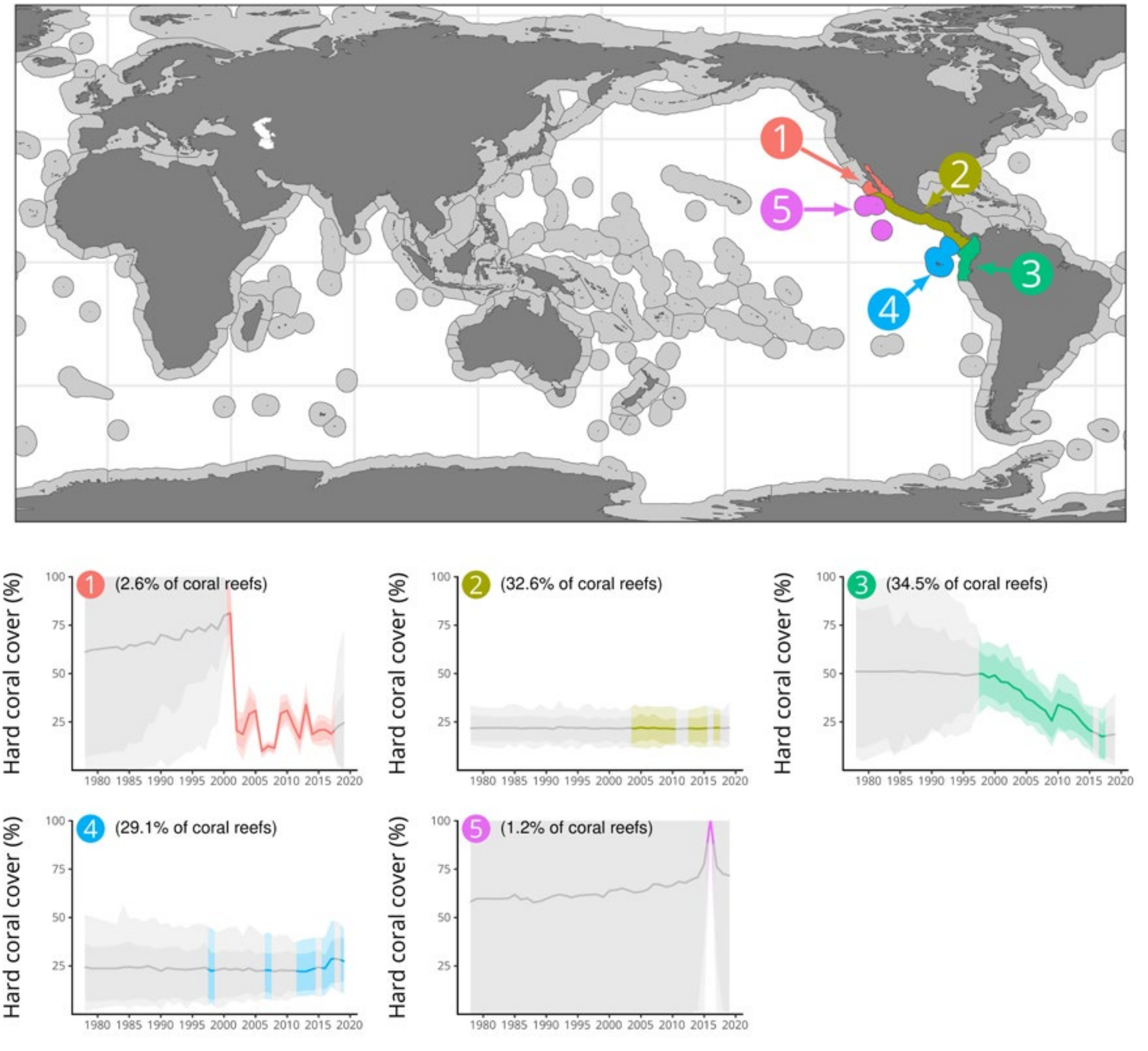

Figure 10.5. Estimated average cover of live hard coral within each subregion comprising the Eastern Tropical Pacific region. The solid line represents the estimated mean and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods during which no field data were available. The proportion of all coral reefs in the Eastern Tropical Pacific region within each subregion is indicated by the % of coral reefs.

In subregion 1, there was a sharp increase in the average cover of algae after the 1997-98 ENSO event, followed by decline to 2010 and a moderate increase to 2018 (Fig. 10.6). Subregions 2 and 4 showed high (~50%) and stable trends in algal cover. In contrast, subregion 3 showed a moderate increase in algal cover from 1997 to 2007, followed by a decrease to 2016. This was followed by an relatively sharp increase in algal cover to 2018, suggesting that distinct changes have occurred recently for this subregion (Fig. 10.6). No data describing algal cover were available from subregion 5.

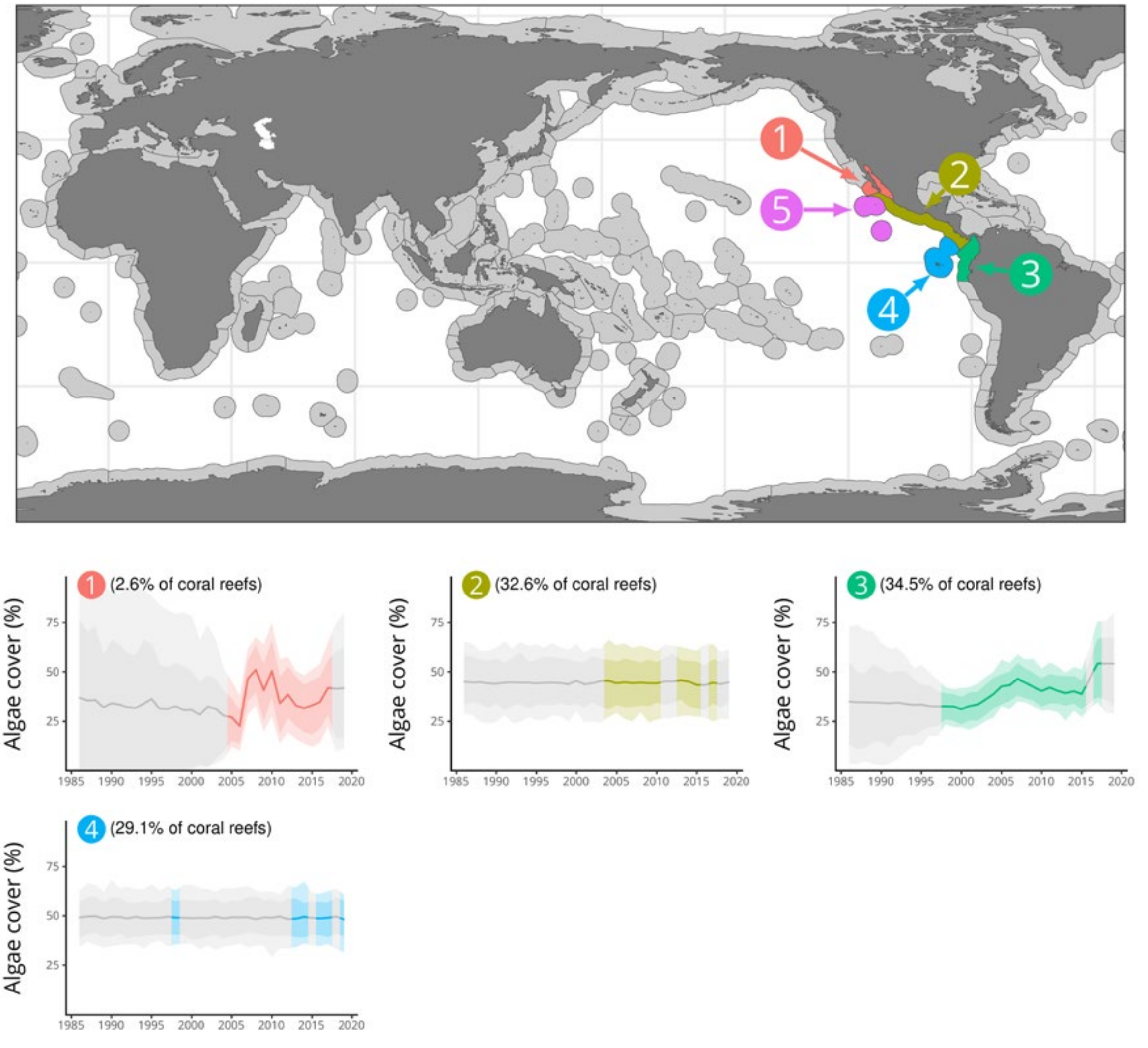

Figure 10.6. Estimated average cover of algae within each subregion comprising the Eastern Tropical Pacific region. The solid line represents the estimated mean and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods during which no field data were available. The proportion of all coral reefs in the Eastern Tropical Pacific region within each subregion is indicated by the % of coral reefs. Note: no data describing the cover of algae were available for subregion 5.

Box 9.

The Allen Coral Atlas

The Allen Coral Atlas provides detailed maps of the world's coral reefs derived from high-resolution satellite images. The Atlas will provide scientists, reef managers, conservationists and countries with an unprecedented amount of data describing the location and structure of coral reefs to help monitor, conserve and restore these critical ecosystems around the world.

The Allen Coral Atlas was launched in December 2017 through a partnership established by Vulcan that now includes Planet, The University of Queensland, Arizona State University and the National Geographic Society. When established, Vulcan and its partners announced the intent to map the world's shallow coral reefs by 2021 and, once reefs were mapped, would deploy a monitoring system to alert Atlas users to changes that could indicate potential coral bleaching.

By late 2018, the Atlas team completed the first ever global photo-mosaic of the world's coral reefs derived from satellite imagery. This map illustrated the global distribution and extent of coral reefs using machine learning tools to differentiate reef area from non-reef area in a globally consistent way. As of December 2020, the Atlas features detailed maps of the Andaman Sea, eastern Africa and Madagascar, eastern Papua New Guinea and Solomon Islands, Hawaiian Islands, Northern Caribbean, Florida and the Bahamas, Southwestern Pacific, Timor and Arafura Seas, Western Indian Ocean and Western Micronesia. The team is on track to complete the global map, at unprecedented resolution, by mid-2021.

In October 2020, the Atlas, in partnership with NOAA's Coral Reef Watch, deployed a time series functionality that displays sea surface temperatures back to October 2018. Most recently, Atlas developers delivered a coral bleaching detection system for the Hawaiian Islands that uses machine learning to analyze changes in the brightness of individual pixels of satellite images over time. This new feature will be expanded globally within the next year and will enable coral scientists to identify areas potentially experiencing coral bleaching and to respond to these events.

As the Atlas matures, it will provide increasingly accurate maps of the distribution and extent of the world's coral reefs. The Atlas will be a key tool used to accurately weight the statistical models that underpin *GCRMN Status of Coral Reefs of the World* reports and to monitor and measure progress against the Convention on Biological Diversity Post-2020 Global Biodiversity Framework goals, targets and indicators. The Allen Coral Atlas will provide the maps and data to help the coral reef monitoring community, including scientists, reef managers, conservationists, countries and networks such as the GCRMN, understand the location, area and status of their coral reefs.

Chapter 11.

Status and trends of coral reefs of the Brazil region

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Collaborators: Maria Bernadete Barbosa, Iara Braga Sommer, Eduardo Cavalcante de Macedo, Jarian Dantas, Daniel Lino Lippi, Maurizelia Brito, Leonora Fritzsche, Ismael Escote, Carlos Henrique Lacerda, Luiza Gomes, Sergio Rezende, Simone Marques

1. Geographic information and context

Key numbers:

- Total area of coral reefs: 1.226 km^2
- Proportion of the world's coral reefs: 0.47%
- Number of countries with coral reefs: 1
- Number of Marine Ecoregions of the World (MEOW) ecoregions: 4

Regional Context:

Brazil supports the only coral reefs in the South Atlantic, spread along 3,000 km of the coast, from 0°50'S to 18°00'S[1]. The continental shelf is carbonatic and narrow along most of its length. Coral reef formations grow parallel to the coast, including fringing as well as long bank reefs[2]. The continental shelf widens in the south at Abrolhos Bank, which is the largest coral reef formation in the region. Coral reef formations are also found on oceanic islands and banks, and on the Fernando de Noronha chain lies the Rocas Atoll, the only atoll in the South Atlantic Ocean[3]. Isolated coral formations occur in the north in the Parcel Manuel Luis in Maranhao (0° 50' S) and occur as far as São Paulo state (24°0' S)[1,4].

Coral reef formations in Brazil are unique both in form and species composition, growing in unique mushroom shapes (chapeirão) that may form pinnacles 20 m high, such as the Abrolhos "chapeirões", or extensive reef tops in shallow areas, by expanding laterally and coalescing in the top[2,3]. Low diversity (23 species of hard coral and five species of hydrocoral) and strong endemism (nine of 28 species are endemic) are distinct characteristics of Brazilian coral reefs[1].

[1] Leão, Z. M., Kikuchi, R. K., Ferreira, B. P., Neves, E. G., Sovierzoski, H. H., Oliveira, M. D., Maida, M., Correia, M. D., & Johnsson, R. (2016). Brazilian coral reefs in a period of global change: A synthesis. Brazilian Journal of Oceanography, 64(SPE2), 97-116.

[2] Leão, Z. M., Kikuchi, R. K., & Testa, V. (2003). Corals and coral reefs of Brazil. In Latin American coral reefs (pp. 9-52). Elsevier Science.

[3] Maida, M., & Ferreira, B. P. (1997). Coral reefs of Brazil: an overview. In Proceedings of the 8th international coral reef symposium (Vol. 1, No. 263, p. 74). Smithsonian Tropical Research Institute Panamá.

[4] Pereira-Filho, G. H., Shintate, G. S., Kitahara, M. V., Moura, R. L., Amado-Filho, G. M., Bahia, R. G., & Motta, F. S. (2019). The southernmost Atlantic coral reef is off the subtropical island of Queimada Grande (24 S), Brazil. Bulletin of Marine Science, 95(2), 277-287.

Present time mesophotic reefs were formed during sea level fluctuations, with transgressive and regressive seas marking different stages of reef development[1,2]. Those give-up reefs, formed during the last low sea level period, are present along the outer shelf from the Amazon, where extensive reefs have been described[5,6], to the whole north-eastern coast where they have been classified as an Ecologically or Biologically Significant Marine Area by the Convention of Biological Diversity[7]. Those deep reefs are part of the coralline seascape, represent a faunal corridor and are interconnected by many populations of reef fish[8].

The coastal zone is home to 25 million inhabitants, with most large cities located along the coast. Coastal reefs that emerge on lower tides are an important feature of this region, inspiring city names like Recife (*reef* in Portuguese), providing coastal protection and most of the catches of the artisanal fisheries that dominate the region. Tourism is a growing industry in the region, with clear waters and coral reefs being the main attraction. Main reef areas are part of marine protected areas (MPAs), such as Rocas Atoll and Fernando de Noronha Island, Abrolhos Bank and the Coral Costa MPA, although strict protection is still very low and presently threatened by increasing pressures[9].

The Brazil region is located in the South Western Atlantic and includes four Marine Ecoregions of the World (MEOW) ecoregions[10] (Tab. 11.1, Fig. 11.1). In subregion 1, sites were located at Rocas Atoll and Fernando de Noronha Archipelago, which are both fully protected (no-take) MPAs. Subregion 2 includes the coastal reefs of the north-eastern region, with sites located at two sustainable-use MPAs, the Coral Reef MPA and the Coral Coast MPA. Subregion 3 includes Porto Seguro reefs and the Abrolhos Marine Park, which is a fully protected MPA.

Table 11.1. **The subregions comprising the Brazil region, the area of reef they support, and the constituent Marine Ecoregions of the World (MEOW)**

Subregion	Reef Area (km^2)*	Proportion of reef area within the Brazil region(%)	Constituent Marine Ecoregions of the World
1	10	0.8	074: Fernando de Noronha and Atol das Rocas
2	349	28.5	075: Northeastern Brazil
3	730	59.5	076: Eastern Brazil 077: Trindade and Martin Vaz Islands**
4	137	11.2	071: Guianan** 072: Amazonia**

***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

5 Moura, R. L., Amado-Filho, G. M., Moraes, F. C., Brasileiro, P. S., Salomon, P. S., Mahiques, M. M., ... & Thompson, F. L. (2016). An extensive reef system at the Amazon River mouth. Science advances, 2(4), e1501252.

6 Francini-Filho, R. B., Asp, N. E., Siegle, E., Hocevar, J., Lowyck, K., D'Avila, N., Vasconcelos, A. A., Batielo, R., Rezende, C. E., Omachi, C. Y., Thompson, C. C., & Thompson, F. L. (2018). Perspectives on the Great Amazon Reef: extension, biodiversity, and threats. Frontiers in Marine Science, 5, 142.

7 CDB - Secretariat of the Convention on Biological Diversity. (2014). Ecologically or Biologically Significant Marine Areas (EBSAs): Special places in the world's oceans. Volume 2: Wider Caribbean and western Mid-Atlantic region. Montreal, QC, Canada: Secretariat of the Convention on Biological Diversity

8 Olavo, G., Costa, P. A., Martins, A. S., & Ferreira, B. P. (2011). Shelf-edge reefs as priority areas for conservation of reef fish diversity in the tropical Atlantic. Aquatic conservation: marine and freshwater ecosystems, 21(2), 199-209.

9 Magris, R. A., Mills, M., Fuentes, M. M. P. B., & Pressey, R. L. (2013). Analysis of progress towards a comprehensive system of marine protected areas in Brazil. Nat. Conserv, 11(1), 1-7.

10 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

**No data were received from this subregion.

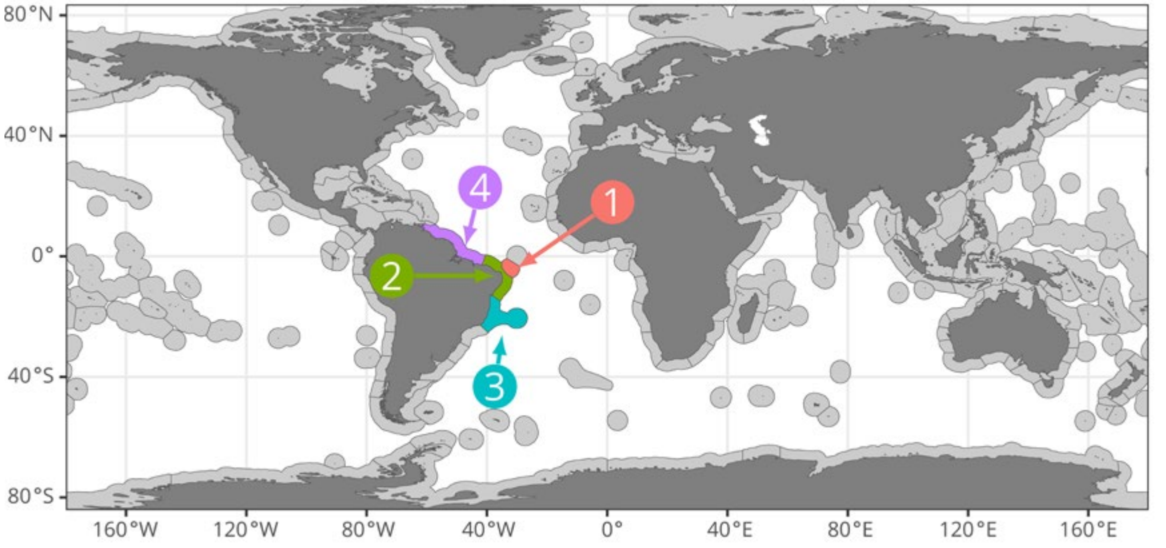

Figure 11.1. Map of each subregion comprising the Brazil region. The number ascribed to each subregion corresponds with that in Table 11.1.

2. Summary of data contributed to this report

Key numbers:

- Number of countries from which monitoring data were used: 1 (of 1)
- Number of sites: 35
- Number of observations: 6,308
- Longest time series: 16 years

General features:

The status and trends of Brazilian coral reefs presented below are based on more than 6,300 observations collected as part of a national coral reef monitoring program that commenced in 2002. Using a Reef Check compatible protocol, 35 sites distributed between 3°5'S and 18°0'S[11] (Tab. 11.2) have been surveyed, with some sites being regularly monitored until 2018-2019. Coral cover data were collected exclusively using point intercept transects (Fig. 11.4), and include both scleractinian hard corals and milleporid hydrocorals, which are the only reef-building branching forms present on Brazilian reefs[12]. These data comprise 0.65% of the global dataset that underpins this GCRMN *Status of Coral Reefs of the World: 2020* report.

The distribution of monitoring effort across Brazilian reefs reflects different local conditions and support for the national monitoring program at different times. The monitoring effort was distributed across the different areas, with the largest number of surveys conducted in subregion 2 due to the

[11] Ferreira, B. P.; Gaspar, A. L. B.; Coxey, M. S.; Monteiro, A. C. G. (2018). Manual de Monitoramento Reef Check Brasil 2018. Ministério do Meio Ambiente, Brasília, DF. Available online: http://www.mma.gov.br/publicacoes/

[12] Coni, E. O. C., Ferreira, C. M., de Moura, R. L., Meirelles, P. M., Kaufman, L., & Francini-Filho, R. B. (2013). An evaluation of the use of branching fire-corals (Millepora spp.) as refuge by reef fish in the Abrolhos Bank, eastern Brazil. Environmental Biology of Fishes, 96(1), 45-55.

long-term support of ongoing projects.

Monitoring sites are generally located within MPAs and have been surveyed between seven and 12 times since 2002. The number of surveys conducted was greater in 2005, 2007, 2009/2010 and 2016 (the last two corresponding with El Niño periods), with monitoring occurring at more than 20 sites (Fig. 11.3B).

Long-term monitoring (>15 years between the first survey and the most recent survey) occurred at nine sites within the Brazilian region, with each site being surveyed over a period of 16 years (Tab. 11.2, Fig. 11.2 and 3A).

Table 11.2. Summary statistics describing data contributed from the Brazil 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.

Brazil 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	6,308	0.65	35	0.29	9	1.53
1	1,755	0.18	11	0.09	4	0.68
2	2,487	0.26	12	0.1	1	0.17
3	2,066	0.21	12	0.1	4	0.68
4	0	0	0	0	0	0

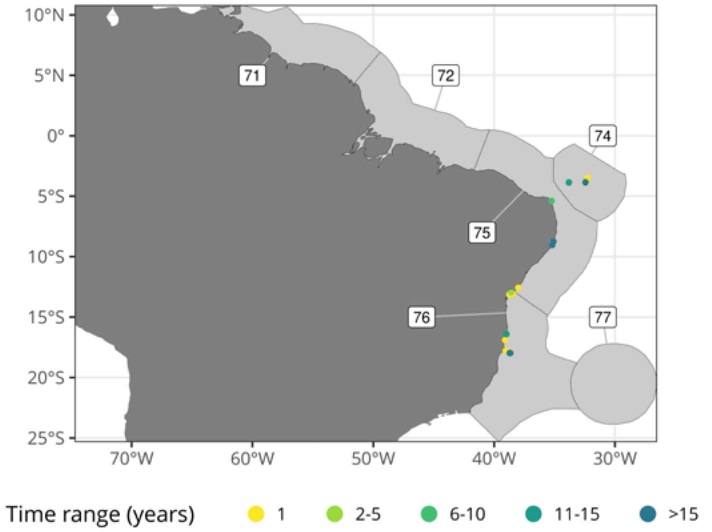

Figure 11.2. The distribution and duration of monitoring at sites across the Brazil region. The colours of dots represent the time span between the first survey and the most recent survey at each site. Numbers refer to the MEOW ecoregions listed in Table 11.1.

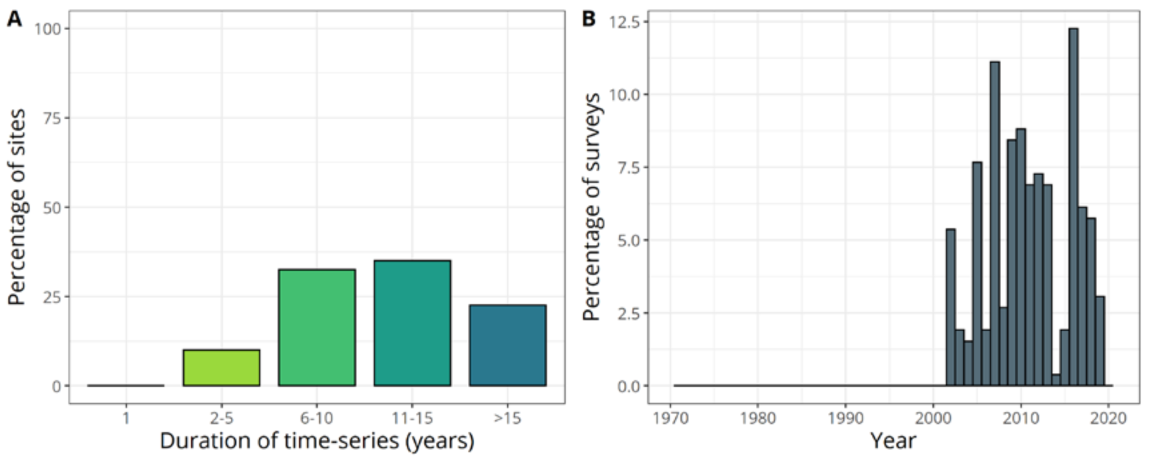

Figure 11.3. The proportion of sites in the Brazil region within each category describing the time span between the first and most recent surveys (A), and the proportion of the total number of surveys conducted in each year (B). The total number of surveys was 261.

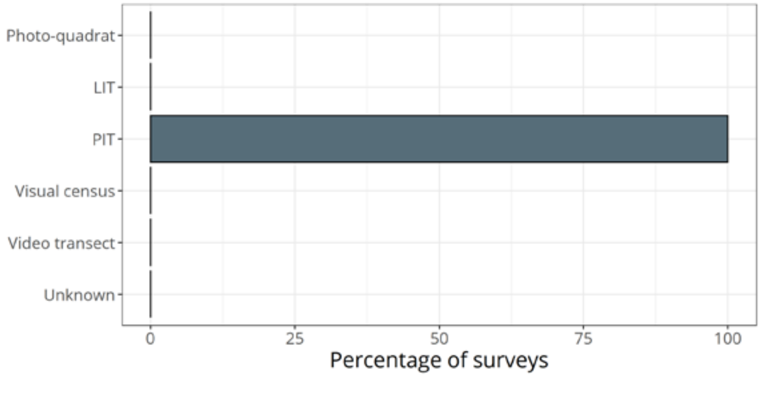

Figure 11.4. The proportion of the total number of surveys conducted in the Brazil region using each survey method. PIT: Point Intercept Transect; LIT: Line Intercept Transect.

3. Status of coral reefs in the Brazil region

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

The trend in average hard coral within the Brazil region fluctuated, initially declining from 19.1% in 2002, when the first data were collected, to 16.3% in 2005, before increasing to 28.9% in 2016 (Fig. 11.5A). Between 2016 and early 2019, a sharp decline in average coral cover to 20.6% was observed. This pattern was largely driven by the eastern subregion (subregion 3), which supports the largest area of reefs in the region (Tab. 11.1).

The average cover of algae almost doubled during the last 15 years. An initial increase occurred between 2002 and 2008 when the average cover of algae increased from 19.5% to 29.1% (Fig. 11.5B). Between 2009 and 2014, the cover of algae remained reasonably stable ranging between 30% (2010) and 27.5% (2014). Since 2015, the average cover of algae has progressively increased to 37% in 2019 (Fig. 11.5B).

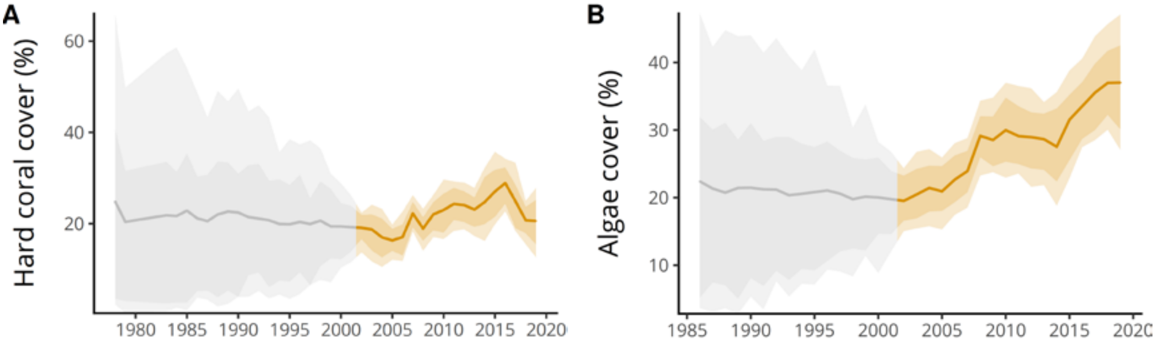

Figure 11.5. Modelled cover of live hard coral (A) and algae (B) for the Brazil Region. The solid line represents the predicted marginal mean and ribbons represent 80% (lighter shade) and 95% (darker shade) credible intervals. Grey areas of the temporal series represent times for which no observed data were available.

Comparisons of the average hard coral cover between the three five-year periods comprising the last 15 years (2005-09, 2010-14, 2015-19) showed that there was a high probability (92-98%) that coral cover had increased between 2005-09 and 2010-14 (4.1% average absolute change) and overall between 2005-09 and 2015-19 (3.0% average absolute change), representing relative increases of 27.0% and 20.3% respectively (Tab. 11.3). However, between 2010-14 and 2015-19, there was weak evidence (69.3% probability) of a decline, which is consistent with possible effect of the mass bleaching event observed during the 2016 El Niño[13].

Table 11.3. Probability and magnitude of mean absolute and relative change in the percent cover of live hard coral in the Brazil 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	98	4.1	27
2010-14 - 2015-19	69	-1.0	-4.6
2005-09 - 2015-19	92	3.0	20.3

[13] Teixeira, C. D., Leitão, R. L., Ribeiro, F. V., Moraes, F. C., Neves, L. M., Bastos, A. C., Pereira-Filho, G. H., Kampel, M., Salomon, P. S., Sá, J. A., Falsarella, L. N., Amario, M., Abieri, M. L., Pereira, R. C., Amado-Filho, G. M., & Moura, R. L. (2019). Sustained mass coral bleaching (2016–2017) in Brazilian turbid-zone reefs: taxonomic, cross-shelf and habitat-related trends. Coral Reefs, 38(4), 801-813.

Comparisons of the average cover of algae over the same three five-year periods showed a moderate probability (88%) of an increase in the cover of algae between 2005-09 and 2010-14, but that there was a very strong probability of an increase between 2010-14 and 2015-19 (99%) and over the longer term between 2005-09 and 2015-19 (100%) (Tab. 11.4). On average, absolute increases in algal cover were considerably greater between 2010-14 and 2015-19 (6.6%) than between 2005-09 and 2010-14 (2.4%). Despite some variation between individual sites and the greater contribution of the eastern subregion (subregion 3) to the analysis, the substantial overall trend suggested that there was, on average, 57% more algae on reefs in the region in 2015-19 compared with 2005-09 (Tab.4) . This pattern was consistent with trends observed in subregions 1 and 3, while in subregion 2 there was little net change despite considerable fluctuations in algal cover since monitoring began in 2002 (Fig. 11.7).

Table 11.4. **Probability and magnitude of mean absolute and relative change in the percent cover of algae in the Brazil 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	88	2.4	10.4
2010-14 - 2015-19	99	6.6	43.5
2005-09 - 2015-19	100	9.0	57.1

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

Historically, chronic land-based threats such as sedimentation and pollution have been the major cause of coral loss on coastal reefs of the Brazilian region[2,3,14], with oceanic and shelf reefs being less affected. In the last decade, increased intensity and frequency of El Niño Southern Oscillation (ENSO) events have overshadowed those threats, with stronger and more widespread events causing mass coral bleaching and affecting coral and algal cover on Brazilian coral reefs. ENSO events impacted Brazilian reefs during 2003, 2005, 2010 and 2016, causing bleaching and mortality, which varied in intensity depending on subregion and local characteristics[13,15,16,17,18].

The moderate El Niño event of 2010 was the first to affect the entire region since the 1998 El Niño. This event caused bleaching in all subregions and although subsequent coral mortality was low[18,19], an increase in the prevalence of diseases was observed at oceanic sites[17]. The eastern subregion (subregion 3) was the most affected by the large-scale global warming event of 2016, which caused mass coral bleaching but low subsequent mortality[13,20].

Conversely, algal cover has been increasing during the last two decades, particularly in the oceanic

[14] Dutra, L. X. C., Kikuchi, R. K. P., & Leão, Z. M. A. N. (2006). Effects of sediment accumulation on reef corals from Abrolhos, Bahia, Brazil. Journal of Coastal Research, 633-638.

[15] Kikuchi, R. K., Leão, Z. M., & Oliveira, M. D. (2010). Conservation status and spatial patterns of AGRRA vitality indices in Southwestern Atlantic Reefs. Revista de biologia tropical, 58, 10-32.

[16] Leão, Z. M. A. N., Kikuchi, R. K., Oliveira, M. D., & Vasconcellos, V. (2010). Status of Eastern Brazilian coral reefs in time of climate changes. Pan-American Journal of Aquatic Sciences, 5(2), 224-35.

[17] Ferreira, B. P., Costa, M. B. S. F., Coxey, M. S., Gaspar, A. L. B., Veleda, D., & Araujo, M. (2012). The effects of sea surface temperature anomalies on oceanic coral reef systems in the southwestern tropical Atlantic. Coral reefs, 32(2), 441-454.

[18] Miranda, R. J., Cruz, I. C., & Leão, Z. M. (2013). Coral bleaching in the Caramuanas reef (Todos os Santos Bay, Brazil) during the 2010 El Niño event. Latin American Journal of Aquatic Research, 41(2), 351-360.

[19] Lisboa, D. S., Kikuchi, R. K. P., & Leão, Z. M. (2018). El Nino, sea surface temperature anomaly and coral bleaching in the South Atlantic: A chain of events modeled with a Bayesian approach. Journal of Geophysical Research: Oceans, 123(4), 2554-2569.

[20] Duarte, G. A., Villela, H. D., Deocleciano, M., Silva, D., Barno, A., Cardoso, P. M., ... & Peixoto, R. S. (2020). Heat waves are a major threat to turbid coral reefs in Brazil. Frontiers in Marine Science, 7, 179.

(subregion 1) and the eastern (subregion 3) subregions. The causes of those increases were unclear but could be associated with eutrophication and intensification of warming events. More studies are necessary to understand the complex patterns of algal dynamics[21].

- Changes in resilience of coral reefs within the Brazil region

To identify changes in the resilience of coral reefs in the Brazil region, patterns of disturbance and recovery were examined within sampling units 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%. Of the 11 such sampling units, more than half (7) did not recover to at least 90% of their pre-disturbance hard coral cover (Tab. 11.5). The average decline in hard coral cover between the first and most recent surveys within these sampling units was almost 6% representing a loss of 17.2% of the existing hard coral cover. The average maximum absolute decline in hard coral cover within these sampling units was 10.4%, which represents a relative loss of 38.8% of hard coral (Tab. 11.5).

Increases in the frequency of bleaching events may lead to direct or indirect coral mortality, due to the prevalence of diseases and competition with algae. Prior to 2016, bleaching-associated coral mortality on Brazilian coral reefs was low compared with other regions of the world, suggesting that these reefs might represent a thermal refuge[21,22]. More recently however, the 2019-2020 coral bleaching event, caused by a massive marine heat wave[20], caused widespread bleaching across all subregions, with estimated mortality exceeding 50% for some species, according to local reports[23,24] and our own observations which were obtained after the data collation period for this report. Coral mortality associated with the 2019-2020 event was the greatest ever recorded in Brazil and it marked a shift in the prevalent view that Brazilian marginal reefs were less vulnerable to global climate patterns. This contrasts with the relative stability observed until now, and highlights both the importance of continuous monitoring and local management measures to mitigate predicted impacts.

Table 11.5. 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
11	7	63.6	10.4	38.8	5.8	17.2

[21] Teixeira C. D., Chiroque-Solano P. M. , Ribeiro F. V., Carlos-Júnior L. A., Neves L. M., Salomon P. S, et al. (2021) Decadal (2006-2018) dynamics of Southwestern Atlantic's largest turbid zone reefs. PLoS ONE 16(2): e0247111. https://doi.org/10.1371/journal.pone.0247111

[22] Mies, M., Francini-Filho, R. B., Zilberberg, C., Garrido, A. G., Longo, G. O., Laurentino, E., ... & Banha, T. N. (2020). South Atlantic coral reefs are major global warming refugia and less susceptible to bleaching. Frontiers in Marine Science, 7, 514.

[23] Ferreira, L. C. L, Grillo, A. C., Repinaldo Filho, F. P. M., Negrao, F., & Longo, G. O. (2021). Different responses of massive and branching corals to a major heatwave at the largest and richest reef complex in South Atlantic. Mar Biol 168, 54 (2021). https://doi.org/10.1007/s00227-021-03863-6

[24] Gaspar, T. L., Quimbayo, J. P., Ozekoski, R., Nunes, L. T., Aued, A. W., Mendes, T. C., Garrido, A. G., & Segal, B. (2021). Severe coral bleaching of Siderastrea stellata at the only atoll in the South Atlantic driven by sequential Marine Heatwaves. Biota Neotropica, 21(2).

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

For the Brazilian region, the trends in hard coral cover among the three different subregions varied, indicating some heterogeneity in exposure to disturbance and recovery related to local conditions, including coral communities present in each subregion.

Subregions 1 and 3 showed a decline in average hard coral cover, with subregion 1 showing a gradual but steady decrease, and subregion 3 showing more oscillations through time with a sharper decline in the last five years (Fig. 11.6). At oceanic sites (subregion 1), it is worth noting that coral cover decrease was recorded mainly in shallow areas. In subregion 2, which supports about a third of the coral reefs of Brazil and where most sites are located near the coast, coral cover increased, while algal cover remained stable. Increased protection, through the control of damage by fishing and tourism inside MPAs and the prohibition of collection and trade in corals, has helped to maintain and improve coral cover, mainly due to recovery and growth of milleporids.

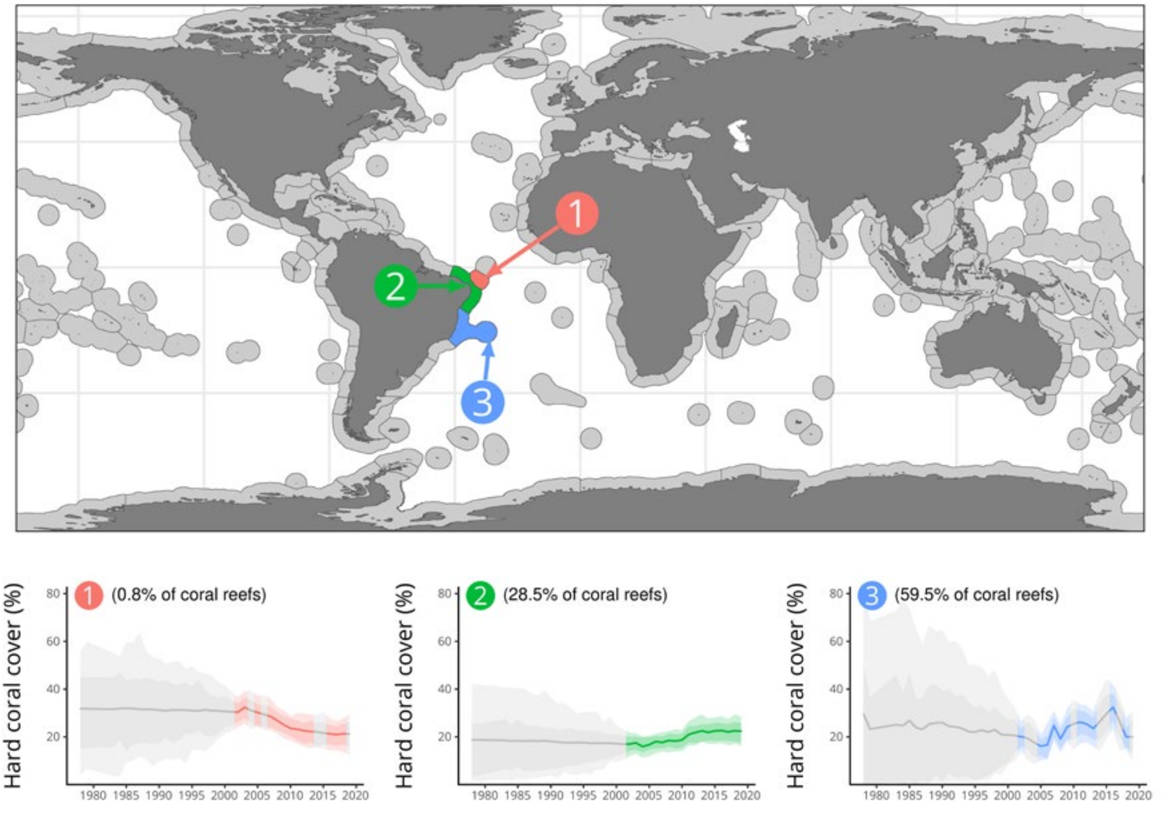

Figure 11.6. Estimated average cover of live hard coral within each subregion comprising the Brazil region. The solid line represents the estimated mean and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods during which no field data were available. The proportion of all coral reefs in the Brazil region within each subregion is indicated by the % of coral reefs.

Similar to hard coral cover, trends in the cover of algae varied among different subregions (Fig. 11.7). Subregions 1 and 3 showed an increase in the average cover of algae, especially in the last decade during which time it almost doubled in subregion 1 (Fig. 11.7). This trend could be related to warming conditions observed over the same period. In subregion 2, the average cover of algae has remained relatively stable during the last 15 years.

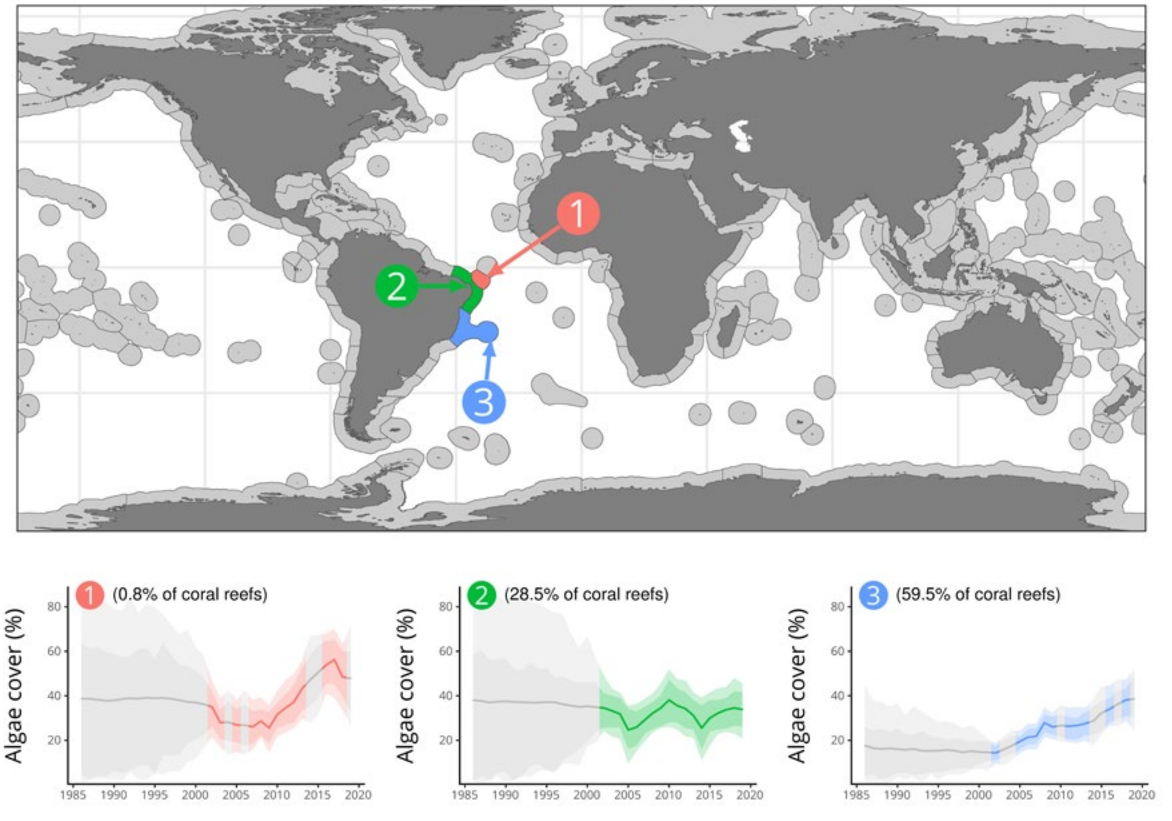

Figure 11.7. Estimated average cover of algae within each subregion comprising the Brazil region. The solid line represents the estimated mean and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods during which no field data were available. The proportion of all coral reefs in the Brazil region within each subregion is indicated by the % of coral reefs.

Chapter 12.

Status and trends of coral reefs of the Caribbean region

Data providers: A. Acosta-Chaparro, Lorenzo Alvarez-Filip, Juan José Alvarado, Jesus Ernesto Arias Gonzalez, Francisco Armando Arias Isaza, Fabien Barthelat, Paulo Bertuol, Tadzio Bervoets, Claude Bouchon, Yolande Bouchon-Navaro, José Luis Cabrera Pérez, Ruleo Camacho, Belkis Carolina Montalvan, Juan Carrasco Navas, Julien Chalifour, Michael Colella, Rachel Collin, Nicole Craig, Marcia Creary Ford, Aldo Croquer, Monique Curtis, Thomas Dallison, Ian Drysdale, Caren Eckrich, Peter Edmunds, Dan Exton, Graham E. Forrester, Roxanne-Liana Francisca, Jan Freiwald, David Gilliam, Ana Giro, Martha Catalina Gomez-Cubillos, Diana Gómez-López, J. Gonzalez-Corredor, Silvia Patricia González Díaz, Carlos González-Gándara, Luis Andres Gradiz Villalobos, Hector Guzman, Nicole Hayes, Mike Helion, Alex Henderson, Quetzalli Hernández, Emma Hickerson, Jerry Jermain Enoe, Michelle Johnston, Kimani Kitson-Walters, Patricia Kramer, Ayumi Kuramae Izioka, Jean-Philippe Maréchal, Gloria Marino, Melanie McField, Melanie Meijer zu Schlochtern, Fiama Molina, Peter Mumby, Thaddeus J.T. Murdoch, R. Navas-Camacho, Marissa Nuttall, Yunier Olivera, Hazel Oxenford, Fernando J. Pardo-Urrutia, Esmeralda Pérez Cervantes, Horacio Pérez España, Fabian Pina Amargos, Angela Randazzo-Eisemann, Andrea Rivera-Sosa, Joaquín Rodrigo Garza Pérez, Robert Ruzicka, L. Sanchez-Valencia, G.P. Schmahl, Janina Seemann, Nuno Simões, Melina Soto, Johan Stapel, Robert Steneck, Ruben Torres, Erica K. Towle, Ewan Trégarot, Henri Valles, Jelle van der Velde, Mark J.A. Vermeij, Gabrielle-Jae Watson, Sven Zea

Co-writers: Mary E. Allen, Tadzio Bervoets, Emma Doyle, Peter E.T. Edwards, Jane Hawkridge, Jean-Philippe Maréchal, Melanie McField, Maria Pena, Sandrine Pivard, David Souter, Erica K. Towle

1. Geographic information and context

Key numbers:

- Total area of coral reefs: 26 397 km^2
- Proportion of the world's coral reefs: 10.17%
- Number of countries with coral reefs: 25
- Number of Marine Ecoregions of the World (MEOW) ecoregions: 10

Regional Context:

The Caribbean Region represents only 1% of Earth's marine surface but hosts 10% of the world's coral reefs, including fringing reefs, which are most common, barrier reefs such as the Mesoamerican Reef, which is the largest barrier reef in the Western Hemisphere, bank reefs, patch reefs, and a few atolls.

Caribbean shallow and mesophotic reefs are characterized by relatively low coral species diversity (70 hard coral species including two Acroporid species*: Acropora palmata* and *A. cervicornis*) and high levels of endemism, making them unique among the world's reefs.

The physical geography of the Caribbean region is also complex with continental coasts (north, central, and south America), large continental islands (Greater Antilles), numerous small sandy islands (The Bahamas), volcanic islands (most of the Lesser Antilles), and coral islands (some Lesser Antilles islands).

The Caribbean is politically and culturally diverse with 30 sovereign states (continental and insular) and 16 European overseas territories or outermost regions (British, Dutch, and French), and considerable economic disparities between nations (e.g. per capita Gross Domestic Product in the USA was USD63,544 compared with less than USD1,200 in Haïti)[1].

About 70% of people in the Caribbean live near the coast. Indeed, Caribbean economies depend heavily on coral reefs and associated ecosystems (seagrasses and mangroves) for recreation and tourism (e.g., sandy beaches, snorkeling, and SCUBA diving), livelihoods, food (e.g., fishes, queen conch, lobsters), and other social, cultural, and economic benefits. Socio-economic monitoring (SocMon) in the Caribbean region, carried out largely according to the GCRMN SocMon protocol, is in use as an approach for coral reef managers and provides valuable insights on how coastal communities value and depend on coral reefs. Thus, SocoMon assessments have been conducted for almost 20 years in the region, including a series of workshops conducted recently beginning in 2016 (Jamaica) to the most recent in 2019 (MesoAmerica) by SPAW-RAC and supported by a NFWF-funded project to develop and refine a set of integrated coral reef monitoring guidelines that explicitly include human dimensions characteristics. For a detailed analysis of the SocMon Caribbean socio-economic assessments, please see the Global SocMon report that is forthcoming in 2022.

Socio-economic monitoring is important in order to understand the human interactions with coral ecosystems so that we can mitigate negative effects to coral reefs while promoting positive benefits that reefs provide [http://socmon.icriforum.org/]. SocMon has been part of the wider GCRMN effort since 1997 and was developed with the intent for socio-economic monitoring to complement biophysical monitoring. While SocMon data are not included in the present analysis, future work should and will seek to integrate Caribbean node socio-economic data with biophysical data.

The Caribbean is divided into 10 Marine Ecoregions of the World (MEOW) Ecoregions[2] that were grouped into five subregions for the analyses underpinning this report (Tab. 1). There are coral reef marine protected areas (MPAs) in many countries in the Caribbean, as well as MPA networks such as MPAConnect and CaMPAM. The MPAs are usually small and generally located in nearshore areas. Efforts to support coral monitoring and capacity-building are underway with support from partner organisations such as the UN Environment Programme/ Cartagena Convention Secretariat, the National Oceanic and Atmospheric Administration (United States of America), the Gulf and Caribbean Fisheries Institute, the Specially Protected Areas and Wildlife protocol and its regional activity center (SPAW-RAC), through regional projects and via multi-national programmes. MPA financing, enforcement, fisheries management, monitoring and communications are among the top management capacity building needs identified by coral reef managers to implement effective marine protection.

[1] World Bank database (https://data.worldbank.org/indicator/NY.GDP.PCAP.CD)

[2] 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 12.1. The subregions comprising the Caribbean region, the area of reef they support, and the constituent Marine Ecoregions of the World (MEOW).

Subregion	Reef Area (km^2)*	Proportion of Total Reef Area within the Caribbean Region (%)	Constituent Marine Ecoregions of the World
1 (BER/ BAH)	5,698	21.6	062: Bermuda 063: Bahamian
2 (E, S Carib)	2,913	11.0	064: Eastern Caribbean 066: Southern Caribbean
3 (Ant)	8,640	32.7	065: Greater Antilles
4 (SW W Carib)	7,197	27.3	067: Southwestern Caribbean 068: Western Caribbean
5 (GoM, FL)	1,949	7.4	043: Northern Gulf of Mexico 069: Southern Gulf of Mexico 070: Floridia

*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

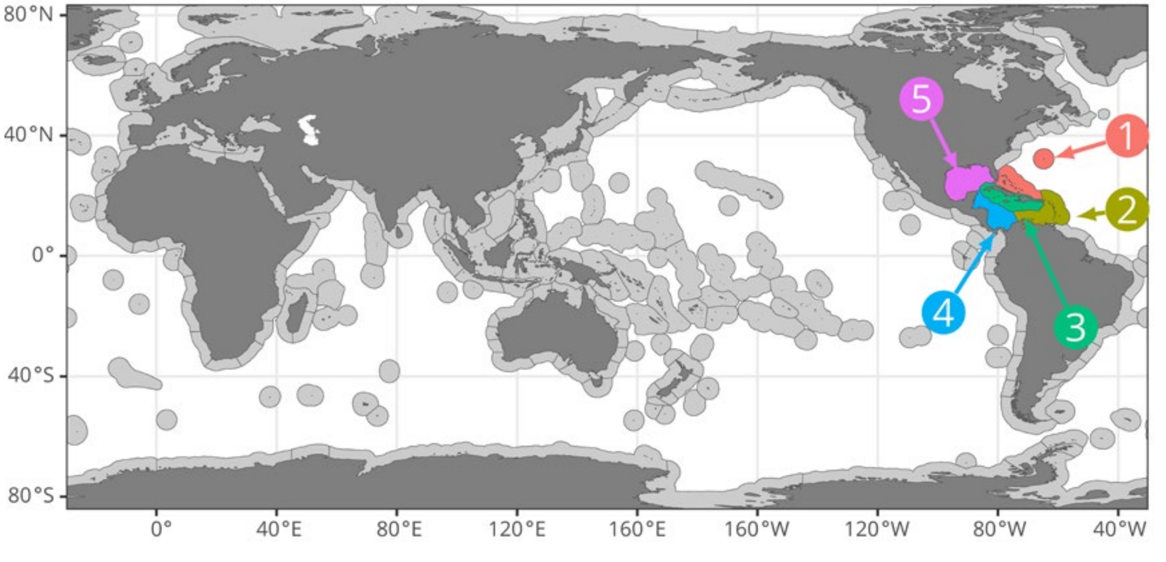

Figure 12.1. Map of each subregion comprising the Caribbean region. The number ascribed to each subregion corresponds with that in Table 1.

2. Summary of data contributed to this report

Key numbers:

- Number of countries from which monitoring data were used: 20 (of 25)
- Number of sites: 3,166
- Number of observations: 209,823
- Longest time series: 29 years

General features:

The status and trends in the cover of hard coral and algae on coral reefs in the Caribbean region presented below are based on almost 210,000 observations collected using a diverse range of methods (Fig. 12.4) by more than 30 entities from 3,166 sites distributed across 20 countries (Tab. 12.2). The first observations contributed to this report were collected in 1983 (Fig. 12.3B). Most observations (36.64%) collected within the Caribbean region were collected in the Eastern and Southern Caribbean (subregion 2). A smaller number of observations were recorded in subregions 1: Bermuda and The Bahamas (12.91%), 3: Greater Antilles (9.36%), 4: Southwestern and Western Caribbean (19.14%) and 5: Gulf of Mexico and Florida (21.96%) (Tab. 12.2).

Table 12.2. Summary statistics describing data contributed from the Caribbean region. An observation is a single record within the global dataset (*i.e.* one row) and may represent a single indivisible observation or the sum or mean of several observations depending on how aggregated the data were when they were contributed to this analysis. 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 that period.

Caribbean subregions	Observations			Sites			Long term monitoring sites		
	Total Number	Proportion of regional dataset	Proportion of global dataset	Total Number	Proportion of regional dataset	Proportion of global dataset	Total Number	Proportion of regional dataset	Proportion of global dataset
All	209,823	100	21.64	3,166	100	26.04	135	100	22.96
1 (BER/BAH)	27,088	12.91	2.79	618	19.52	5.08	0	0	0
2 (E, S Carib)	76,877	36.64	7.93	904	28.55	7.43	41	30.37	6.97
3 (Ant)	19,632	9.36	2.02	389	12.29	3.2	2	1.48	0.34
4 (SW W Carib)	40,157	19.14	4.14	668	21.10	5.49	25	18.52	4.25
5 (GoM, FL)	46,069	21.96	4.75	587	18.54	4.83	67	49.63	11.39

A limited number of sites in this dataset were surveyed between 1983 and 1995, but after 1996 the number of surveys increased dramatically through 2016 (Fig. 12.3B). The number of surveys from which data were provided declined after 2016, particularly in 2018 and 2019, which may be a consequence of the time required to process and share more recently collected data at the time the call for data was announced for this meta-analysis in 2019. The vast majority of sites (80%) had only a single year of survey data (Fig. 12.2 & 12.3A). However, about 6% of sites were monitored for more than a decade, and 4% of sites were monitored for more than 15 years (Fig. 12.2 & 12.3A). Long-term monitoring (>15 years between the first survey and the most recent survey) occurred at 135 sites within the Caribbean region, particularly within the Gulf of Mexico and Florida (67), the Eastern and Southern Caribbean (41), and the Southwestern and Western Caribbean (25) (Tab. 12.2).

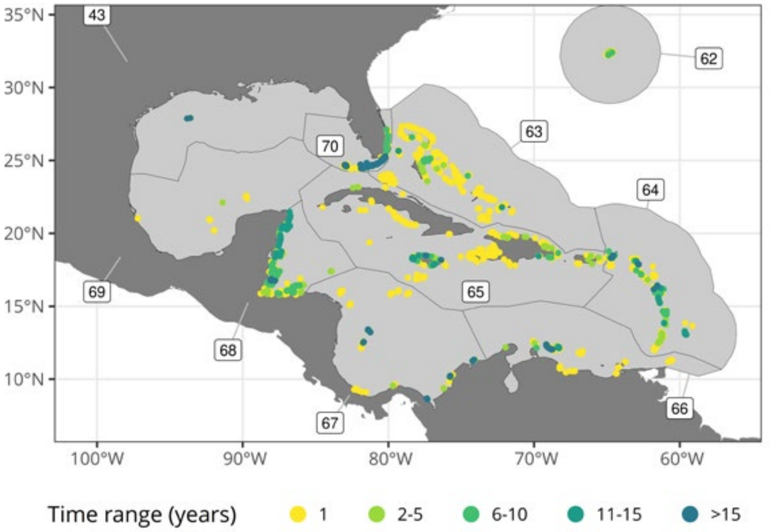

Figure 12.2. The distribution and duration of monitoring at sites across the Caribbean region. The colours of dots represent the time span between the first survey and the most recent survey at each site. Numbers refer to the MEOW ecoregions listed in Table 12.1.

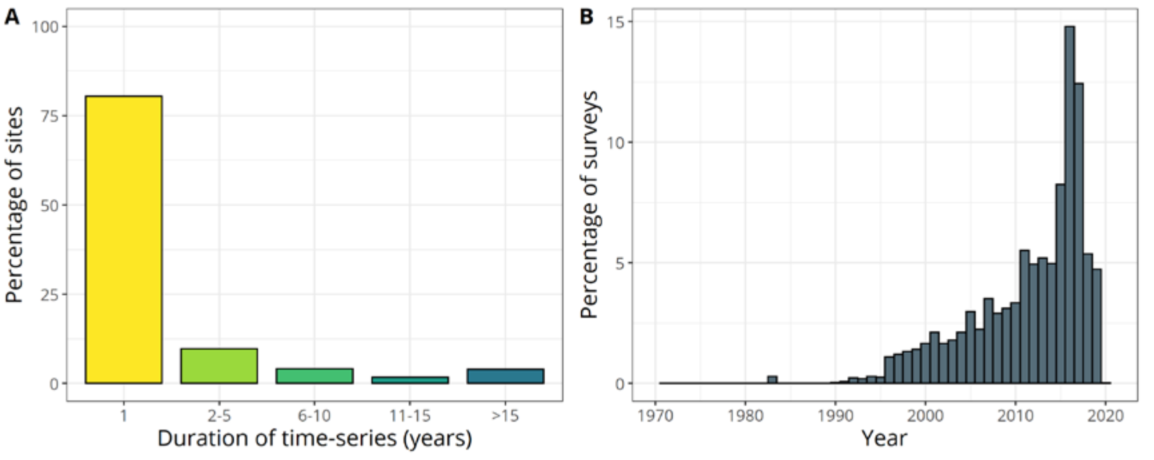

Figure 12.3. The proportion of sites in the Caribbean region within each category describing the time span between the first and most recent surveys (A), and the proportion of the total number of surveys conducted in each year (B). The total number of surveys was 7,127.

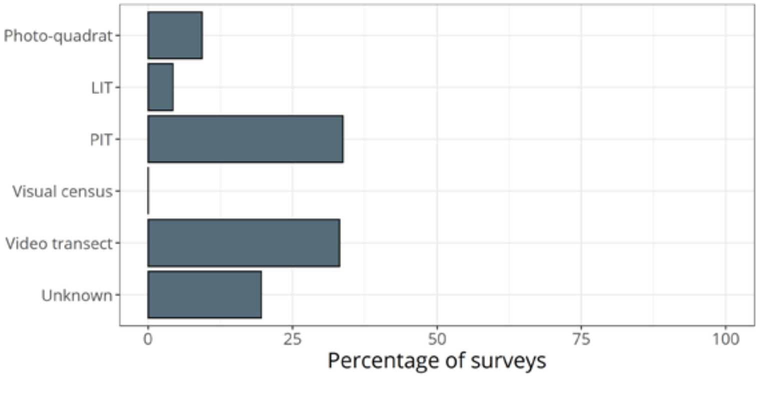

Figure 12.4. The proportion of the total number of surveys conducted in the Caribbean region using each survey method. PIT: Point Intercept Transect; LIT: Line Intercept Transect.

3. Status of coral reefs in the Caribbean region

- Region-wide status of hard coral cover

In 1983 when the earliest data contributed to this report were collected, the estimated average live hard coral cover for the entire Caribbean region (all five subregions pooled) was 18% (Fig. 12.5A), which already represents substantial decline from the average (35%) reported for the period between 1970-1983[3]. The trend from this analysis suggests continued decline in mean hard coral cover during the subsequent 16 years from 1983 (18%) to 1999 (16.5%); however, it should be noted that there is considerable uncertainty surrounding these early estimates due to the scarcity of data available during this time (Fig. 12.5A). Additional declines continued with a mean coral cover of 15.2% in 2005 and 14.6% in 2011 (Fig. 12.5A). Data from this meta-analysis suggest that mean coral cover was 15.9% in 2019, the last year in the current dataset. Overall, the trend suggests that at a region-wide scale, mean coral cover has declined from approximately 18% in 1983 to 15.9% in 2019, (a 2.1% overall decrease in that 36 year period).

The results of this meta-analysis with respect to coral cover may be surprising to those familiar with the region who may have expected steeper declines. The overall decrease presented in this analysis would have been had it included the 1970-1983 baseline from Jackson *et al*. (2014)[3]. It is also important to note that wide variability exists throughout the Caribbean region and data included in this meta-analysis reflect a wide range of degraded to healthy sites throughout the Caribbean. The trends seen in figure 12.5A should be interpreted with two contextual notes.

First, coral reefs in the Caribbean region suffered significant disturbances from hurricanes and/or mass coral bleaching in 1998 and 2005. As a consequence, average hard coral cover across the entire region was at a historical low level (14.1% in 2007). In the absence of further large-scale disturbances between approximately 2007 to 2013, hard coral cover may have recovered in some Caribbean subregions and not in others. Second, this analysis was designed to examine changes in average hard coral cover at the broad regional scale. While the estimate of the region-wide Caribbean average coral cover does consider average coral cover at the five subregional scales, the contribution of the different subregions was weighted according to the area of coral reefs (km^2) in each subregion. The subregions within the Caribbean region that had the greatest area of coral reefs was subregion 3, which was the only subregion that exhibited marginal increases in average coral cover between 1983-2019 (Fig. 12.6). As a consequence, additionally, it should be noted that data from the United States Caribbean territories (included within subregions 2 and 5) are experiencing a much steeper decline than the overall region-wide trend from this meta-analysis. Trends analyses in coral cover for the U.S. Caribbean indicate significant declines in coral cover between 2013-2019[4]. In 2019, mean coral cover was approximately 5% or less in all regions[4].

[3] Jackson JBC, Donovan MK, Cramer KL, Lam VV (editors). (2014) Status and Trends of Caribbean Coral Reefs: 1970-2012. Global Coral Reef Monitoring Network, IUCN, Gland, Switzerland.

[4] Edwards KF, Blondeau J, Grove LJW, Groves SH, Hile SD, Johnson MW, Langwiser C, Siceloff L, Towle EK, Viehman TS, Williams B (2021). National Coral Reef Monitoring Program Biological monitoring summary U.S. Virgin Islands and Puerto Rico: 2019. Coral Reef Conservation Program (U.S.). NOAA technical memorandum CRCP 40. DOI: https://doi.org/10.25923/fdp6-qv15

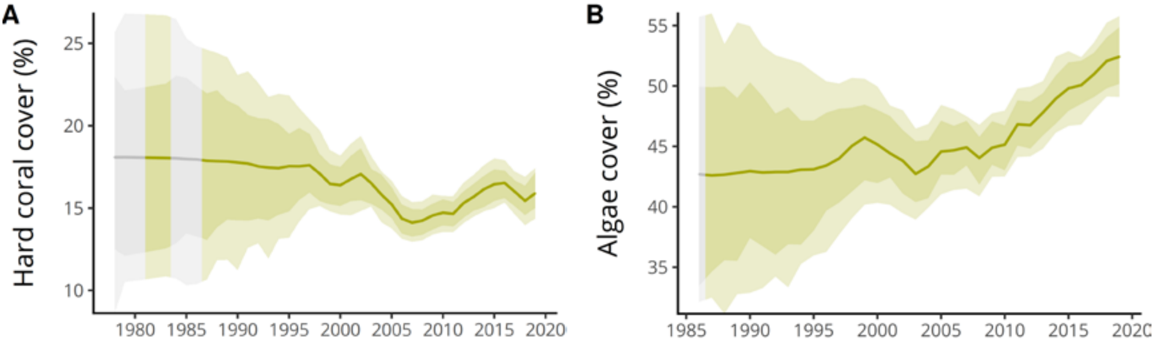

Figure 12.5. Estimated regional average cover of live hard coral (A) and algae (B) for the Caribbean region. The solid line represents the estimated mean and associated 80% (darker shade) and 95% (lighter shade) confidence intervals, which represent levels of uncertainty. Grey areas represent periods during which no field data were available in the Caribbean region.

Table 12.3. Probability and magnitude of mean absolute and relative change in the percent cover of live hard coral in the Caribbean region among 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	1.2	10.3
2010-14 - 2015-19	70	0.3	2.6
2005-09 - 2015-19	99	1.6	13.1

Data from this meta-analysis show that region-wide (all five subregions pooled) mean hard coral cover in the Caribbean declined by 2.1% between 1983 (18%) and 2019 (15.9%). This decline would likely appear much steeper had it included the 1970-1983 (35%) baseline data from Jackson *et al.* (2014)[3]. This analysis was also weighted by area of coral reef (km^2), and the largest subregion was also the only subregion to experience a marginal increase (subregion 3) in hard coral cover over the last two decades. However, all subregions other than subregion 3 experienced overall declines in hard coral cover between 1999-2019, with subregion 2 experiencing the largest overall decline.

- Status of algae cover

As with coral cover, estimates of the average cover of algae (all types) across the Caribbean region prior to about 2001 have large uncertainties owing to the scarcity of data (Fig. 12.5B). Despite this uncertainty in early estimates, the average algal cover remained relatively stable between 1987 (42.6%), when the earliest data contributed to this report were collected, and 1994 (43.1%). From 1995, the algal cover increased until it reached 45.7% in 1999, before declining to 42.7% in 2003. However, since 2003, the average algal cover within the region has progressively increased, reaching 52.4% in 2019 (Fig. 12.5B).

The increase in algal cover between 2005-09 and 2015-19 is unequivocal , with on average almost 31% more algae on Caribbean reefs during the period 2015-19 (Tab. 12.4).

Table 12.4. Probability and magnitude of mean absolute and relative change in the percent cover of algae in the Caribbean 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	3.3	14.3
2010-14 - 2015-19	99	3.4	14.6
2005-09 - 2015-19	100	6.7	30.9

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

At least three widespread ecological disturbances have strongly negatively impacted Caribbean coral reefs during the last five decades: i. White-Band-Disease in the 1970s and 1980s caused the collapse of *Acroporid* populations (*A.palmata* and *A.cervicornis*) which were the main coral reef builders in very shallow coastal environments of the Caribbean; ii. the die-off of sea urchin (*Diadema antillarum)* populations, which are among the most efficient invertebrate herbivores in the Caribbean, that occurred between 1983 and 1984 due to a pathogen; and iii. the mass coral bleaching event that affected the entire Caribbean in 2005.

In addition to large-scale ecological disturbances, more local, chronic threats to Caribbean coral reefs have increased during the last several decades. Coastal water pollution and eutrophication, stemming partially from resident and tourist population growth in concert with inadequate sewage treatment and land-use changes in watersheds, have been significant factors responsible for reducing coral health. Water pollution and eutrophication may facilitate coral disease outbreaks and macroalgal blooms due to increased nutrient inputs. Herbivorous fish and *Diadema* urchins have historically helped contain algal populations at low levels but overfishing and the pathogen that caused *Diadema* die-off have dramatically reduced their numbers and therefore, their ability to help control algal overgrowth. As such, the Caribbean region has been experiencing a phase shift from coral-dominated to algal-dominated reefs. It was caused in part by declines in live coral cover due to storms, disease, and bleaching, algal overgrowth related to eutrophication of coastal waters, and in part by reduced grazing by invertebrate and fish herbivores due to disease and overfishing. Specifically, the overfishing of key herbivorous fish like parrotfishes has greatly contributed to algal overgrowth and proliferation on Caribbean reefs. There are disparities throughout the region in the application and availability of fisheries management tools, as well as in fisheries enforcement and policy-making which impact coral reef health and resilience. Additionally, more frequent and more intense coral bleaching events as well as hurricanes continue to threaten Caribbean reefs. More recently, Caribbean coral reefs have faced a series of new emerging threats from invasive lionfish, to pelagic *Sargassum* influx (since 2011), and the emergence and spread of the novel, highly virulent Stony Coral Tissue Loss Disease (SCTLD).

SCTLD was first observed in Florida in 2014 and affects at least 34 species of stony corals in the Caribbean, including the primary reef-building species in the Atlantic-Caribbean region. The disease has a very large geographic range and as of October 5, 2021 has been confirmed in 19 countries and territories across the wider Caribbean region[5,6]. Prevalence rates of this disease in highly susceptible species have been documented at 66-100% (compared with 3-5% prevalence rates observed with other coral diseases). Most infected coral colonies die. Unlike coral bleaching, individual coral polyps

5 https://www.agrra.org/coral-disease-outbreak/

6 https://oref.maps.arcgis.com/apps/dashboards/54b5df5c111b4fcc986e300c6aea63a3and

cannot recover from SCTLD, although colonies may survive, particularly when treated. SCTLD spreads and progresses very rapidly across reef areas and within individual colonies. Complete mortality within several weeks has been observed in relatively large coral colonies[7]. SCTLD continues to spread across the Caribbean. Many countries in the Caribbean region that have been affected by this disease rely heavily on coral reefs to support their local economies and fisheries and do not currently have adequate resources and capacity to respond to the disease. While the losses suffered as a result of SCTLD are still being evaluated, losses in coral cover of up to 60% have been observed at some reefs in the Virgin Islands[8], and other affected countries have now documented losses of up to 50% of their coral cover[9]. Because so much of the devastation caused by SCTLD in the Caribbean has occurred within only the last several years, its effects are not fully reflected in the present analysis.

- Changes in resilience of coral reefs within the Caribbean region

To identify changes in the resilience of coral reefs in the Caribbean region, patterns of disturbance and recovery were examined within sampling units 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%. It should be noted that resilience is based on many more factors than solely percent coral cover, but for this global analysis, that was the only metric widely available. Among the 247 such sampling units within the Caribbean, 199 (80.6%) did not recover to at least 90% of their pre-disturbance hard coral cover (Tab. 5). On average, hard coral cover declined by 7.2% between the first and most recent survey of these sampling units, which represents a loss of more than half (57.4%) of the hard coral at these sites. The average maximum decline in hard coral cover was 12.3%, which represents a loss of 77.6% of that hard coral within these sampling units (Tab. 12.5).

Increases in the frequency and intensity of disturbances to coral reefs in the Caribbean (especially bleaching and major hurricanes) compounded by chronic water pollution have changed long-term disturbance-recovery patterns as Caribbean reefs have begun to face back-to-back disturbances year-after-year. Consequently, many reefs are not recovering completely between disturbances and the combination of chronic stressors and more frequent disturbances may overwhelm the reefs' ability to recover.

Table 12.5. 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
247	199	80.6	12.2	77.6	7.2	57.4

[7] https://www.agrra.org/wp-content/uploads/2019/07/ONLINE-SCTLD-Infographic_22-02_19.png

[8] University of the Virgin Islands, 2021

[9] Estrada-Saldívar, 2021

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

- Subregional trends in hard coral cover

The trends in hard coral cover varied among the five Caribbean subregions (Fig. 12.6) within the period covered by the database. In Bermuda and The Bahamas (subregion 1), the early data from 1999 showed an average coral cover of 17.6%. A substantial decline in coral cover was observed between 2002 and 2005 followed by failure to recover. The results presented here indicate that long-term mean coral cover has decreased between 1999 (17.6%) and 2019 (13.3%), representing an approximate average decline of 4.3% in those 10 years.

The longest historical time series in the Caribbean region was from subregion 2, which includes the Lesser Antilles, Trinidad and Tobago, the Southern Dutch Caribbean ABC islands, and Venezuela (Fig. 12.6). The data indicate that coral cover has progressively declined within subregion 2 since 1999 when mean coral cover was approximately 26.2% to 14.5% by 2019. This represents an approximate 11.7% live coral cover decrease in this region during the last two decades.

The Greater Antilles (subregion 3) was the only subregion in the Caribbean that exhibited an overall increase in average coral cover over the period for which data were contributed (Fig. 12.6). While slight declines occurred between 1997 and 1999 and between 2005 and 2007, the average coral cover increased by approximately 5.4%, from 10.7% in 1999 to 16.1% in 2019.

Coral reefs in subregion 4, which includes Colombia, Panama, Costa Rica, Nicaragua, Honduras, Belize, Guatemala, and Mexico, exhibited subtle changes in trajectory (Fig. 12.6). Average coral cover slowly decreased from approximately 22.6% average coral cover in 1999 to 21.6% in 2019.

Average coral cover has progressively declined on reefs in the Gulf of Mexico and Florida (Subregion 5) from approximately 13.3% in 1999 to 9.1% in 2019, representing an overall average decrease of 4.2% in that 20-year period (Fig. 12.6).

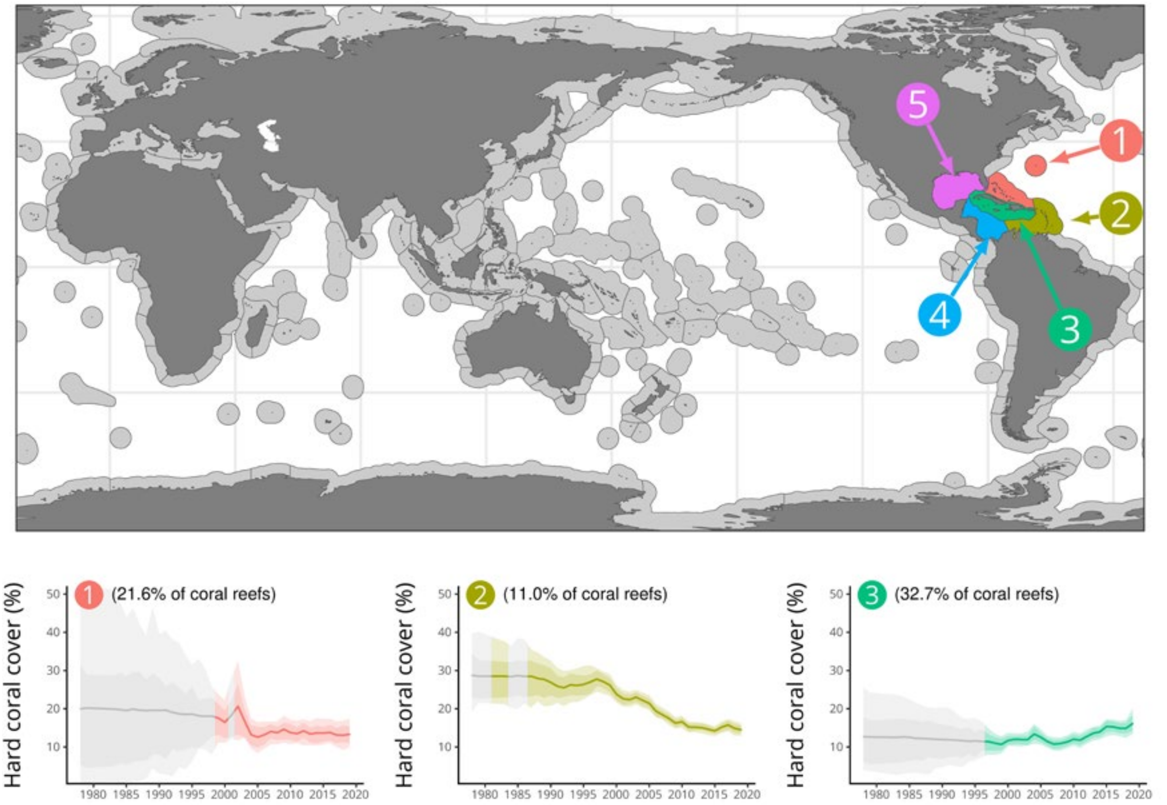

Figure 12.6. Estimated average cover of live hard coral within each subregion comprising the Caribbean region. The solid line represents the estimated mean and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods during which no field data were available. The proportion of all coral reefs in the Caribbean region within each subregion is indicated by the % of coral reefs.

- Subregional trends in algal cover

While the period for which data describing the cover of algae varied among the five different subregions (Fig. 12.7), algae constituted a large proportion of the reef community in each subregion, particularly in subregions 1, 3, and 4. It should be noted that macroalgal cover is highly variable by the timing/seasonality of sampling, reef substrate/habitat type, and specific functional group or species of macroalgae. Subregions 3 and 4 exhibited high initial average algal covers of 54.9% and 45%, respectively, and relatively little change over time (Fig. 12.7). Subregion 1 also exhibited a high initial average algal cover of 44.8% in 1999, but greater variation over the next 12 years ranging between 37.5% and 44.8%. However, between 2011 and 2019, the average cover of algae in subregion 1 progressively increased to 64.4% in 2019 (Fig. 12.7).

Slightly longer time-series were made available from subregions 2 and 5 (Fig. 12.7). In both subregions, the initial average cover of algae was considerably lower and has since increased over time. In subregion 2, the initial average cover of algae was 17.2% in 1987. During the next 33 years, the amount of algae on these reefs almost tripled, reaching 48.3% in 2019. In subregion 5, algal cover also increased over time, particularly from 2006 onward. Between 1992 when the first data were collected and 2005, algae cover decreased from 22% to 16.9% (Fig. 12.7). However, between 2006 and 2015, algal cover increased approximately 2.3-fold reaching 39% in 2015.

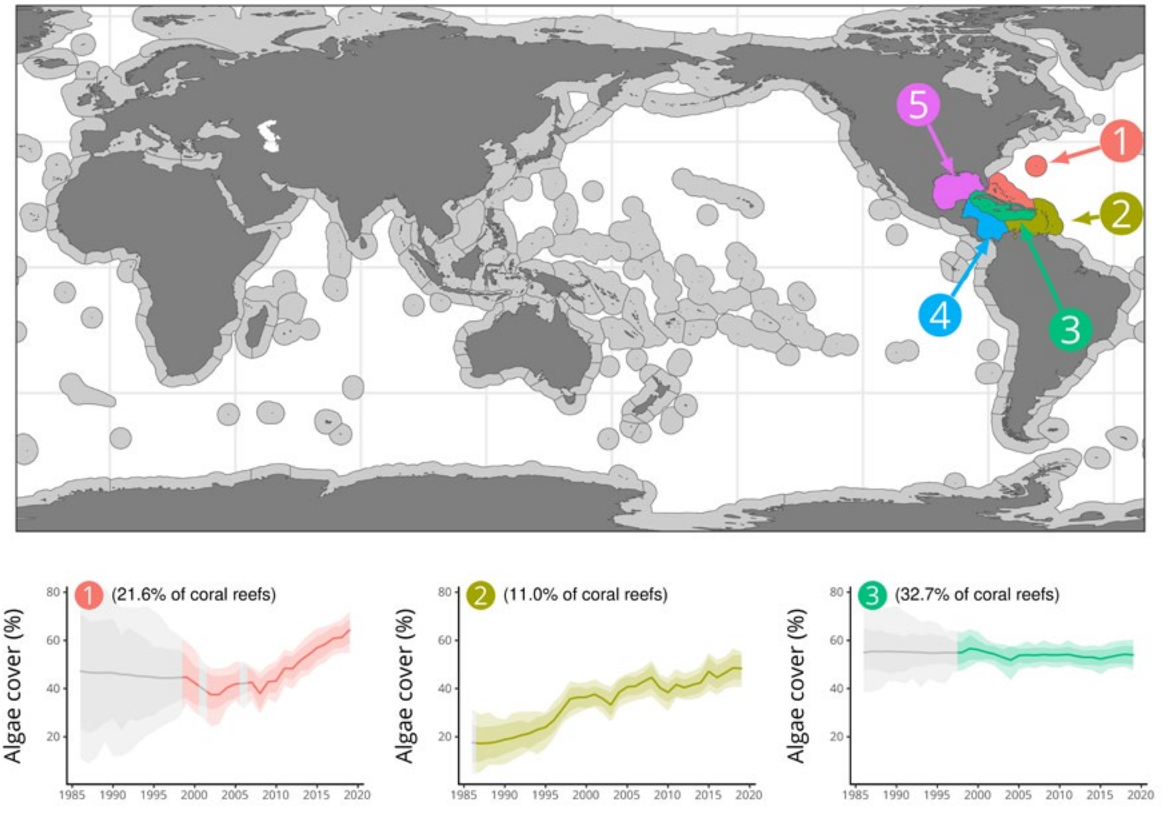

Figure 12.7. Estimated average cover of algae within each subregion comprising the Caribbean region. The solid line represents the estimated mean and associated 80% (darker shade) and 95% (lighter shade) credible intervals, which represent levels of uncertainty. Grey areas represent periods during which no field data were available. The proportion of all coral reefs in the Caribbean region within each subregion is indicated by the % of coral reefs.

Conclusion:

This regional chapter confirms, as in Jackson *et al.* (2014)[3], that live coral cover and algal cover have reverse trajectories. Comparative trends over the period indicate an acceleration of the shift in subregions 2, 3, and 4 of the Caribbean.

Widespread overexploitation of herbivorous fish, heavy development in coastal areas, more frequent and intense coral bleaching events as well as stronger hurricanes are threatening Caribbean reefs that are also facing emerging issues such as lionfish, *Sargassum* influx, and SCTLD. Increases in the frequency and intensity of disturbances to coral reefs in the Caribbean compounded by chronic water pollution have disrupted long-term disturbance-recovery patterns, particularly since Caribbean reefs have begun to face back-to-back disturbances year-after-year.

The GCRMN-Caribbean Steering Committee suggests the following recommendations to stakeholders and decision makers:

- Reduce runoff in coastal areas, as well as ship discharges;
- Manage ballast water throughout the wider Caribbean region;

- Ban the use of destructive fishing gear (spearguns, gill nets, fish traps, trammel nets);
- Reduce parrotfish fishing, and consider fishery bans on large herbivorous species and large groupers;
- Implement restoration plans for other key herbivores such as *Diadema;* and
- Enhance overall biodiversity and resilience by implementing more fully protected replenishment zones within existing and/or new MPAs.

The GCRMN-Caribbean Steering Committee strongly calls for a more holistic approach for the next global status report and to start organising the data for such an approach. In particular; socio-economic monitoring (SocMon) that provides essential data on the human dimensions of coral reefs should not stand alone, but should be considered integral to GCRMN data collection on biophysical conditions. It is not only critical to better understand the desired ecosystem services, drivers and pressures of change, state of the ecosystem, and appropriate responses, but also absolutely needed for successful coral reef conservation and effective management. In the same way, more biophysical data, including fish and other benthic fauna, should also be included in the next global report.

Box 10.

NOAA Coral Reef Watch: Providing Decision Support Products to Enhance Coral Reef Ecosystem Management in a Warming World

Derek Manzello[1] and Jacqueline De La Cour[1,2]

[1]NOAA/NESDIS/STAR Coral Reef Watch
[2]Earth System Science Interdisciplinary Center/ Cooperative Institute for Satellite Earth System Studies, University of Maryland

First observed in the early 1980s, mass coral bleaching (i.e., widespread bleaching spanning >100s km) has become one of the most visible and damaging marine ecological impacts of increasing ocean temperatures. If a coral is severely bleached, and/or subjected to repeated bleaching, it will likely die. The corals that survive are usually immunocompromised, as well as having impaired reproduction and growth for years after the heat stress subsides. Severe coral bleaching has become more extensive, frequent, and intense. This can be seen in the acceleration of heat stress events that cause mass bleaching, and in new multi-decadal bleaching observation datasets. As manifested by the devastating 2014-2017 global coral bleaching event (considered the longest, most widespread and most damaging bleaching event ever) and by other, recent, severe, large-scale bleaching events on different reef areas (including, in 2020, on the Great Barrier Reef, many South Pacific and Indian Ocean reefs, Southeast Asia, Taiwan, and the coast of Brazil), mass bleaching events often last many months; are beginning to occur near-annually in some locations; and are impacting reefs that never bleached before (including reefs far-removed from direct human impacts). It is clear that consistent, remote monitoring of coral reefs and the development of actionable intelligence are critical for early detection, on-the-ground response, communication, and future resilience planning to better protect these ecosystems from further degradation and loss.

In response to these concerns, the U.S. National Oceanic and Atmospheric Administration (NOAA) established the Coral Reef Watch (CRW) program. Since 2000, CRW has utilized remote sensing, modeled and *in situ* data to observe, predict, and report to its users on the coral reef environment worldwide. CRW provides the only global early-warning system of coral reef ecosystem environmental changes. Its next-generation daily, global and regional 5 km-resolution satellite coral bleaching heat stress products and modeled Four-Month Coral

Bleaching Outlook have successfully and accurately monitored and predicted all major mass bleaching events observed globally since 1997. CRW's products help resource managers, scientists, decision makers, monitoring networks, and the public monitor climate impacts to reef ecosystems; better understand links between environmental conditions and ecosystem impacts; and implement timely, protective responses and adaptation actions (including restoration efforts), improving coral reef management in a warming world. In response to CRW products, users have reduced local stressors during high heat stress (e.g., closing scuba diving and fishing areas), rescued rare corals, and shaded/cooled key nursery reefs.

NOAA CRW provides essential environmental intelligence. Its extensive partnership network with data providers, scientists, and reef managers allows CRW to leverage key U.S. and international partner efforts to undertake research to develop the best possible products for its users, and to better understand how stakeholders use its tools. CRW works closely with its users from product conceptualization through to operationalization, providing training in appropriate product use, and garnering feedback to improve management tools. This places CRW at the forefront of providing services to improve understanding of climate change threats to coral reefs, and establishes sound practices for the use of its products to enhance resilience-based coral reef management.

Acknowledgements:

The scientific results and conclusions, as well as any views or opinions expressed herein, are those of the author(s) and do not necessarily reflect the views of NOAA or the Department of Commerce.

Box 11.

Stony coral tissue loss disease (SCTLD) - novel threats to coral reefs

Margaret Miller, Lorenzo Alvarez-Filip, Rosa Rodríguez-Martínez, Jennifer Koss.

In 2014, a new threat to the integrity of coral reefs emerged in Florida and was termed stony coral tissue loss disease (SCTLD). SCTLD affects more than 30 coral species, and colonies of highly susceptible species can die within weeks. Given the large number of species affected, the rapid spread of the disease across reefs and regions, and the temporal persistence of the disease (6 years and still going), this disease outbreak is the most lethal disturbance ever recorded in the Caribbean[1,2,3]. The rapid spread of SCTLD across the Caribbean has reef scientists, managers, and the general population highly concerned. Reports have now registered for the Western Caribbean, Bahamas, Puerto Rico, the US Virgin Islands and the Lesser and Greater Antilles (https://www.agrra.org/coral-disease-outbreak/). Population losses range from > 90% on highly susceptible species to <10% in less affected species[1,2,3]. Stony coral diversity, density, and amount of live tissue correspond with differential SCTLD susceptibility and have resulted in significant changes in the structure and composition of coral communities, further impairing the integrity of coral reefs across the entire geography of the regions that have been impacted.

The emergence of the disease occurred in association with a severe thermal bleaching event and a dredging project, at ground zero, in a highly impacted, urban reef area[3]. However, subsequent studies have found no clear link between high water temperatures and the spread or prevalence of SCTLD[4] s. Ecological (e.g. coral density and composition) and environmental conditions, including nutrient concentrations and turbidity, are likely to influence disease prevalence and progression.

Given the intensity of this emerging threat, SCTLD has also been the target of unprecedented research efforts to determine the cause and ecology of the disease, and intervention efforts to minimize mortality from the disease. Although the modes of transmission and specific causative agents are not yet fully understood, the disease is clearly transmitted through

1 Alvarez-Filip, L., Estrada-Saldívar, N., Pérez-Cervantes, E., Molina-Hernández, A., and González-Barrios, F. J. (2019). A rapid spread of the stony coral tissue loss disease outbreak in the Mexican Caribbean. PeerJ 7:8069. doi: 10.7717/peerk.8069

2 Dahlgren C, Pizarro V, Sherman K, Greene W and Oliver J (2021) Spatial and Temporal Patterns of Stony Coral Tissue Loss Disease Outbreaks in The Bahamas. Front. Mar. Sci. 8:682114. doi: 10.3389/fmars.2021.682114

3 Gintert, B. E., Precht, W. F., Fura, R., Rogers, K., Rice, M., Precht, L. L., et al. (2019). Regional coral disease outbreak overwhelms impacts from local dredge project. Environ. Monit. Assess. 191, 1–39. doi: 10.1007/s10661-019-7767-7767

4 Estrada-Saldívar N, Quiroga-García BA, Pérez-Cervantes E, Rivera-Garibay OO and Alvarez-Filip L (2021) Effects of the Stony Coral Tissue Loss Disease Outbreak on Coral Communities and the Benthic Composition of Cozumel Reefs. Front. Mar. Sci. 8:632777. doi: 10.3389/fmars.2021.632777

seawater, bacteria are involved at some level in disease progression[5], and viruses of the algal symbionts have been reported in pathological studies. Complex interactions of primary and secondary pathogens are likely involved.

Despite a lack of definitive disease causation, novel and effective, if labor-intensive interventions have been developed and applied to stop disease progression. Topical amoxicillin (antibiotic) embedded in a silicon-based paste and applied to the lesion margins can arrest tissue loss along the treated margin in multiple coral species[6,7,8]. Still, new lesions can appear on the same colony over time, and repeated treatments are commonly required[7,8,9]. There has also been some benefit demonstrated from applying endemic probiotic bacteria (of the genus *Pseudoalteromonas*) in arresting disease progression. Unfortunately, the expense and labour-intensity of these interventions likely put them beyond reach for widespread implementation in many affected regions. Local responses to SCTLD outbreaks have also involved local communities in disease surveillance and 'strike teams', ramping up of genetic archiving[10] (Grosso-Becerra et al. 2021) and restoration activities. In some cases, unaffected colonies from areas ahead of the disease front have been removed to captivity to provide material for future repopulation efforts.

Figure 1. map showing the spread of SCTLD in the Caribbean showing where it is absent (green) versus present (red). Source: Kramer, P.R., Roth, L., and Lang, J. 2019. Map of Stony Coral Tissue Loss Disease Outbreak in the Caribbean. www.agrra.org. ArcGIS Online. [29 September 2021].

5 Aeby GS, Ushijima B, Campbell JE, Jones S, Williams GJ, Meyer JL, Häse C and Paul VJ (2019) Pathogenesis of a Tissue Loss Disease Affecting Multiple Species of Corals Along the Florida Reef Tract. Front. Mar. Sci. 6:678. doi: 10.3389/fmars.2019.00678

6 Neely KL, Macaulay KA, Hower EK, Dobler MA. 2020. Effectiveness of topical antibiotics in treating corals affected by Stony Coral Tissue Loss Disease. PeerJ 8:e9289 https://doi.org/10.7717/peerj.9289

7 Walker BK, Turner NR, Noren HKG, et al (2021) Optimizing Stony Coral Tissue Loss Disease (SCTLD) Intervention Treatments on *Montastraea cavernosa* in an Endemic Zone. Frontiers in Marine Science 8:746. https://doi.org/10.3389/fmars.2021.666224

8 Shilling, E. N., Combs, I. R., and Voss, J. D. (2021). Assessing the effectiveness of two intervention methods for stony coral tissue loss disease on *Montastraea cavernosa*. Sci. Rep. 11:8566. doi: 10.1038/s41598-021-86926-4

9 Neely K, Shea C, Macaulay K, Hower E, Dobler M. 2021 Short- and Long-Term Effectiveness of Coral Disease Treatments. Front Mar Sci 8:1031. DOI=10.3389/fmars.2021.675349

10 Grosso-Becerra, M.V., Mendoza-Quiroz, S., Maldonado, E. et al. Cryopreservation of sperm from the brain coral Diploria labyrinthiformis as a strategy to face the loss of corals in the Caribbean. Coral Reefs 40, 937–950 (2021). https://doi.org/10.1007/s00338-021-02098-7

Figure 2. disease front on Meandrina meandrites

Figure 3. SCTLC infecting multiple adjacent colonies and multiple lesions on individual colonies. Photos: Lorenzo Alvarez.

Box 12.

The Human Dimensions of Coral Reef Management and Monitoring

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The Role of Social Values in Ecosystem-based Management

Coral reefs are among the most productive and biologically diverse ecosystems on Earth, but are facing a number of complex pressures, such as mass coral bleaching, ocean acidification, coral disease, and the impacts from human activities. Despite the recognition of anthropogenic impacts on coral reefs, a vast majority of research tends to focus on the biophysical rather than the human dimensions of reef ecosystems, which can limit our understanding of social relationships with these environments as well as potential solutions for reef recovery. Ecological and biophysical data are an essential component, yet management questions cannot be fully addressed with this information alone. The effectiveness and success of management strategies or mitigation actions will ultimately depend on society's values and preferences.

In practice, coral reef resources are managed for society. People are an integral participant in this ecosystem. Their actions may influence pressures upon the ecosystem, but they are also the beneficiaries of the services produced by that ecosystem. These ecosystem services are the benefits created by particular sets of ecological conditions and processes that are explicitly linked to social value and human wellbeing. Millions of people around the world depend on coral reefs for a variety of ecosystem services, including food production, jobs and income, tourism, recreation, protection from storm damage and coastal erosion, aesthetic and cultural value. All of these services are things that people care about – the "so what" of coral reefs.

Efforts to successfully "conserve and sustainably use marine resources" (Sustainable Development Goal 14) are dependent upon the human dimensions of coral reef management[1]. The manner in which reefs are managed in different ways for various purposes is a reflection of what society wants from those reefs. The ways in which society values coral reefs are

[1] See GCRMN Global Societal Priorities at https://gcrmn.net/about-gcrmn/global-societal-priorities/.

diverse and these values form the basis for how people interact with the ecosystem and respond to coral reef issues. Management is far more complex than simply “preserving” the resource. Rather, it seeks to achieve a balance between the social and environmental goals in the research, monitoring, and management context in order to sustain the ecosystem services valued by society.

We have shifted into an ecosystem-based management (EBM) approach which recognizes that: 1) the biophysical and human components of an ecosystem interact in many complex ways and lead to tradeoffs between social and ecological conditions, 2) society relies upon and benefits from the ecosystem through ecosystem services, and 3) ecosystem services are directly and indirectly affected by multiple human activities/uses. Implementing EBM requires an interdisciplinary and collaborative effort that places questions of human uses and values at the center of their approach for research and monitoring.

Socioeconomic Monitoring of Global Coral Reefs

Similar to ecological parameters, changes in human values and behaviors associated with coral reefs should be measured over time. Socioeconomic monitoring is important in order to track how people use and depend on coral reefs, and to understand human impacts on coral ecosystems so that we can mitigate negative effects while promoting positive benefits. The Global Socioeconomic Monitoring Initiative for Coastal Management (SocMon/SEM-Pasifika) fills this critical need by advancing a global and regional understanding of human interactions with and dependence on coastal resources.

SocMon has been part of the wider GCRMN monitoring effort since 1997. Like GCRMN, SocMon works through a network of stakeholders with the primary goal of supporting management and conservation of coral reefs. The SocMon program was developed with the intent for socioeconomic monitoring to complement biophysical monitoring. There are seven regions throughout the world that are conducting socioeconomic monitoring through SocMon. These regions include the Caribbean, Central America, Southeast Asia, Western Indian Ocean, Pacific Islands, South Asia and Brazil.

Since its inception, SocMon has excelled in expanding socioeconomic monitoring across the world’s coral reefs - providing social science training, developing products and tools for monitoring and management, and being involved with communities to address local issues. To date, there have been at least 140 socioeconomic assessments conducted in 42 countries, resulting in over 21,000 surveys and interviews conducted worldwide. A key aspect of these assessments is community involvement to address local management issues. The goals for site assessments are tailored to each site’s needs and have focused on a variety of topics regarding community concerns of coastal management including:

- Development of socioeconomic profiles for fisheries
- Identifying priority issues based on how people value and depend on reefs, their perceptions of resource conditions and changes over time, and perceived threats to reefs
- Assessment of management effectiveness of MPAs to inform and adapt management
- Evaluating tradeoffs between the use and protection of coral reef resources; limits of acceptable change in conditions

- Evaluating stakeholder support for or opposition to different management strategies, and which stakeholders are negatively or positively impacted
- Determining the adaptive capacity of coastal communities to climate change
- How to target communication and outreach for enhanced stewardship or behavior change.

Concurrent with this status report, a Global SocMon report is being prepared on the status of socioeconomic factors affecting coral reefs and includes case studies of SocMon data collected in each region. For more information on SocMon or access to publications, visit http://socmon.icriforum.org/.

Moving Forward

Support for Socioeconomic Monitoring. It is critical to recognize that SocMon is essential for successful conservation and effective management. Without good global-level social and economic data, we have only a limited understanding of how people value and depend on coral reefs. Moving forward, a major issue that needs addressed is the recognition of socioeconomic monitoring and its inclusion in GCRMN. While SocMon has been acknowledged as a need, there needs to be more effort to include social scientists in GCRMN discussions and planning. The socioeconomic component should not be considered separately or after the fact.

The lack of funding and organizational priorities for SocMon have made it difficult for each region to maintain monitoring efforts. More people are recognizing the importance of social-economic science, but priorities and budgets tend to favor biological data monitoring. Moving forward, the SocMon coordinators are searching for alternative funding opportunities. But we can begin to overcome some of these challenges by sharing the value of socioeconomic monitoring and our success stories, while expanding the GCRMN network with new opportunities for collaboration and partnership.

A Holistic Approach for GCRMN. There is a pressing need to integrate biophysical and socioeconomic monitoring to better inform holistic ecosystem-based management. Essential data on the human dimensions of coral reefs should not stand alone, but should be considered integral to GCRNM data collection on biophysical conditions. SocMon is meant to complement the biophysical monitoring and can be used in a comprehensive holistic approach to better understand the desired ecosystem services, drivers and pressures of change, state of the ecosystem, and appropriate responses[2].

Increased collaboration and interdisciplinary work within the GCRMN is needed to understand the links within the social-ecological system. GCRMN and SocMon must collaborate to integrate biophysical and socioeconomic monitoring data and to gain new perspectives. Effective coastal resource management is only possible if biophysical and social science disciplines work together at the inception of any monitoring program. This involves aligning our goals and combining complementary research questions in order to evaluate the status

[2] Kelble, C.R., Loomis, D.K., Lovelace, S., Nuttle, W.K., Ortner, P.B., Fletcher, P., Cook, G.S., Lorenz, J.J., and Boyer, J.N. (2013). The EBM-DPSER conceptual model: Integrating ecosystem services into the DPSIR framework. PLoS ONE, 8(8), e70766.

of coral reefs, and depends on our ability to provide desired ecosystem services and respond to emerging threats in coastal-marine areas.

Integration of social and biophysical information has been acknowledged by the Caribbean regional node of GCRMN[3]. The GCRMN-Caribbean developed a framework for monitoring programs to contribute comparable data that support a regional understanding of status and trends of Caribbean coral reefs and will allow us to assess the basic socioeconomic impacts of large-scale future changes in coral reef health in the Caribbean region. An integrated approach is needed in all regions of GCRMN for a holistic understanding of the status of coral reefs and the communities who depend on those reefs.

Conclusion

The incorporation of human dimensions will significantly enrich our understanding of the complex interactions between society and coral reef ecosystems. By integrating socioeconomic and biophysical monitoring, we can unravel the drivers of change and assess the interdependence of factors associated with the ecosystem. This is imperative if society is going to have a more sustainable relationship with natural resources, services, values, and the ecosystems on which they are reliant. If socioeconomic monitoring (SocMon) cannot be sustained long-term, however, integrated comprehensive monitoring will not be possible and management will lack critical information necessary to manage coral reefs on behalf of society.

[3] GCRMN-Caribbean. (2017). Combined Biophysical and SocMon Report of the GCRMN Caribbean Capacity Building for Coral Reef and Human Dimensions Monitoring within the Wider Caribbean Workshop. https://gcrmn.net/wp-content/uploads/2019/08/GCRMN-Caribbean-capacity-building-workshop-report-Oct-2017.pdf

Chapter 13.

Data collation and processing

Author: Jérémy Wicquart

1. Data acquisition

Based on advice from GCRMN regional coordinators and with the support of the International Coral Reef Initiative (ICRI), owners and custodians of data previously provided to the GCRMN, regional organizations, NGOs and researchers were approached to contribute coral reef monitoring data to the GCRMN *Status of Coral Reef of the World: 2020* report. Data sharing agreements were signed with each data contributor, which governed how their data could be used and provided assurances that their contribution would be recognised appropriately in associated GCRMN outputs. Only raw data for which the contributors were considered official custodians were collated. Except in rare cases, data extracted from scientific literature were not included because these data often lack complete metadata. Where necessary, data were homogenized in consultation with data contributors in order to maximize the reliability of the final results. Data acquisition was conducted throughout 2019 and required 12 months to complete. As a consequence, the majority of data on which the report was founded pre-date 2019.

2. Data homogenization and processing

Numerous monitoring programs have been established around the world at different times, for different purposes and using different protocols. Some methodological standards (e.g. GCRMN[1], Atlantic and Gulf Rapid Reef Assessment (AGRRA), Reef Check) have emerged during the last two decades but different standards tend to be used in different regions and by different monitoring programs. Thus, datasets collected by different coral reef monitoring programs differ in their formats, and use different variables, units and taxonomic resolution. As a consequence, it was essential to implement a rigorous process to standardize the format of all contributed datasets in order to create a unique and homogenous global dataset for quantitative analysis. All data homogenization was performed by a single person within the data analysis team in order to ensure consistency, provide a single point for issue tracking and reduce the burden on data contributors (Fig. 13.1).

[1] English, S.A, Wilkinson, C., Baker, V.J. (1997). Survey manual for tropical marine resources. 2nd Edition. Australian Institute of Marine Science, Townsville, Australia. 378p.

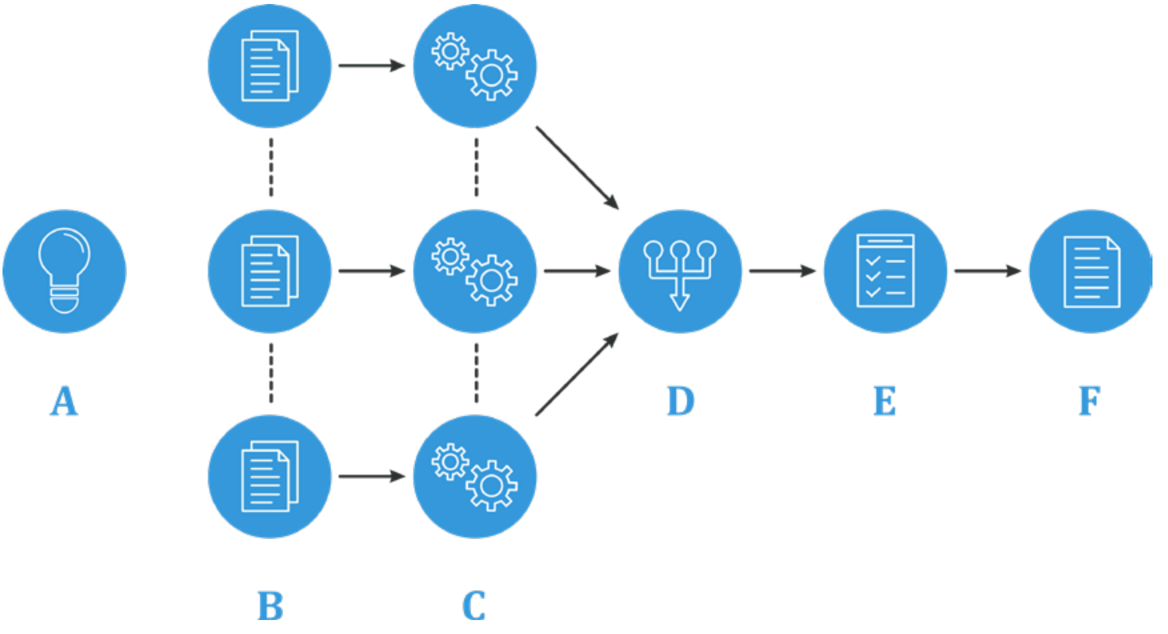


Figure 13.1. Steps used in the data homogenization and cleaning process. A: selection of variables and levels; B: export of individual raw datasets in csv format (i.e. as provided by data contributors); C: cleaning of all datasets individually; D: merging of all individually cleaned datasets; E: quality assurance and quality control (QAQC); F: exportation of the global dataset.

The first step in the homogenization process was to define the variables required for the synthetic global dataset (Step A, Fig. 13.1). The 22 variables listed in tab. 13.1 were selected. These variables spanned four broad groups: spatial variables (2 to 12), temporal variables (13 and 14), methodological variables (15 and 16) and taxonomic variables (17 to 21). Spatial and taxonomic variables were nested. For example, a given location can include several sites, each of which could be comprised of several replicates.

Table 13.1. Variables included in the synthetic global dataset.

	Variable	Type	Description
1	DatasetID	Factor	Dataset ID
2	Area	Factor	GCRMN region (see Fig. 13.2)
3	Country	Factor	Country
4	Archipelago	Factor	Archipelago
5	Location	Factor	Location or island
6	Site	Factor	Site within the location
7	Replicate	Integer	Replicate ID
8	Quadrat	Integer	Quadrat ID
9	Zone	Factor	Reef zone
10	Latitude	Numeric	Latitude of the site
11	Longitude	Numeric	Longitude of the site
12	Depth	Numeric	Mean depth at which data were collected
13	Year	Integer	Year in which data were collected

14	Date	Date	Date (YYYY-MM-DD) on which data were collected
15	Method	Factor	Method used to collect the data
16	Observer	Factor	Name of individual who collected the data
17	Category	Factor	See Tab. 13.2
18	Group	Factor	See Tab. 13.2
19	Family	Factor	Family name
20	Genus	Factor	Genus name
21	Species	Factor	Species name
22	Cover	Numeric	Percentage cover

Next, raw datasets were converted into csv format (Step B, Fig. 13.1) and then individually homogenized (Step C, Fig. 13.1). Homogenization consisted of:

1. Deleting, renaming and adding variables (to be consistent with those listed in Tab. 13.1); and
2. Ensuring consistency in the format of latitude and longitude (e.g. from hexadecimal to decimal format), date (e.g. from DD-MM-YYYY to YYYY-MM-DD), and the units for depth (e.g. from feet to meters) and cover (e.g. number of points counted on a transect to percentage cover).

The positions of sites were visually verified using an interactive map. When data were missing or ambiguous, clarification was sought from data contributors.

Standardized datasets were then merged (Step D, Fig. 13.1). In order to deal with the variation in the taxonomic level at which benthic data were recorded by different monitoring programs, it was necessary to standardize records at an equivalent level. This was achieved by ensuring that each record was completely described by five variables (*Category, Group, Family, Genus and Species*). The variables *Category* and *Group* (Tab. 13.2) were adapted from English et al. (1997)[1]. The variables *Family, Genus* and *Species* reflect actual taxonomic levels and their validity was assessed using *World Register of Marine Species* (WoRMS)[2]. Particular attention was given to genus names that were identical between distinct taxonomic groups to avoid re-categorization errors. For example, *Turbinaria* is a genus of both algae and coral.

[2] WoRMS Editorial Board (2022). World Register of Marine Species. Available from https://www.marinespecies.org at VLIZ. Accessed 2021-11-03. doi:10.14284/170

Table 13.2. Selected levels for the variables Category and Group.

Category	Group
Abiotic	Rock
	Rubble
	Sand
	Silt
Algae	Coralline algae
	Macroalgae
	Turf algae
Hard bleached coral	
Hard dead coral	
Hard living coral	
Other fauna	Actiniaria
	Alcyonacea
	Antipatharia
	Asteroidea
	Bivalvia
	Bryozoa
	Corallimorpharia
	Crinoidea
	Decapoda
	Echinoidea
	Gastropoda
	Holothuroidea
	Hydrozoa
	Ophiuroidea
	Polychaeta
	Porifera
	Tunicata
	Zoantharia
Seagrass	

The final step in the data homogenization process was quality assurance and quality control (QA/QC) (Step E, Fig. 13.1). This was achieved by first calculating the sum of percentage covers of all categories at the lowest sampling unit (e.g. transect). The natural assumption is that the sum of all percentage covers would equal 100%. However, this was not always the case. As a consequence, the following QA/QC protocols were applied based on the sum of the percent cover calculated for each sample:

1. Percent cover lower than 0% - This result was possible only when there was an error either in data entry by a data contributor or an error in data homogenization. After verification of the data cleaning process for the corresponding dataset (Step C, Fig. 13.1) during which corrections were made if needed, all samples with total cover lower than 0% were removed from the global dataset.

2. Percent cover between 0% and 100% - This occurred when observations of some cover categories (e.g. non-living substrates, tape, wand, shadows) were removed from a sample by data contributors or if data were collected on only a specific subset of benthic cover categories (e.g. living hard living coral). This was acceptable and all corresponding samples were retained in the global dataset.

3. Percent cover equal to 100% - This was the best case and occurred when all information in a sample was available. All corresponding samples were retained in the global dataset.

4. Greater than 100% - This result was possible only when there was an error either in data entry by a data contributor or an error in data homogenization. In this scenario, the data cleaning process for the corresponding dataset was verified (Step C, Fig 13.1) and corrections were applied if necessary. If the data cleaning process was accurate, further investigation was conducted. Occasionally, the total cover was very close to but still exceeded 100%. This occurred when the data provided were rounded averages rather than raw data. In order not to exclude these potentially valid data, a threshold of 101% was applied and percent covers within such samples were reduced to achieve a total cover of 100%. If, after verification of data cleaning and the application of corrections, the sum of percent covers within a sample remained greater than 100%, the sample was removed from the global dataset.

All data homogenization procedures were done within the R Statistical and Graphical Environment (version 3.6.3) mainly using packages contained in the tidyverse (version 1.3.1)[3].

3. Limitations

The data homogenization process was designed to eliminate a maximum number of errors, which sometimes led to a significant loss of data (up to 10% of samples within a given dataset), usually during the QA/QC step (Step E, Fig. 13.1). Due to the great diversity of categories used by data contributors, it was not possible to implement an automatic re-categorization process. This step was conducted manually and, as a consequence, may have introduced errors. In order to reduce the influence of potential errors introduced in key categories (e.g. living hard coral), individual trends were compared with those reported in associated documents (e.g. reports, scientific articles) provided by data contributors or, when uncertainty remained, clarification was sought from the data providers.

Description of homogenized data

The data homogenization process made it possible to build a global dataset based on the aggregation of data contained in 248 datasets, collected from 12,160 monitoring sites and provided by more than 300 contributors.

All data were assigned to one of the 10 GCRMN regions (Fig. 13.2) for analysis and reporting. The boundary of each region broadly corresponded with historical GCRMN regional boundaries based on existing national or informal networks.

The total area of coral reefs within each GCRMN region varies greatly, ranging from 780 km² in the Eastern Tropical Pacific to 78,272 km² in the East Asian Seas region, which includes the Coral Triangle (Tab. 13.3). The East Asian Seas, Pacific and Australia regions together account for almost 73% of world's coral reef area.

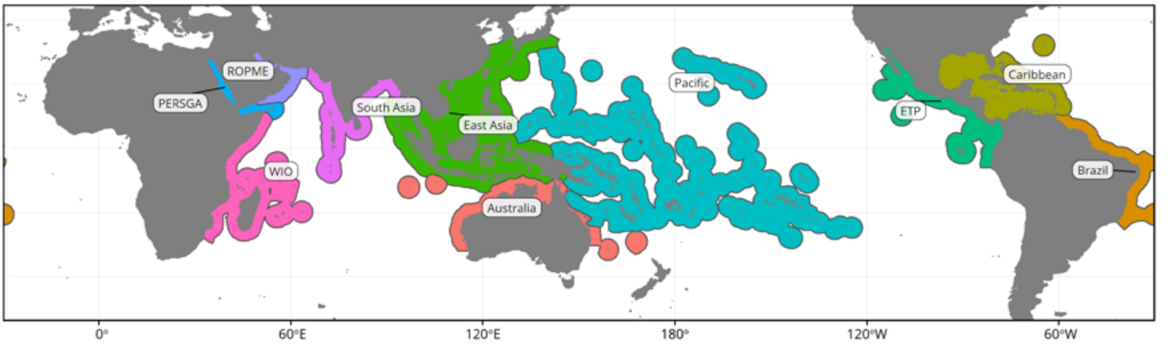


Figure 13.2. The 10 GCRMN regions. ETP is the Eastern Tropical Pacific. PERSGA is the area included within the Regional Organization for the Conservation of the Environment of the Red Sea and Gulf of Aden. ROPME is the sea area surrounded by the eight Member States of the Regional Organisation for the Protection of the Marine Environment. WIO is the Western Indian Ocean.

[3] Wickham, H. et al., (2019). Welcome to the tidyverse. Journal of Open Source Software, 4(43), 1686, https://doi.org/10.21105/joss.01686

Data were contributed from all 10 GCRMN regions (Fig. 13.3A). Eighty percent of sites surveyed were located in the Pacific, East Asian Seas and Caribbean regions. The patchiness and remoteness of reefs in some regions limited the spatial coverage of surveys, particularly in the Pacific and East Asian Seas regions which have the greatest areas of coral reefs. The vast majority of surveys were conducted at depths shallower than 20 m, with 25% conducted at 5 m (Fig. 13.3D).

Table 13.3. Summary statistics for each GCRMN region describing the area of coral reefs and the number sites and long-term monitoring sites from which data were compiled for the global dataset. 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, and may have been surveyed multiple times in the interim.

Region	Reef area*		Sites		Long term monitoring sites	
	Reef area (km²)	Proportion of total reef area	Total Number	Proportion of global dataset	Total Number	Proportion of global dataset
East Asian Seas	78,272	30.15	2,570	21.13	158	26.87
Pacific	69,424	26.73	4,050	33.31	50	8.5
Australia	41,802	16.1	372	3.06	157	26.7
Caribbean	26,397	10.17	3,166	26.04	135	22.96
Western Indian Ocean	15,179	5.85	915	7.52	64	10.88
Red Sea and Gulf of Aden	13,605	5.24	243	2	7	0.01
South Asia	10,949	4.22	389	3.2	9	1.53
ROPME Sea Area	2,009	0.77	68	0.56	0	0
Brazil	1,226	0.47	35	0.29	9	1.53
Eastern Tropical Pacific	780	0.3	352	2.89	6	1.02

* 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

Most surveys were conducted after 2005, with the proportion of surveys conducted in each year increasingly rapidly until 2016/17 (Fig. 13.3C). The decline in the proportion of surveys conducted after 2017 was likely an artefact of the timing of the data acquisition and collation process which occurred during 2019 and thus potentially before contributors had fully collated or published their most recent survey data.

More than 75% of sites were surveyed only once (Fig. 13.3B). The high proportion of single surveys was attributable to the widespread adoption random sampling designs that were based on surveys of haphazardly chosen sites that are unlikely to be revisited.

Repeated surveys of fixed sites were conducted by some monitoring programs, although the time span over which sites were monitored was generally less than 10 years (Fig. 13.3B). Only 2% of sites were considered long-term monitoring sites, with data collected over periods greater than 15 years. The greatest proportion of long-term monitoring sites occurred in the East Asian Seas, Australia and Caribbean regions (Tab. 13.3, Fig. 13.3A).

The use of fixed or random sites has profound implications for data analyses and interpretation of results. Random sampling typically provides less biased estimates of reef condition and potentially better spatial coverage, whereas repeated surveys of fixed sites provide greater power to detect change and more precise estimates of temporal trends.

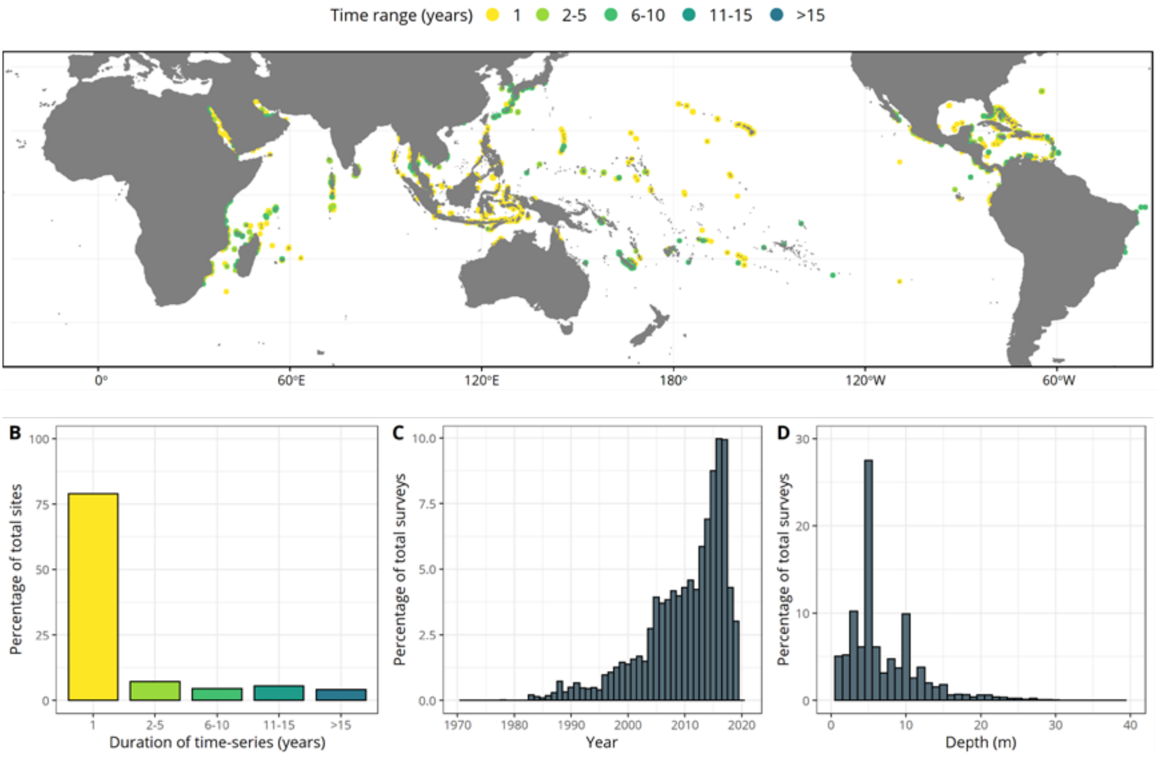


Figure 13.3. Distribution and duration of monitoring sites across the world (**A**), proportion of sites within each category describing the time span between the first and most recent surveys (**B**), proportion of the total number of surveys conducted in each year (**C**) and percentage of the total number of surveys by depth (**D**). For figures 13.3A and B, colours represent the time span between the first survey and the most recent survey at each site.

Box 13.

Enhancing the value and utility of coral reef monitoring data: Lessons from the production of the GCRMN *Status of Coral Reefs of the World: 2020* report

Jeremy Wicquart

Facilitating data integration and increasing data availability

The production of this report has provided a unique opportunity to reinvigorate and strengthen the GCRMN network following a 13 year hiatus since the release of the last GCRMN *Status of Coral Reefs of the World* report in 2008. Given the emphasis of this report on the quantitative analysis of a global coral reef monitoring dataset, substantial efforts were made to acquire data by contacting past supporters of the network, NGOs, research institutes and coral reef researchers. In addition, hosting multiple workshops in several GCRMN regions greatly increased awareness of the report further enhancing data contributions. This process generated considerable enthusiasm to share data, and enabled the establishment of a register of collaborators and data contributors that can be drawn upon during the production of future GCRMN *Status of Coral Reefs of the World* reports.

While it is anticipated that the acquisition of data for future reports will be easier, the process of integrating data from different contributors (*i.e* organising the data into a standard format for subsequent analysis) will have to be repeated for each new report to incorporate updates to existing datasets and new contributions. To enhance the efficiency of this essential, but time-consuming step, the production of future editions of the report will be able to rely on the protocol developed for this report and on the R code used for data integration which has been deposited on Github (a collaborative coding platform).

Appropriately, the use of data contributed for this report was governed by data sharing agreements (DSA) with the numerous data custodians. Most contributors shared their data on the basis that they would only be used for the GCRMN *Status of Coral Reefs of the World: 2020* report, and any other use of the data would require either a new DSA or renegotiation of the existing agreement. This is understandable given that generally, most data custodians want to use their data for their own purposes before sharing with a third party, particularly considering the cost of monitoring, require appropriate acknowledgement for the use of their data, and want to ensure that their data are used for purposes appropriate for the specific dataset. As a consequence, one of the challenges to producing the next GCRMN Status report and to re-using data that underpin this report will be the renegotiation of DSAs with data contributors.

During the last decade, the emergence of data papers in specialized (*e.g.* Scientific data) and traditional journals (*e.g.* Ecology) has helped to democratise data. Data papers allow contributors to deposit a dataset and its metadata associated with a scientific article in a repository (*e.g.* zenodo, figshare). Data deposited with data papers are then findable, have adequate metadata to facilitate their appropriate re-use and are citable (as they are associated with a unique Digital Object Identifier (DOI)).

Encouraging data contributors to write data papers or simply deposit their data in data repositories has several advantages. For data contributors, it increases the visibility of their monitoring program and ensures their work is appropriately acknowledged and used. For the GCRMN, it facilitates data acquisition and integration, and improves the transparency and reproducibility of the global dataset. Beyond the scope of the GCRMN, such synthetic datasets may also increase the re-use of data to answer broader research questions or facilitate comparative analyses.

Broadening the suite of standard indicators used to measure coral reef status

The cover of live hard coral is the most globally recognised and used indicator to track changes in the status of coral reefs. However, as an indicator, the cover of live hard coral represents only one element of the considerable complexity that characterises these highly diverse ecosystems. To provide a better understanding of the condition of coral reefs, a broader suite of complementary metrics need to be commonly and consistently used. For example, the measurement of demographic indicators such as the size and number of coral colonies and recruits provides valuable information on the structure and recovery potential of coral communities. Further, more widespread and standardised measurement of indicators (e.g. density and size) describing fish and invertebrate communities provides a broader view of the condition, functional diversity and resilience of coral reefs, and informs the management and conservation of these species, particularly those that are ecologically and/or economically valuable. Based on experiences gained during the production of this report, the integration of fish and invertebrate data across different monitoring programs presents considerably greater challenges compared with benthic data owing to differences in methodologies, inconsistent use or failure to use species names, observer effects and greater natural variability in the data. Finally, more widespread monitoring of socio-economic indicators is crucial to understand both the anthropogenic drivers affecting coral reefs and the impacts that changes to these critical ecosystems have on dependent human populations.

One of the immediate priorities for the GCRMN is to work with members of the network to provide guidance and technical support that improves the availability, interoperability and re-use of coral reef monitoring data so that a more complete view of the status of coral reefs of the world, including fish, invertebrates and socio-economic aspects, can be gained.

Chapter 14.

Statistical Methods

Author: Murray Logan

1. Modelling considerations

The sampling design of most monitoring programs is typically tailored somewhere along a continuum between a configuration of perpetually fixed sampling sites and a configuration of randomly selected sites, depending on the purpose, resources and logistics of the program. Whist fixed sites act as their own baselines over time and thus provide relatively efficient means for estimating temporal trends, the resulting estimates are biased towards the selected locations (which may not be collectively representative of the broader area). By contrast, a configuration of uniquely random sites is less likely to be biased and hence more representative, but usually requires a considerably greater number of sites in order to detect change from within the noise.

The focus and challenge for the current report was to utilise a collection of datasets from a large number of disparate monitoring programs from around the world in order to provide estimates of status and trends at much broader spatio-temporal scales.

Whenever multiple data sets are integrated together (particularly if each is used to represent different areas), the issues of representativeness and bias are exacerbated. First, quantitative estimates are always driven by sample sizes. Within any well designed monitoring program, efforts are made to ensure the design remains relatively balanced. However, this is not the case across programs. Therefore, when aggregating multiple datasets at a broader scale, it is important to be able to control for varying samples sizes so as to minimise the risks of biasing towards the more heavily replicated datasets. Moreover, sample size and density does not necessarily reflect the density and distribution of the underlying landscape. For example, in the case of coral reefs, sampling intensity is likely to be a function of the relative prosperity of the surrounding populations and proximity to major population centers rather than the density and distribution of the reefs themselves.

Enormous (and complex) spatio-temporal models that employ full positional encoding to evaluate the spatial patterns between all possible pairs of sampling units (sites) have the potential to allow the transferal of information from the fine, observation scale measurements to the broader geographic scales of this report. By assuming that a response variable (such as percent live hard coral cover) varies continuously over an entire two-dimensional surface, such models are potentially able to leverage trends in areas of relatively high sample density to estimate the trends in neighbouring areas of sparse sampling density - albeit with greater uncertainty. However, such models proved to be too computationally burdensome and were incredibly difficult to tune to ensure they yield sensible outcomes. They also assumed that changes over space were relatively gradual and thus, can easily smooth over what would otherwise be considered abrupt local changes. Furthermore, incorporating information about the spatial distribution of reefs as well as physical barriers to auto-correlative process was far from trivial.

As an alternative, we explored hierarchical models in which sampling units were progressively aggregated with their neighbours into larger and larger units. For example, neighbouring quadrats were grouped together into sites, sites into global grid locations (see below) and so on up to the level of the entire globe. This represents a pseudo-spatial model in that although the influence of neighbouring data does deteriorate along the hierarchy, it does so in increments relating to group membership rather than as a continuous function of spatial distance. Hence, in the case of an area comprising of ten sub-areas, each of the sub-areas will share some information with the other sub-areas even though any one of them might be geographically closer to a member of another area than most of the sub-areas in its designated area (the classic nearest vs average neighbour conundrum). In any case, all attempts to fit full, global hierarchical models with the very disparate datasets proved very difficult to stabilise.

Instead, smaller hierarchical models (Fig. 1), fit separately to each Marine Ecosystem of the World (hereafter MEOW) Ecoregion[1], were integrated together within a spatially weighted aggregation hierarchy in which individual model posteriors (annual estimates) were propagated up through the hierarchy. Although this approach does still have some elements of the pseudo-spatial hierarchy that permits data poor areas to leverage patterns off data richer areas, the leveraging is quarantined to within MEOW Ecoregions where processes are more likely to be homogeneous and thus the resulting trends are more likely to be consistent with the observed data. More details about the spatial weights are discussed in section 3 and the statistical models are discussed in section 4.

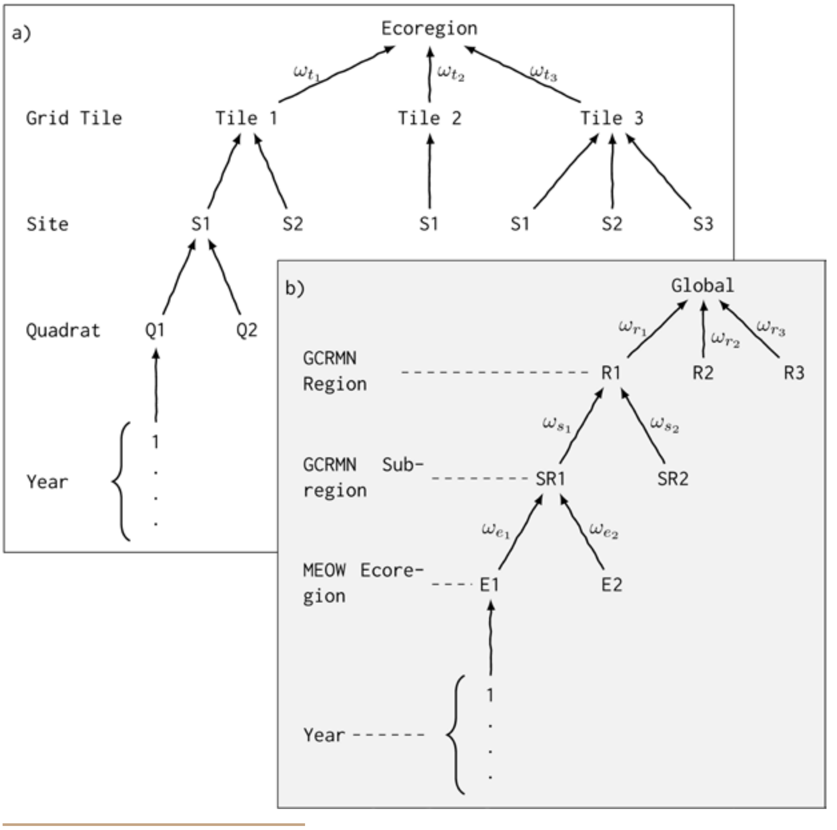
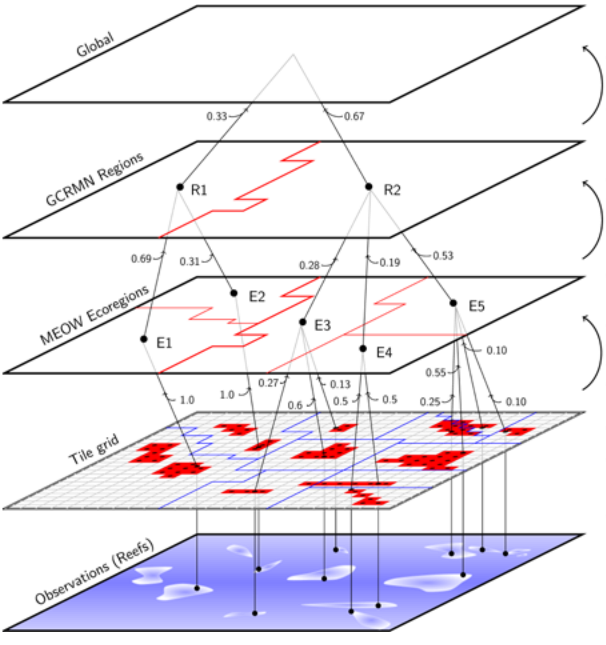


Figure 14.1. Schematic representation of the a) individual Marine Ecosystem of the World Ecoregion Bayesian modelling hierarchies and b) spatial aggregation hierarchy. Note the quadrat-level is de-emphasized to highlight that the quadrat to site level aggregation has occurred outside of the statistical model. The symbolise the use of spatial weights.

[1] Spalding, Mark D., Helen E. Fox, Gerald R. Allen, Nick Davidson, Zach A. Ferdaña, Max Finlayson, Benjamin S. Halpern, et al. 2007. "Marine Ecoregions of the World: A Bioregionalization of Coastal and Shelf Areas." BioScience 57 (7): 573–83. https://doi.org/10.1641/B570707.



Region Weights

Region	Area	Weight
R1	26	0.33
R2	53	0.67

Ecoregion Weights

Region	Ecoregion	Area	Weight
R1	E1	18	0.69
R1	E2	8	0.31
R2	E3	15	0.28
R2	E4	10	0.19
R2	E5	29	0.53

Tile Weights

Ecoregion	Tile ID	Area	Weight
E1	T11-20	18	1.00
E2	T16-18	8	1.00
E3	T05-11	4	0.27
E3	T13-11	9	0.60
E3	T21-13	2	0.13
E4	T05-05	5	0.50
E4	T06-04	5	0.50
E5	T15-03	16	0.55
E5	T21-03	3	0.10
E5	T20-07	3	0.24
E5	T22-05	7	0.10

Figure 14.2. Schematic diagram illustrating the hierarchical structure relating the hypothetical observations (bottom layer) to the level of a 10 km x10 km grid tile, Marine Ecosystem of the World (MEOW) Ecoregions, GCRMN Regions and Global scale. The grid tile layer depicts the 10 km x10 km tile containing reef (red) and the voronoi polygons (blue lines) used to partition area zones of sample unit influence. The MEOW Ecoregions layer illustrates five fictitious Ecoregions which are aggregated into two GCRMN Regions in the layer above. Vertical lines illustrate the aggregation of data along the hierarchy and the numbers along these paths represent the aggregation weights (also tabulated).

2. Spatial hierarchy

The pseudo-spatial hierarchy outlined above necessitates incremental jumps in spatial scale from the level at which observations were collected up to the Global (or even regional) scale. However, if the jumps are too large, the information (temporal patterns) shared across neighbouring spatial units might be driven by very different underlying conditions and thus, are not appropriate.

The original datasets collated in this study were provided at scales of either quadrat/transect or spatial aggregations thereof. These can be group ed naturally into sites (or individual reefs) as the first incremental scale jump; however, subsequent increments are less obvious.

There are numerous ways of grouping coral reef locations into broader geographic areas, or alternatively, dividing the globe up spatially. Some candidates considered were: Exclusive Economic Zones[2], Veron Ecoregions[3] or Marine Ecosystems of the World[1]. Consensus amongst a large panel of coral reef regional representatives was that the MEOW global classification system was the most appropriate as it has a strong bio-geographic focus capturing important, community, evolutionary, dispersal and isolation processes[1]. The MEOW Ecoregions were further grouped up into GCRMN subregions and regions (Tab. 1) to provide additional modelling and reporting granularity.

[2] Flanders Marine Institute. 2019. "Maritime Boundaries Geodatabase: Maritime Boundaries and Exclusive Economic Zones (200nm), Version 11." Available online at http://www.marineregions.org/. https://doi.org/10.14284/386.

[3] Veron, J. E. N. 2000. Corals of the World. Vol. 1–3. Australian Institute of Marine Science, Townsville.

Table 14.1. Spatial hierarchy relating Marine Ecosystems of the World Ecoregions† to GCRMN Regions and Subregions.

GCRMN Region	GRCRMN Subregion	MEOW Ecoregion
Australia	Australia.1	142: Torres Strait Northern Great Barrier Reef
		143: Central and Southern Great Barrier Reef
		202: Tweed-Moreton
	Australia.2	140: Arnhem Coast to Gulf of Carpenteria
		141: Bonaparte Coast
		144: Exmouth to Broome
		145: Ningaloo
		210: Shark Bay
		211: Houtman
	Australia.3	120: Cocos-Keeling/Christmas Island
	Australia.4	151: Lord Howe and Norfolk Islands
Brazil	Brazil.1	074: Fernando de Naronha and Atoll das Rocas
	Brazil.2	075: Northeastern Brazil
	Brazil.3	076: Eastern Brazil
		077: Trindade and Martin Vaz Islands
	Brazil.4	071: Guianan
		072: Amazonia
Caribbean	Caribbean.1	062: Bermuda
		063: Bahamian
	Caribbean.2	064: Eastern Caribbean
		066: Southern Caribbean
	Caribbean.3	065: Greater Antilles
	Caribbean.4	067: Southwestern Caribbean
		068: Western Caribbean
	Caribbean.5	043: Northern Gulf of Mexico
		069: Southern Gulf of Mexico
		070: Floridian

GCRMN Region	GRCRMN Subregion	MEOW Ecoregion
East Asia	East Asia.1	126: Palawan/North Borneo
		127: Eastern Philippines
		128: Sulawesi Sea/Makassar Strait
	East Asia.2	129: Halmahera
		130: Papua
		131: Banda Sea
		133: Northeast Sulawesi
		138: Gulf of Papua
		139: Arafura Sea
	East Asia.3	115: Gulf of Thailand
		116: Southern Vietnam
		117: Sunda Shelf/Java Sea
		118: Malacca Strait
	East Asia.4	119: Southern Java
		132: Lesser Sunda
	East Asia.5	109: Andaman and Nicobar Islands
		110: Andaman Sea Coral Coast
		111: Western Sumatra
	East Asia.6	112: Gulf of Tonkin
		113: Southern China
		114: South China Sea Oceanic Islands
	East Asia.7	121: South Kuroshio
ETP	ETP.1	060: Cortezian
		061: Magdalena Transition
		164: Revillagigedos
		165: Clipperton
	ETP.2	166: Mexican Tropical Pacific
		167: Chiapas-Nicaragua
		168: Nicoya
	ETP.3	170: Panama Bight
		171: Guayaquil
	ETP.4	169: Cocos Islands
		172: Northern Galapagos Islands
		173: Eastern Galapagos Islands
		174: Western Galapagos Islands
PERSGA	PERSGA.1	087: Northern and Central Red Sea
	PERSGA.2	088: Southern Red Sea
	PERSGA.3	089: Gulf of Aden

GCRMN Region	GRCRMN Subregion	MEOW Ecoregion
ROPME	ROPME.1	090: Arabian (Persian) Gulf
	ROPME.2	091: Gulf of Oman
	ROPME.3	092: Western Arabian Sea
South Asia	South Asia.1	106: Chagos
	South Asia.2	105: Maldives
	South Asia.3	103: Western India
		104: South India and Sri Lanka
	South Asia.4	107: Eastern India
		108: Northern Bay of Bengal
WIO	WIO.1	093: Central Somali Coast
		094: Northern Monsoon Current Coast
		095: East African Coral Coast
	WIO.2	096: Seychelles
	WIO.3	097: Cargados Carajos/Tromelin Island
		098: Mascarene Islands
	WIO.4	099: Southeast Madagascar
		100: Western and Northern Madagascar
	WIO.5	101: Bight of Sofala/Swamp Coast
		102: Delagoa

† Spalding, Mark D., Helen E. Fox, Gerald R. Allen, Nick Davidson, Zach A. Ferdaña, Max Finlayson, Benjamin S. Halpern, et al. 2007. "Marine Ecoregions of the World: A Bioregionalization of Coastal and Shelf Areas." BioScience 57 (7): 573–83. https://doi.org/10.1641/B570707.

The jump in spatial scale from Site (reef) to MEOW Ecoregion can be very large and encompass a wide range of influential processes and drivers. Therefore, we sought an additional intermediate scale. Such a scale could be based on collections of reefs or broad communities, although such information was not universally available. An intermediate scale could also be achieved by dividing the globe up into an array (grid) of cells or tiles of a constant size. Moreover, the use of grid tiles provided a way of abstracting away design differences between fixed and random annual site selections thus, providing a mechanism by which multiple sampling designs could be incorporated in the one model.

3. Spatial Weights

In order to help maximise the chances that the hierarchical aggregations were reflective of broad spatial patterns and not heavily biased by sampling effort alone, the aggregations were weighted by the proportion of reef area represented by each spatial unit.

Estimating the distribution and area of global coral reefs is a challenging problem. As is the case with sampling effort consistency across the globe, the granularity and accuracy of coral reef mapping varies substantially from region to region. New initiatives such as the Allen Coral Atlas will help to address these challenges as satellite imagery improves and algorithms mature and achieve recognition and acceptance within the broader scientific community. However, for the purposes of weighting analyses underpinning this *Status of Coral Reefs of the World: 2020* report, Tropical Coral Reefs of the

World[4,5] digital shapefiles were used to provide a potentially less biased and more uniform method of estimating coral reef area. The intermediate spatial scale between observed sites and MEOWs was provided by generating a 10 km x10 km grid of tiles across the entire globe and assigning a unique identifier to each tile.

3.1 Tile level weights

All observed site level locations were assigned to a grid tile on the basis of nearest neighbour within 10 km. To estimate the amount of reef area within each MEOW that was represented by each of the observed sites, voronoi polygons were generated from the unique site locations and overlayed onto the grid (Fig. 3). The reef area associated with each voronoi cell was then expressed as a proportion of the total MEOW reef area, thereby representing the relative weight that each grid tile should carry in the analyses.

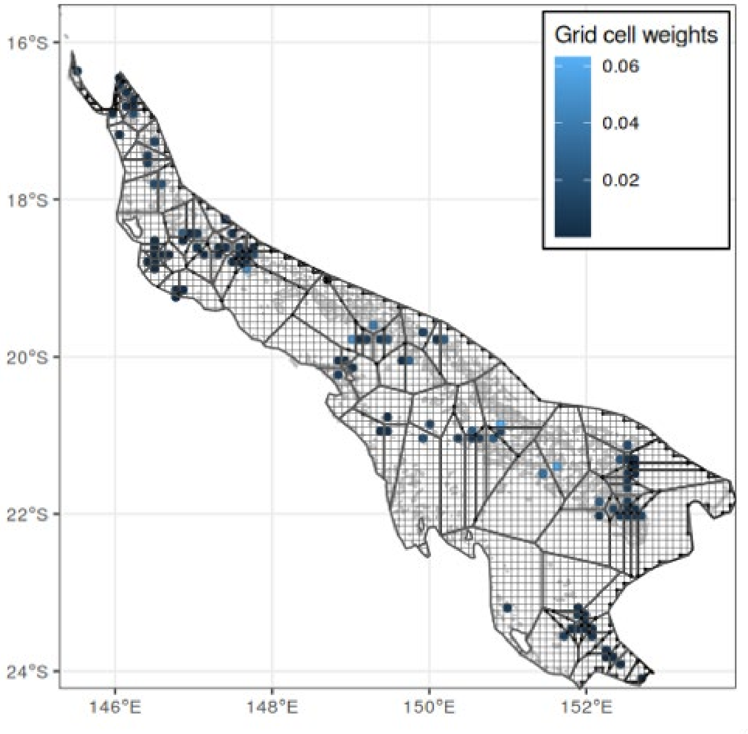


Figure 14.3. Illustration of voronoi polygons overlayed on the 10 km x10 km grid and reefs (grey). Shaded grid tiles represent grid tiles containing observed sites and colour of the grid tile shading represents the relative weights (proportion of reef area in each grid tile).

[4] 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

[5] Burke, L., K. Reytar, M. Spalding, and A. Perry. 2011. "Reefs at Risk Revisited." Washington, DC, USA: Word Resources Institute.

3.2 *Larger scale weights*

The weights (relative contributions) of each MEOW Ecoregion in aggregating up to GCRMN subregions was calculated as the proportion of MEOW reef area within each GCRMN subregion (see Fig. 4). Similarly, GCRMN subregion and region weights (used in aggregations to GCRMN Region and Global levels respectively) were calculated from the respective proportions of reef areas in GCRMN regions and globally.

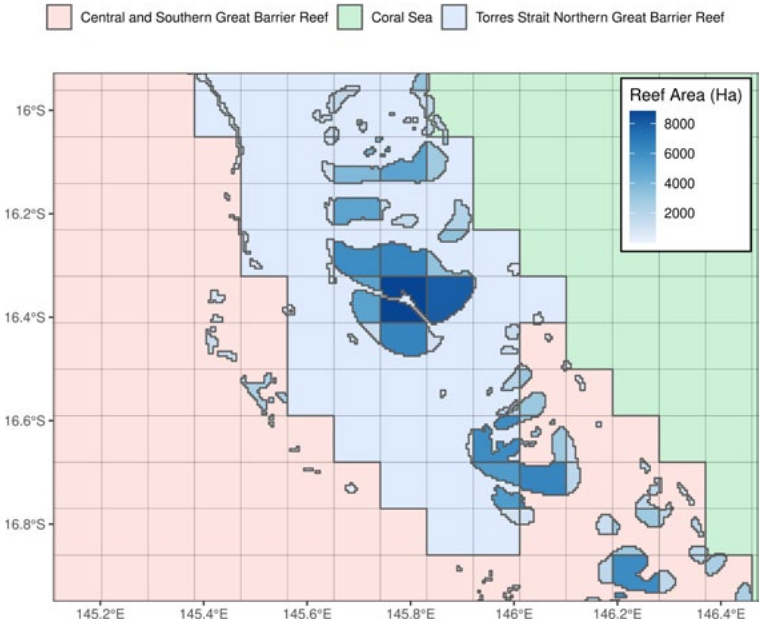


Figure 14.4. Illustration of the relative reef area represented by each 10 km x10 km grid tile within three example MEOW Ecoregions in the GCRMN Australia Region. The colour of reef fill is proportional to the relative area of reef in the MEOW.

4. Statistical Models

Live hard coral cover and algal cover were calculated by summing observation level data across associated taxonomic groupings.

Separate MEOW Ecosystem Bayesian hierarchical models were constructed within the stan statistical modelling platform[6] via the rstan[7] interface. Each model comprised a model matrix representing year dummy coded as cell means contrasts, a model matrix representing Dataset coded as sum to zero contrasts as well as varying effects representing the hierarchical structure of Sites nested within grid tiles (Fig. 1). Weights were also applied to the grid tiles in order to allow the influence of each grid tile to be proportional to the relative area of reef present within each grid tile.

Separate models were fitted to explore trends in live hard coral cover (HCC) and algae cover (A). In each case, cover was modelled against a beta distribution (logit link). Cover values of either 0 or 1 were first

6 Carpenter, Bob, Andrew Gelman, Matthew Hoffman, Daniel Lee, Ben Goodrich, Michael Betancourt, Marcus Brubaker, Jiqiang Guo, Peter Li, and Allen Riddell. 2017. "Stan: A Probabilistic Programming Language." Journal of Statistical Software, Articles 76 (1): 1–32. https://doi.org/10.18637/jss.v076.i01.

7 Stan Development Team. 2019. "RStan: The R Interface to Stan." http://mc-stan.org/.

shrunk by 0.01 for compatibility with the beta distribution. Weakly informative priors were applied to the beta shape parameters as well as the varying effects parameters and their standard deviations.

In order to impute missing year combinations and smooth over short-term oscillations in estimates resulting from short-term fluctuations in sampling designs and data availability, priors on Year effects (except that associated with the first observed year of data in a MEOW Ecoregion) were weakly informative normal priors centred around the posterior of either previous Year (in the case of Years after the initial observed year) or after (in the case of Years prior to the initial observed year). For the initial observed Year, standard (zero centred) weakly informative priors were applied.

The Dataset effects were included to act as proxies for all the many and varying ways that different datasets differ including depth, sampling unit type (quadrats, transects, etc) and observer experience. Weakly informative normal priors were applied to the Dataset effects.

The statistical models can be summarised as:

$$
\begin{aligned}
y &\sim Beta(\mu\phi, (1-\mu)\phi) \\
logit(\mu) &= \boldsymbol{\beta}_{\mathbf{y}}\mathbf{X}_{\mathbf{y}} + \boldsymbol{\beta}_d\mathbf{X}_{\mathbf{d}} + \boldsymbol{\gamma}_{\mathbf{s}}Z_s + \omega\boldsymbol{\gamma}_{\mathbf{t}}Z_t \\
\boldsymbol{\gamma}_{\mathbf{s}} &= \sigma_s \times z_s \\
\boldsymbol{\gamma}_{\mathbf{t}} &= \sigma_t \times z_t \\
\phi &\sim \Gamma(0.01, 0.01) \\
z_s, z_t &\sim N(0,1) \\
\sigma_s, \sigma_t &\sim t(3,0,10) \\
\boldsymbol{\beta}_{\mathbf{y_i}} & \begin{cases} i = O_y, \sim N(0, \sigma_y) \\ i > O_y, \sim N(\beta_{s_{i-1}}, \sigma_{y1}) \\ i < O_y, \sim N(\beta_{s_{i+1}}, \sigma_{y1}) \end{cases} \\
\boldsymbol{\beta}_{\mathbf{d}} &\sim N(0, 0.1)
\end{aligned}
$$

where *y* is the cover of either live hard coral or algae, β_y and β_d represent the effects of Year and Dataset respectively, X_y and X_d represent cell-means Year and sum-to-zero Dataset model matrices respectively, γ_s and γ_t are the sum-to-zero varying effects, and Z_s and Z_t represent the Site and grid tile codes respectively. o_y represents the initial observed Year within the MEOW Ecoregion and *i* is a year iterator.

Trends in hard coral cover to algae ratio (HCC:A) employed structurally very similar models to those described above, yet the ratio was modelled against a Gaussian distribution.

All models were run with 10,000 no-u-turn MCMC iterations, a warmup of 5000 and a thinning rate of 5 for each of three chains (each with random initial values). Diagnostics indicated that all chains converged on stable, well mixed posteriors (Rhat values < 1.05) and low MCMC sample auto-correlation (< 0.2).

4.1 Hierarchical aggregation

The full posteriors for the Year effects (on the logit scale) of each MEOW Ecoregion were averaged together within each GCRMN subregion (Fig. 2). The resulting posteriors were then summarised by back-transforming to the response scale (inverse logit transform in the case of beta models) and calculating the means and highest probability density intervals (80% and 95%). Similarly, the un-standardised GCRMN subregion posteriors were aggregated (with weights) up to GCRMN Region and then Global level (Fig. 2).

4.2 Half-decadal pairwise contrasts

The modelled trends in the covers of live hard coral and algae provide a visual representation of the annual fluctuations within the long-term patterns. In addition, there was a need to be able to provide quantified estimates of the degree of medium to long term changes over time. To achieve this, we combined together the modelled posteriors (hard coral and algae separately) into half-decadal time units (working backwards from the most recent year of available data) and compared the three most recent half-decadal time units (2004-2009, 2010-2014 and 2015-2019) together in a pairwise manner. From each pairwise contrast, we calculated the exceedance probabilities of both positive and negative changes as well as the associated mean absolute and percentage changes.

Half-decadal time units were chosen as they provided a convenient way to evenly partition the time since the last GCRMN *Status of Coral Reefs of the World* report in 2008, encompassed the time span for which reefs where more extensively monitored and provided a good compromise between short and long-term intervals. Whilst it is recognised that the selected half-decadal time boundaries might mask the impact of some local disturbance events, we considered that it was important to maintain consistent time units across the entire scope of the analyses for the purpose of comparability of discussions.

4.3 Proportion of sampling units not recovering

Disturbances are a natural driver within any ecosystem. Nevertheless, over time, a healthy and resilient ecosystem would be expected to recover from disturbances. For sampling units (typically quadrats or transects) that were repeatedly monitored for at least 15 years, we enumerated the number of these units that had experienced a relative decline in raw (un-modelled) hard coral cover of at least 20 percent. We then calculated the percentage of these units that had subsequently recovered to within 90 percent of their pre-decline cover. To provide greater insights about the changes within these units, we also calculated the mean maximum absolute and percentage coral cover declines as well as the long-term (difference in cover between first and last sampling time) mean maximum absolute and relative declines in coral cover. Similar analyses were performed on incidences of algae cover increases and subsequent declines.

For the above calculations it was critical that only fine-scale sampling units (e.g. quadrats/transects) were used rather than higher scale locations such as Sites. This is because benthic data can vary enormously even at fine scales and thus comparing Site level data that comprise different sampling units over time will likely yield very distorted apparent declines and recoveries.

4.4 Sea Surface Temperature Anomalies

The above analyses provided the first large scale, quantitative estimates of the status and trends in the covers of live hard coral and algae. The resulting trends showed clear indications of fluctuations in hard coral cover at a global scale. Since numerous incidences of coral cover decline (both regionally and globally) had reportedly been attributed to coral bleaching resulting from elevated sea surface temperatures, we explored associations between the global trends in live hard coral cover and global trends in sea surface temperature and other climatic indices (e.g. ENSO).

HadSST4 is a global dataset that provides gridded (5x5 degrees) sea surface temperature anomalies across the world as well as global monthly averages[8]. The HadSST4 data were restricted to the temporal range of 1977 to 2020 so as to coincide with the availability of observed benthic data collated for this report. An 18 month rolling mean was used to smooth the trend in HadSST4 anomaly. The relative rate of change in smoothed HadSST4 per unit of time was estimated by calculating derivatives via finite differences.

[8] Kennedy, J. J., N. A. Rayner, C. P. Atkinson, and R. E. Killick. 2019. "An Ensemble Data Set of Sea‐surface Temperature Change from 1850: The Met Office Hadley Centre HadSST.4.0.0.0 Data Set." Journal of Geophysical Research: Atmospheres 124: 7719–63. https://doi.org/10.1029/2018JD029867.

After overlaying the smoothed HadSST4 trend and associated derivatives over the trend in global hard coral cover, a number of features became apparent. Periods of coral cover decline appeared to be associated with either smoothed HadSST4 anomalies that exceeded 0.45 or when the rate of smoothed HadSST4 change exceeded 0.15 for two consecutive months. Whilst these are not strictly statistical tests, they do provide the basis of future statistical explorations.

The above associations were communicated visually by plotting smoothed HadSST4 anomaly trend over the trend in global hard coral cover and overlaying vertical light red bars (50% opacity) to indicate when the rate of smoothed HadSST4 change exceeded 0.15 for two consecutive months and vertical dark red bars (20% opacity) to indicate when the smoothed SST anomaly exceeded a value of 0.45.

Conclusions

The value of coral reefs

Coral reefs occur in more than 100 countries and territories and whilst they cover only 0.2% of the seafloor, they support at least 25% of marine species and underpin the safety, coastal protection, food and economic security of hundreds of millions of people. The value of goods and services provided by coral reefs is estimated at US$2.7 trillion per year, including US$36 billion in coral reef tourism. Maintaining the integrity and resilience of coral reef ecosystems is essential for the wellbeing of tropical coastal communities worldwide, and is a critical part of the solution for achieving the Sustainable Development Goals under the 2030 Agenda for Sustainable Development.

Coral reefs are among the most vulnerable ecosystems on the planet to anthropogenic pressures, particularly those influenced by climate change, such as mass coral bleaching events tropical storms and ocean acidification. In addition, the world's coral reefs face myriad other local threats such as land-based pollution particularly nutrients and sediments from agriculture, marine pollution, overfishing and destructive fishing practices, outbreaks of crown-of-thorns starfish and coral diseases that cause local-scale degradation of coral reefs.

A quantitative analysis of a global dataset

This sixth edition of the GCRMN Status of *Coral Reefs of the World* report is the first since 2008, and the first based on the quantitative analysis of a global dataset compiled from raw monitoring data contributed by more than 300 members of the network. The global dataset spanned 41 years from 1978 to 2019 and consisted of almost 2 million observations from more than 12,000 sites in 73 reef-bearing countries around the world.

The vast majority of these observations have been collected since 1998, which is when the first global-scale coral bleaching event occurred, affecting nearly all coral reef regions. This event triggered a substantial increase in global monitoring effort to measure the impacts on the world's coral reefs. Since then, many monitoring programs have been maintained and new programs have been established, often in response to more recent mass bleaching events. This has resulted in greater spatial and temporal resolution of monitoring data and increased knowledge of the status of coral reefs at national, regional and global scales.

However, despite the increase in the amount of coral reef monitoring data, there was considerable variation in the way in which data were collected, the level of taxonomic detail recorded, and the way in which data were described (metadata) for sharing and re-use. Although, the data were collated and homogenized into a standard format that enabled statistical analysis of common variables, only live hard coral cover and algal cover were measured in a sufficiently consistent manner by different monitoring programs around the world to support a quantitative global analysis.

While the covers of both live hard coral and algae are globally accepted and universally used indicators of coral reef health, the report was unable to describe changes in coral community composition, the status of coral reef-associated fish populations, or the human dimensions associated with coral reefs. This highlights that there is a clear need for greater interoperability of coral reef monitoring data. This can be achieved through the adoption of more comparable data collection methods to enhance the resolution of information collected and to facilitate integration of data from different sources. Further, the adoption of data standards will promote appropriate storage, access, sharing and re-use of data.

In many regions of the world, enhancing the quality and interoperability of coral reef monitoring data will require considerable investment in building capability and capacity to monitor coral reefs. Such investment can be enhanced by combining it with the use of new and emerging technologies, which range from satellite mapping to automated analysis of coral reef images. In the future, a collaborative, integrated approach using traditional methods and new technologies for data collection and analysis will be critical to enable rigorous and timely reporting of the status of coral reefs at local, national and global scales. Availability, interoperability and reliability of data are crucial to inform coral reef management and investment in coral reef protection and restoration. The GCRMN has a role in supporting vital, ongoing investment in the development of methodological approaches, new technologies, capability and capacity to achieve this in the future.

Global status of coral reefs

Prior to the first major mass coral bleaching event in 1998, global average cover of hard coral was high (>30%) and stable. The global average cover of algae was also stable at about 15% until 2011. On average, there was twice as much coral on the world's reefs compared with algae.

The first global mass coral bleaching event in 1998 killed about 8% of the world's coral, which is roughly the equivalent of removing all the coral currently living on coral reefs in any of the Caribbean, Red Sea and Gulf of Aden, South Asia or Western Indian Ocean regions. The global average cover of algae did not change in response to the 1998 global coral bleaching event.

In the absence of large-scale disturbances, the global average cover of hard coral recovered to pre-1998 levels within a decade. However, between 2009 and 2018, there was a progressive loss amounting to 14% of the coral from the world's coral reefs, which is more than all the coral currently living on Australia's coral reefs. During this period, the amount of algae on the world's coral reefs increased by about 20%. As a consequence, the ratio between the global average covers of hard coral and algae has declined from 2.4 in 2010 (i.e. 2.4 times as much coral on the world's reefs as algae) to 1.7 in 2019. This global pattern of decreasing coral cover and increasing amounts of algae is a strong indication that the condition of the world's coral reefs is declining. A progressive transition from coral to algal dominance reduces the complex three-dimensional habitat that is essential to support high biodiversity and provide valuable goods and services for reef-dependent human communities.

The primary cause of the decline in global average coral cover was recurring large-scale coral bleaching events caused by elevated sea surface temperatures (SST). At a global level, strong positive global SST anomalies correspond with the major episodes of coral decline. All three global coral bleaching events (1997-98, 2010 and 2015-2017) have coincided with consecutive months of rapidly increasing SST anomalies, while sustained high SST anomalies after the 2010 event and from 2013 onwards may have hindered the recovery of corals and facilitated progressive increases in the cover of algae.

During the last decade, the interval between mass coral bleaching events has been insufficient to allow coral reefs to recover, highlighting their vulnerability to marine heatwaves, which is a phenomenon that is likely to happen more frequently as the planet continues to warm. The Intergovernmental Panel on Climate Change (IPCC) predicted that coral reefs would decline by 70-90% with global warming of 1.5°C and virtually lost with 2°C of warming. The most recent report by the IPCC showed that warming will continue at least until mid-century under all emission scenarios and predicts that 1.5°C and 2°C will be exceeded this century unless deep reductions in greenhouse gas emissions occur in coming decades.

Local and regional-scale threats, such as coral diseases, crown-of-thorns starfish outbreaks, tropical storms, overfishing and destructive fishing and poor water quality resulting from land-based pollution continue to exert significant influence on coral reefs. Controlling these threats rightly remains the focus of local-scale management.

Implications for management and policy makers

This report showed a strong association between a decline in coral cover and progressively rising sea temperatures associated with climate change. It is clear that a reduction in global emissions is necessary to deliver a positive future for coral reef ecosystems and the human communities that depend on them. Global action through the Paris Agreement to hold the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels is crucial for the future of coral reefs.

However, the report also showed that despite increasingly frequent mass coral bleaching events, which has been insufficient to allow coral reefs to fully recover, periods of recovery have been observed during the last two decades, and most recently in 2019 with coral reefs regaining 2% of the coral cover that was previously lost. These increases in coral cover are important, as they indicate that many of the world's coral reefs remain resilient and can recover if conditions permit. It shows that all is not lost for the world's coral reefs, but that our window for securing their future is closing, and a concerted global effort is required to ensure the trajectory of coral reef health is positive, while at the same time, reducing local threats.

Annex

List of acronyms:

AGRRA	Atlantic and Gulf Rapid Reef Assessment
AIMS	Australian Institute of Marine Science
API	Application Programming Interface
AUD	Australian Dollar
BNMP	Bonaire Marine National Park
$CaCO_3$	Calcium Carbonate
CBD	Convention on Biological Diversity
CCC	Coral Cay Conservation
CHICOP	Chumbe Island Coral Park
CNSI	Caribbean Netherlands Science Institute
CO_2	Carbon Dioxide
CORDIO	Coastal Oceans Research and Development – Indian Ocean
CRC	Coral Restoration Consortium
CRCP	Coral Reef Conservation Program
CREMP	Coral Reef Evaluation and Monitoring Project
CRIOBE	Centre de Recherches Insulaires et Observatoire de l'Environnement
CRIOBE	Agencement Temporel des Populations et des Peuplements (ATPP) programme
CRW	Coral Reef Watch
DRRH	Deep Reef Refugia Hypothesis
DBCA	Department of Biodiversity, Conservation and Attractions
EAS	East Asian Seas
ENSO	El Niño-Southern Oscillation
ETP	Eastern Tropical Pacific
FFI	Fauna and Flora International
FGBNMS	Flower Garden Banks National Marine Sanctuary
GBF	Global Biodiversity Framework
GBR	Great Barrier Reef
GCRMN	Global Coral Reef Monitoring Network
GDP	Gross Domestic Product
GEOBON	Group on Earth Observations Biodiversity Observation Network
GPS	Global Positioning System
ICRI	International Coral Reef Initiative
INVEMAR	Instituto de Investigaciones Marinas y Costeras
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Service
IPCC	Intergovernmental Panel on Climate Change
IRD	Institut de Recherche pour le Développement
IUCN	International Union for Conservation of Nature
LIT	Line Intercept Transect
LTMP	Long-Term Monitoring Program
MCE	Mesophotic Coral Ecosystems
MEOW	Marine Ecosystems of the World
MERMAID	Marine Ecological Research Management AID

MPA	Marine Protected Area
NGO	Non-Governmental Organization
NOAA	National Oceanic and Atmospheric Administration
PERSGA	Regional Organization for the Conservation of the Environment of the Red Sea and Gulf of Aden
PIT	Point Intercept Transect
RCP	Representative Concentration Pathway
RLE	Red List of Ecosystems
ROPME	Regional Organization for Protection of the Marine Environment (surrounded by the eight Member States of ROPME: Bahrain, I.R.Iran, Iraq, Kuwait, Oman, Qatar, Saudi Arabia and the United Arab Emirates)
RORC	Réseau d'Observation des Récifs Coralliens de Nouvelle-Calédonie
RRAP	Reef Restoration and Adaptation Program
SCTLD	Stony Coral Tissue Loss Disease
SECREMP	The Southeast Coral Reef Evaluation and Monitoring Project
SST	Sea Surface Temperature
TMP	Tun Mustapha Park
TNC	The Nature Conservancy
UN	United Nations
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
USD	United States Dollar
WIO	Western Indian Ocean
WRI	World Resource Institute

CORDIO

CRIOBE
USR3278
Centre de Recherches Insulaires et
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