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Ordinary People and Emerging Technologies

How Citizen Science and Improvements in Artificial Intelligence and Remote Sensing can be employed in Monitoring and Managing Future Great Barrier Reef Coral Bleaching Events

Introduction to the Reef and the Key Threats to its Health

The Great Barrier Reef is one of the world's most spectacular ecosystems - marine, terrestrial, or otherwise. First declared as a marine park in 1979 and inscribed as a UNESCO World Heritage Area in 1981, Australia's Great Barrier Reef (GBR) spans an area larger than Italy and longer than the western coast of the United States, and contains well over 3,000 individual reefs.[1] Not only is it geographically large, it is one of the most biodiverse marine ecosystems in the world; the northern tip of the GBR alone is home to over 1500 individual fish species.[2] With an area so large and containing such immense biodiversity, from the microscopic algae to the sixty-foot whale shark, management and conservation is no simple task.

In order to address the complexities of monitoring and managing the GBR, there first needs to be an understanding of the challenges the reef faces. The Great Barrier Reef Marine Park Authority (GBRMPA)—the Australian Government's GBR management agency—has identified climate change, land-based runoff, coastal development, and certain forms of direct extractive use as the greatest threats to the health of the GBR and the services it provides in each assessment report since 2009.[3] While a holistic management approach is necessary given that protecting the reef against one threat still leaves it vulnerable to others, the only two threats assessed to be simultaneously "almost certain" and "catastrophic" in the GBRMPA's 2019 risk assessment matrix are ocean acidification and sea-temperature increase, both of which are direct products of climate change.[4] To make matters worse, the impacts of ocean acidification and sea-temperature increase on

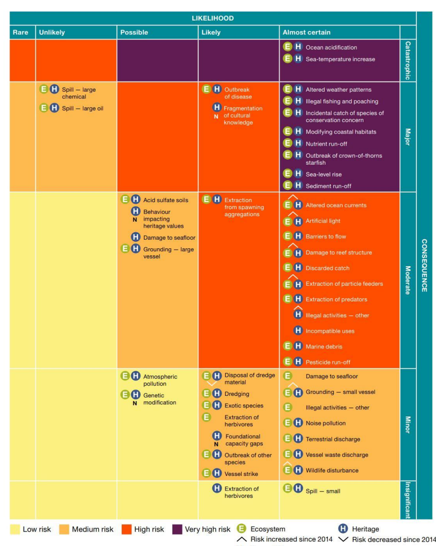

Figure 9.1 Risks to the Region's ecosystem and heritage values from identified threats
This risk matrix is consistent with the principles, framework and processes outlined by the Australian Standard (AS ISO 31000) using terms and definitions detailed in Appendix 7. The assessment is based on current and documented future trends in the identified threats and existing management measures. The compounding effects of threats are not considered. The full description for each of the identified threats is provided in Appendix 6 and the risk assessment for each threat is summarised in Appendix 8. The four threats added in 2019 are marked as new additions. Symbols indicate where a threat has been assessed as having the same combination of likelihood and consequence ratings for both ecosystem and heritage values (that is, its natural, Indigenous, historic and other heritage values). If a threat has different ratings for ecosystem and heritage, it is presented twice and each entry is shown with a single symbol. Some threats are only relevant to heritage values and only appear once. If the assessed risk has increased or decreased since the 2014 Outlook Report this is indicated.

[1] Great Barrier Reef Marine Park Authority, *Great Barrier Reef Outlook Report 2019*, p5
[2] Hutchings, Kingsford, and Hoegh-Guldberg, *The Great Barrier Reef*, p126
[3] Great Barrier Reef Marine Park Authority, *Great Barrier Reef Outlook Report 2019*, p245
[4] Great Barrier Reef Marine Park Authority, *Great Barrier Reef Outlook Report 2019*, p248

coral reefs are some of the most difficult to understand, measure, and track overtime on a scale as large as the GBR. This paper addresses the challenges in monitoring coral bleaching and, using an analysis of past methods and emerging technologies, proposes a best-practice approach to using citizen science and technology in monitoring and managing the GBR in response to the increased threat of mass coral bleaching events.

Coral Bleaching within the Great Barrier Reef Marine Park

Mass coral bleaching events, which are caused by sea-temperature increases, are becoming more frequent and more severe, calling for an increase in the quantity and quality of coral reef monitoring as it relates to coral bleaching. The GBR itself was first impacted by a mass coral bleaching event in the summer spanning 1997-1998 and has since experienced regional mass bleaching events during the marine heat waves of 2002, 2006, 2008, 2011 and reef-wide mass bleaching events in 2016 and 2017, affecting two-thirds of the entire 2,300km stretch.[5] Additionally, GBR bleaching events have been steadily increasing in scope and intensity since the GBRMPA began monitoring bleaching in the 1980s.[6] Before further exploring bleaching and its monitoring on the GBR, it is important to understand the mechanism behind coral bleaching, what qualifies as a mass bleaching event, and why bleaching is such an extreme threat to the GBR.

Fossil fuel combustion and other human activities have greatly increased the concentrations of greenhouse gasses (GHGs) in earth's atmosphere, causing average global temperatures to rise dramatically over the past century and especially the past few decades. While many are well aware of the increases in atmospheric temperatures, lesser-known consequences are being caused by increasing ocean temperatures, driven by the fact that 90% of the excess heat generated by GHG emissions has been absorbed by the ocean.[7] As a direct result of anthropogenic climate change, global sea surface temperature (SST) has increased 0.88℃ since pre-industrial times and is virtually certain to continue rising throughout the 21st century, putting the existence of highly temperature-sensitive corals at great risk.[8] Some of the most rapid warming has occurred in the Western Pacific Ocean, which contains the GBR. Making matters worse, the taxonomic order of the GBR's foundational reef-building corals, scleractinian corals, are particularly sensitive to changes in SST.[9] When SST rises, the symbiotic dinoflagellate zooxanthellae (algae) that live inside coral tissue and provide them with nutrition from photosynthesis begin to produce toxins and the corals expel them. Without the algae, corals have lost their main source of food and are at greater risk of starvation, disease, reproductive failure, and loss of competitive viability. And, given that the algae provide corals with their coloration, corals undergoing thermal stress who expel their algae turn white, hence the name coral bleaching. [10]

[5] 'Coral Bleaching Events | AIMS'.
[6] Great Barrier Reef Marine Park Authority, *Great Barrier Reef Outlook Report 2019*.
[7] Fox-Kemper et al., 2021, *Ocean, Cryosphere and sea level change*.
[8] IPCC, 2021: Summary for Policymakers.
[9] Hoegh-Guldberg et al., 2017, 'Coral Reef Ecosystems under Climate Change and Ocean Acidification'.
[10] Hoegh-Guldberg et al., 2017, 'Coral Reef Ecosystems under Climate Change and Ocean Acidification'.

Looking to the future, it is virtually certain that mass bleaching events will continue to increase in frequency and severity within the GBR, especially if the world does not reach net-zero GHG emissions by mid-century.[11] Even under the most stringent emissions-reductions policies, correlated to the Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathway (RCP) 2.6, 40% of the coral area in the Western Pacific Ocean (which contains the GBR) is expected to experience annual bleaching meanwhile under a business-as-usual scenario, nearly 100% of coral in the Western Pacific are expected to experience annual bleaching.[12] Regardless of which emissions scenario the global community pursues, significant portions of the GBR have already experienced and will continue to experience mass bleaching events, making evident the need for spatially and temporally extensive and detailed monitoring of coral bleaching.

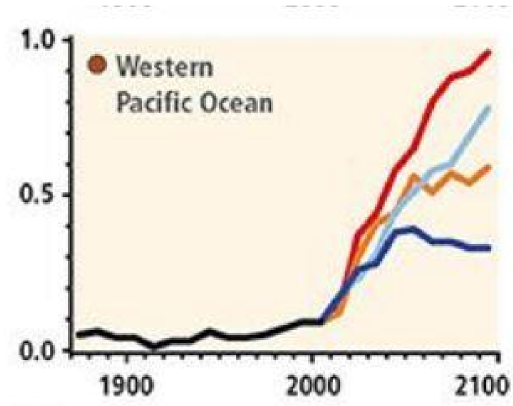

Figure 2: The y-axis represents the proportion of Western Pacific Ocean coral grids experiencing annual mass bleaching events and the y-axis represents the year CE from the industrial revolution to the end of the 21st Century. The black line represents data through 2009 from the Hadley Center Interpolated SST dataset while the colored lines represent future projections post-2009 using CMIP5 data. The dark blue line correlates to IPCC RCP2.6, light blue to RCP4.5, orange to RCP6.0, and red to RCP8.5 with RCP2.6 requiring net-zero emissions by 2050 and RCP8.6 representing a business-as-usual scenario (Hoegh-Guldberg 2014).

The Past and Current State of Great Barrier Reef Monitoring

Monitoring is at the core of GBR management as it provides answers to questions such as: What is there? What is the status of what is there? How is it changing? Why is it changing? What does this mean for the ecosystem going forward? and What can we do to assist or sustain the ecosystem? The Australian Institute of Marine Science (AIMS) has been attempting to answer these questions since their first rapid ecosystem surveys in the 1980s which involved dragging observers behind boats and recording their observations every few hundred meters (manta tow surveys). In its first phase in the 20th century, such tactics only provided non-specific data for the perimeter of between 200 and 300 reefs (recall that the GBR contains well over 3,000 individual reefs) and was of minimal utility for any intensive research. Moving into the 1990s, AIMS decided that percent coral cover—the percentage of a given

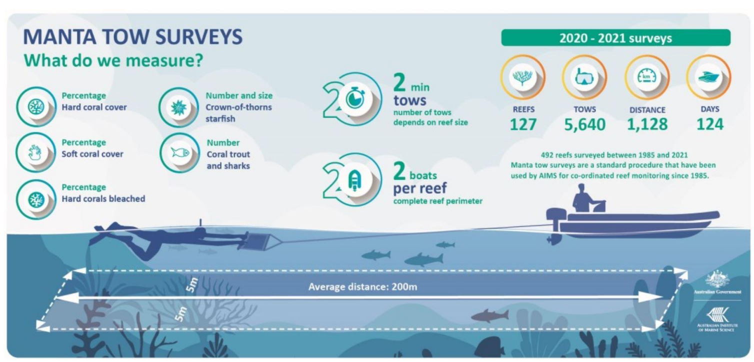

Figure 3: AIMS Manta Tow Surveys Overview Information

[11] Hoegh-Guldberg et al., 2014, 'The Ocean'.
[12] Hoegh-Guldberg et al., 2014, 'The Ocean'.

region with the coral present—would be used as the primary indicator of reef health observed during manta tow surveys, and this indicator has remained the standard through present day. While this is a convenient metric, especially with the limitations of the type and specificity of data that can be collected through manta tow surveys, percent coral cover does not provide information on the type or state of the coral present and may not accurately reflect changes in the type of coral present. It is easy to assume that any coral cover is good coral cover, but in reality, more "weedy" coral taxa like branching coral and plate coral are the fastest-growing and therefore first to recover after a bleaching event but they are also the most vulnerable to bleaching and other coral threats like ocean acidification and storms. As such, it is important to know *what* corals are present, not just how much of the area is covered by corals.[13] Unfortunately, as seen in **Figure 3**, even with dedicating 124 days to conducting manta tow surveys from 2020-2021, only 127 of the over 3,000 reefs on the GBR were monitored, and since 1985 only 492 individual reefs have been monitored in this manner. The size of the GBR is simply beyond the scope of AIMS's ability to regularly and fully monitor, creating a need for other sources of data on the reef. While there is still significant room for improvement, tourist and community-based citizen science, artificial intelligence, and remote sensing have begun to meet this need.

Tourism on the Great Barrier Reef

Tourism is a major industry and an integral part of the economy for the coastline along the Great Barrier Reef. Prior to COVID-19 travel restrictions, over two million tourists visited the Great Barrier Reef Marine Park (GBRMP) annually.[14] Of these visitors, more than half undertook recreational diving and snorkeling (RDS) activities, amounting to 3.1 million total RDS activities in 2007.[15] This represents a diverse market of activities for visitors, as well as potential economic and scientific risks and opportunities. Scuba diving and snorkeling, in particular, represent some of the world's fastest-growing sport activities, with the number of certified divers hovering around 27 million.[16] This growth in RDS activities has been focused on tropical coral reefs like the Great Barrier Reef, largely because of the organismal, ecological, and geophysical diversity that the reefs provide.[17] With this growth in RDS activities, GBRMPA Environmental Management Charge (EMC) data has shown that reef-based tourism on the GBR has increased steadily in the last three decades.[18]

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[13] Scott Bainbridge, Monitoring the GBR: Technology and Solutions, 13 June 2022

[14] "Great Barrier Reef Tourist Numbers" (GBRMPA), https://www.gbrmpa.gov.au/our-work/Managing-multiple-uses/tourism-on-the-great-barrier-reef/numbers.

[15] Jim Binney, "The recreational dive and snorkelling industry in the Great Barrier Reef profile, economic contribution, risks and opportunities" (GBRMPA, no. 95, 2009).

[16] B.M. Musso and G.J. Inglis, *Developing Reliable Coral Reef Monitoring Programs for Marine Tourism Operators and Community Volunteers* (CRC Reef Research Centre, 1998), 14; "2019 Worldwide Corporate Statistics: Data for 2013-2018" (PADI, 2019), 2.

[17] Joleah B. Lamb et al., "Scuba Diving Damage and Intensity of Tourist Activities Increases Coral Disease Prevalence" (Biological Conservation 178, 2014), 88.

[18] "Great Barrier Reef Tourist Numbers" (GBRMPA).

Concurrent with the increase in reef-based visitations on the GBR, the health and overall future of global reefs have grown increasingly alarming. In order to monitor the health of the reef in the last 25 years, visitors have become citizen scientists, providing valuable information through voluntary reef-monitoring services.[19] Programs like Waterwatch and Coastcare have served to protect water quality and coast conservation, while Coral Cay, REEFWATCH, CANARI, and the GBRMPA's Eye on the Reef have provided data on coral reef visitor patterns, animal sightings, recreational activity monitoring, and biological and physical variables, such as the abundance and species diversity of fish and underwater visibility.[20]

Citizen Science on the Great Barrier Reef

Although many of the programs already mentioned have been particularly designed to fit the interests and capabilities of local communities or international visitors, there has been a strong push for health and impact surveys with emphasis on climate-driven coral bleaching and biodiversity reporting.[21] Thus, the vast majority of long-standing volunteer programs on the GBR are survey-based monitoring services that are focused on describing the health state of reefs, as well as the distribution of species and state of biodiversity.[22] Current worries over climate change have driven the GBRMPA and researchers to utilize repeatedly sampled sites from volunteer data to evaluate long-term trends and biophysical processes.[23]

For many years, professional monitoring was prioritized on the reef because it is distinctly precise, but it is also labor and resource-intensive, as well as time-consuming.[24] Despite the relative precision of these programs, the constantly degrading health of the GBR has made spatial and temporal data collection expectations change. Rapidly and regularly performed observations have thus been prioritized because of their ability to sort out cryptic and ephemeral data collections across the GBR's hundreds of individual reefs. Using citizen science, reef managers can frequently obtain large amounts of data across the entire GBR. From this, volunteer science can "provide a valuable method to detect broad-brush changes on a local, regional and global scale, as well as increasing public support for coral reef conservation."[25] This data can come in the form of repeatedly performed individual surveys of reefs or much more advanced technical information.

[19] "Eye on the Reef: Case Study" (Eye on the reef: Case study - DAWE), https://www.awe.gov.au /parks-heritage/great-barrier-reef/case-studies/eye-on-the-reef.
[20] B.M. Musso and G.J. Inglis, *Developing Reliable Coral Reef Monitoring Programs*, 4-5.
[21] "Eye on the Reef: Case Study" (Eye on the reef: Case study - DAWE)
[22] Wilkinson, C.R. & R.W. Buddemeier, *Global Climate Change and Coral Reefs: Implications for People and Reefs, Report of the UNEP-IOC-ASPEI-IUCN Global Task Team on the implications of climate change on coral reefs*(IUCN, 1994), vi.
[23] Scott Bainbridge, Monitoring the GBR: Technology and Solutions, 13 June 2022
[24] Roger John Beedan, "A Dynamic Understanding of Coral Reef Health Informs Resilience-Based Management of the Great Barrier Reef" (James Cook University, 2014).
[25] Gregor Hodgson, "A Global Assessment of Human Effects on Coral Reefs," Marine Pollution Bulletin 38, no. 5 (May 1999).

Citizen scientists have, for example, been employed as a part of James Cook University's (JCU) mapping of the Great Barrier Reef in 2018.[26] After identifying citizen vessels as an untapped resource, the program provided $10,000 for volunteers to install any necessary echo sounders or GPS systems to their boats. This investment ultimately contributed to the development of an accurate 3D model of areas of the GBR that were historically too remote for scientists to devote time to mapping themselves. This simple process could continually provide data that is essential for monitoring the long-term vulnerability of the reef, particularly through mass bleaching events.

Efficacy, Utility, and Reliability of Citizen Science

Although studies like this far-reaching JCU project have maintained scientific accuracy in utilizing precise and advanced technology, the majority of survey-based citizen science projects lack this degree of accuracy. The Eye on the Reef program, the most expansive citizen science network on the GBR, for example, relies on Rapid Health Impact Surveys (RHIS).[27] In these surveys, volunteers are tasked with estimating percentages of different types of benthic covers, such as scleractinian corals, macroalgae, sand, and others.[28] With thousands of such RHIS completed over decades, concerns surrounding their quality and consistency have been brought to light. Despite the strong incentives for the GBRMPA and other marine managers to implement volunteer-based citizen science, such as cheap labor and access to remote areas, high variability in data has deterred some researchers from trusting citizen science in significant studies of reef health.[29]

One of the main arguments against citizen science centers on the assumption that volunteers lack the knowledge or competency to accurately complete their surveys. In order to evaluate the reliability and utility of citizen science projects, researchers at AIMS and other organizations have compared long-term ecological monitoring programs performed by citizen scientists to identical monitoring programs performed solely by experts.[30] The goal of this experiment, performed by Reef Check Australia (RCA), was to test the efficacy of citizen science in filling the gaps in formal government programs. This largely came in the form of identifying categories of benthic cover or other easily identifiable structures, after the volunteers were briefly educated on the different categories of benthos. When tested, the volunteers were proven highly effective in providing very accurate estimates of benthic distribution. This came despite the fact that there was sometimes an uneven distribution of reef benthos, imprecisely prepared experimental conditions (inconsistent quadrant demarkations, for example), and the use of different volunteers throughout the

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[26] Robin Beaman, "Citizen Scientists to Help Map the Reef," Townsville: James Cook University Media Releases (February 2019). https://www.jcu.edu.au/news/releases/2019/february/c itizen-scientists-to-help-map-the-reef.
[27] "Eye on the Reef: Case Study" (Eye on the reef: Case study - DAWE)
[28] Roger John Beedan, "A Dynamic Understanding of Coral Reef Health Informs Resilience-Based Management of the Great Barrier Reef."
[29] Charles Jacoby, et al. "Three Recent Initiatives for Monitoring of Australian Coasts by the Community." Ocean & Coastal Management 36, no. 1-3, (1997). https://www.sciencedirect.com/science/article/abs/pii.
[30] Terence Done, "Reliability and Utility of Citizen Science Reef Monitoring Data Collected by Reef Check Australia, 2002–2015." Marine Pollution Bulletin 117 (2017). https://www.sciencedirect.com/science/ article/abs/pii.

experiments.[31] This research also revealed that most of the inaccuracies from citizen science come in the form of sway errors, which are inaccuracies that are attributable to changing environmental conditions throughout the survey. Thus, this research indicates that citizen scientists, when employed to observe broad trends that complement formal monitoring, are very effective.

One recent application of citizen science monitoring revealed an additional area that volunteers can supplement professional research, reef marine debris load. Marine debris, such as plastics or fishing lines, has been identified as a significant threatening process by the Australian government, which has been taking considerable action against marine debris since 2009.[32] In 2018, researchers used RCA surveys to assess the distribution of marine debris throughout the Australian coast. Over a five-month period, citizen scientists were able to provide valuable datasets that accurately identified particular locations with significant debris, as well as broad patterns for the distribution of debris.[33] Volunteers found, for example, that areas with high human presence have much more marine debris. This data both bolstered the reputation of citizen science and provided beneficial information for the maintenance of the reef.

In 2014, another large-scale research project employed citizen science rapid surveys over about 10 years. The project, carried out by several researchers at the GBRMPA, JCU, Cornell University, and Laboratoire d'Excellence (CORAIL), simultaneously collected relevant data on reef conditions and refined a simple and effective survey for citizen scientists.[34] This survey, which asks an advanced set of questions used in a form of the Eye on the Reef survey, sought to address two methods for maximizing the effectiveness of citizen science.

The first method was to incorporate brief educational programs prior to the data collection process. The education process included e-learning and training in the water, as well as resources for the identification of benthic cover that could be used before and during the survey. The report found that educating the volunteers, particularly through a self-paced online course, made the collection of data advanced, accurate, and cost-effective. Through this method, volunteers could become certified 'observers,' and following their certification, they could identify benthic cover types with at least 75% accuracy in both categorizing and estimating the percent cover of specific benthic types.[35]

The second method by which this experiment proved the efficacy of standardized citizen science surveys was employing a sufficiently broad method for volunteers to execute. Besides utilizing the

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[31] Terence Done, "Reliability and Utility of Citizen Science Reef Monitoring Data Collected by Reef Check Australia, 2002–2015."

[32] Stephen Smith and RJ Edgar, "Documenting the Density of Subtidal Marine Debris across Multiple Marine and Coastal Habitats." PLOS ONE 9 (2014). https://doi.org/10.1371/journal.pone.0 094593

[33] Anne Bauer-Civiello, Jennifer Loder, and Mark Hamann. "Using Citizen Science Data to Assess the Difference in Marine Debris Loads on Reefs in Queensland, Australia." Marine Pollution Bulletin 135 (2018). https://www.sciencedirect.com/science/article/abs/pii.

[34] Roger John Beedan, "A Dynamic Understanding of Coral Reef Health Informs Resilience-Based Management of the Great Barrier Reef."

[35] Roger John Beedan, "A Dynamic Understanding of Coral Reef Health Informs Resilience-Based Management of the Great Barrier Reef."

Eye on the Reef survey that was used in the educational courses to prepare the volunteers, the research indicated further best practices for time intervals. In short, the volunteers were most effective when they performed three surveys and kept within the time interval of 15-20 minutes per survey.[36] This proved to be a practical method, as it only took one hour to complete the entire set of surveys, but in practice, other volunteers could do as few as one survey and report that data. Thus, this experiment buttressed the credibility of the Eye on the Reef survey by employing their method while testing its high efficacy and value in practice.

Despite experiments like the 2014 RHIS research, which supported simple survey methods like the Eye on the Reef program, other researchers and formal government programs are exploring how emerging technologies can change the entire field of citizen science and environmental monitoring.

Artificial Intelligence and Reef Monitoring Cameras

Outside of refining reliable methods from previous decades, such as citizen science surveys, more promising and budding monitoring technologies have taken the spotlight in monitoring projects for mapping and evaluating reef health.[37] In the past, volunteers were generally used to fill the gaps in formal research by conducting these simple, cost-effective surveys. Recognizing the emergence of artificial intelligence and machine learning algorithms with the capacity to map and detect traits of reef health from simple images, citizen scientists are able to contribute much more valuable information, such as videos and scans of the reef.[38]

One recent and relatively simple example of how technology has changed citizen science is the Reef Vision project. Seeing a need for reef monitoring on artificial reefs, researchers at Murdoch University recruited recreational fishers to provide videos of artificial reefs, and these videos were then analyzed by scientists.[39] In this experiment, 12 volunteers were supplied with camera equipment from the researchers, and they were tasked with recording videos 60 minutes in length of their assigned reef on a monthly basis. The researchers amassed 111 videos across the reefs, and they found this method to be very cost-effective, as their small team of scientists would have taken much more time to capture similar videos. They found the videos to be of sufficient quality to monitor the reefs, and they noted that providing professional equipment to the volunteers ensured high-quality videos. Further, the use of standardized equipment lowered the stigma around utilizing citizen science and increased enthusiasm for volunteering.[40]

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[36] Roger John Beedan, "A Dynamic Understanding of Coral Reef Health Informs Resilience-Based Management of the Great Barrier Reef."

[37] Robin Beaman, "Citizen Scientists to Help Map the Reef."

[38] Sarah Hamylton, Zhexuan Zhou, and Lei Wang. "What Can Artificial Intelligence Offer Coral Reef Managers?" Frontiers in Marine Science 9 (2020). https://doi.org/10.3389/fmars.2020.603829.

[39] James Florisson, et al. "Reef Vision: A Citizen Science Program for Monitoring the Fish Faunas of Artificial Reefs." Fisheries Research 205, (2018). https://www.sciencedirect.com/science/article/abs/pii.

[40] James Florisson, et al. "Reef Vision: A Citizen Science Program for Monitoring the Fish Faunas of Artificial Reefs."

Although the volume of data increased very significantly when citizen science was employed for this 2018 study, the research still required professionals to interpret and analyze all of the data. Researchers around the world are working to optimize this process by eliminating the need for researchers to process any data themselves. In a 2020 study, the University of Georgia and the University of Michigan sought to develop an approach to automatically inspect and categorize images of coral reefs.[41] The algorithms were taught to reconstruct 3D models of the reefs, as well as classify the benthic cover in the 3D models. The program organized the types of benthic cover into 10 categories, including sand, rubble, and coral sorted to the species level. Overall accuracy levels for the program were ~96% for most classes, proving high accuracy acceptable for ecological implementations.[42] Convolutional neural networks such as this offer a feasible solution to the costly and labor-intensive work that scientists have in interpreting data themselves.

Although convolutional neural networks and artificial intelligence have not been used for many large-scale subaqueous monitoring projects, studies are shifting their methods to account for its potential in the future. While monitoring the biodiversity in rocky reef environments in a 2021 study, researchers set very specific parameters and standardized methods for photos to be taken.[43] Although it is generally the best scientific practice to limit the variation between data collection methods, the researchers on this project demanded particular image quality, resolution, photo angle, and other conditions because of future technology. Artificial intelligence was not utilized in this project, but the researchers noted that expert-trained neural networks would be very beneficial in reviewing the data, as it would greatly reduce the analysis time.

With researchers recognizing the value of artificial intelligence in reef observation, there is potential for the application of convolutional neural networks in far-reaching monitoring projects to assess coral bleaching. For many years, AIMS conducted large-scale monitoring projects of reefs by towing scientists behind boats while they conducted underwater surveys and took photos and videos. With the emergence of new video technology, this area of monitoring has changed greatly.[44] Now, AIMS is attempting to tow cameras behind their boats to record videos of the reef for scientists to analyze. Although it seems that utilizing this advanced technology would benefit the research, questions have been raised over the quality of the images and videos, as well as the efficiency of the program, seeing that the videos still need to be interpreted by professionals. In 2021, AIMS researchers set out to test whether towing cameras is more efficient than towing researchers.[45] When compared directly, the cost of the equipment, maintenance, and construction of each method was similar, but the overall

[41] Brian Hopkinson, et al. "Automated Classification of Three-Dimensional Reconstructions of Coral Reefs using Convolutional Neural Networks." PLOS ONE (2020). https://doi.org/10.1371/journal.pone.0230671.
[42] Brian Hopkinson, et al. "Automated Classification of Three-Dimensional Reconstructions of Coral Reefs using Convolutional Neural Networks."
[43] Gonzalo Bravo, Juan Pablo Livore, and Gregorio Bigatti, "Monitoring Rocky Reef Biodiversity by Underwater Geo-Referenced Photoquadrants." Underwater Technology 38, no. 1 (2021). doi:10.3723/ut.38.017.
[44] "Video Monitoring." Australian Institute of Marine Science: Research. https://www.aims.gov .au/docs/research/monitoring/seabed/video-monitoring.html.
[45] Anna K. Cresswell, "A Quantitative Comparison of Towed-Camera and Diver-Camera Transects for Monitoring Coral Reefs." PeerJ 9, e11090 (2021). doi:10.7717/peerj.11090.

quality of the data was notably better when researchers themselves took the photos and videos. The exposure and focus on the data taken by towed cameras were often suboptimal, which made the interpretation of the data more difficult. Despite this, the overall accuracy after interpretation was as high as 97% accurate compared to the data taken by researchers. Overall, the time taken to collect data when cameras were towed was lowered because of the lack of security restraints that are necessary when researchers are towed. Moreover, data could be collected two to four times in 30-60 minutes, whereas researchers would take 45-60 minutes for one collection.[46] Overall, the towed cameras offer an opportunity for expansion of research in a cost-effective way after the initial investment in equipment, and the researchers noted that the use of artificial intelligence would cut down the still labor-intensive and time-consuming work of analyzing the data.

There are, however, drawbacks to using artificial intelligence and advanced cameras for monitoring the reef. One significant problem that researchers currently face is standardizing measurements of reef health and biodiversity. Although costs of implementing various new technologies in large-scale projects have gone down significantly, analyzing, synthesizing, and comparing data across these advancements has been much more difficult to put into practice.[47] There are, however, tested programs that are encouraged by some researchers. In 2017, a collection of researchers around the world tested a method for standardizing data from autonomous reef monitoring structures or ARMS.[48] Although they found promising results in their methods for standardizing sampling and processing of benthic structures, it also became clear that the current limiting factors are not practical procedures and databases, they're the cost and scope of the project. In order to use all of the invaluable data from various monitoring systems in tandem, researchers need to commit to tracking and accounting for all of the small variations in their field techniques, which proves difficult with limited funds. In practice, this is not only a weakness for large-scale projects that attempt to pull data from many different monitoring systems, but it also complicates comparisons in reef health between any two reefs with different monitoring methods.

Remote Sensing in Monitoring Coral Bleaching

While the quality and quantity of citizen science data have improved greatly over the past decade, coupled with advancements in artificial intelligence that increased the value of citizen science data for formal research, these methods remain limited in scope and scalability. Put simply, the Great Barrier Reef is too massive to reasonably collect in-situ data across its entire range. Currently, less than 10% of the estimated 3,000 individual reefs have been physically surveyed despite decades of monitoring programs.[49] Recent advances in remote sensing technologies have helped begin to close

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[46] Anna K. Cresswell, "A Quantitative Comparison of Towed-Camera and Diver-Camera Transects for Monitoring Coral Reefs."
[47] Emma Ransome, et al., "The Importance of Standardization for Biodiversity Comparisons: A Case Study using Autonomous Reef Monitoring Structures (ARMS) and Metabarcoding to Measure Cryptic Diversity on Mo'orea Coral Reefs, French Polynesia." PLOS ONE (2017). https://doi.org/10.1371/jour nal.pone.0175066.
[48] Emma Ransome, et al., "The Importance of Standardization for Biodiversity Comparisons…"
[49] Scott Bainbridge, Monitoring the GBR: Technology and Solutions, 13 June 2022

these gaps by providing high-resolution and frequent satellite images of the world's shallow coral reefs, including the GBR.

Remote sensing is a geospatial monitoring technique in which remote sensors, most commonly satellites in earth's orbit, collect data on the physical characteristics of an environment by measuring reflected and emitted radiation.[50] Because such satellites are already in orbit and can provide high-resolution visible and infrared spectrum images of coral reefs shallower than twenty meters, remote sensing circumvents the challenges of the financial and temporal cost and physical accessibility of monitoring reefs in-situ. To many scientists involved in coral reef monitoring, remote sensing "is likely the only technology able to measure coral reef pressures from anthropogenic stressors at scales sufficiently large enough to capture widespread, often subtle change, or spatially- and temporally-localized and episodic change" and potentially provides more reliable and standardized data than that from citizen science and local environmental knowledge.[51] Additionally, while certain types of remote sensing data analysis in coral reef monitoring have only recently been developed, data sets like the Landsat series (data from a specific group of remote sensors) date back to the 1980s, enabling scientists to track ecosystem change since before the first mass bleaching event in 1998.[52]

In an interview on 7 June 2022, Dr. Nicholas Murray, the director of James Cook University's Global Ecology Lab and remote sensing specialist, discussed the many recent advances in remote sensing technologies and its future potential in coral reef monitoring. The first major breakthrough came in 2008 when the United States' National Aeronautics and Space Administration (NASA) and the United States Geological Survey (USGS) made their satellite data freely accessible. New satellite images of any one region are produced every seven to eight days and, before this switch to open-access, if a researcher wanted to analyze the satellite data for the entire GBR with each new image dump, purchasing access to these images could cost tens of millions of US dollars each year. No university or independent research authority was able, let alone willing, to fund that type of intensive research necessary to monitor processes like coral bleaching. In 2013, Google broke open the potential for remote sensing in ecosystem management by allowing researchers like Dr. Murray to access their processing capabilities. One machine learning training set—data from in-situ monitoring matched with specific satellite image pixels to "teach" a computer what the visual and infrared signature of an image correlates to in the environment—would typically take weeks to process with the computing capacities in a standard research lab. Google's computers can do this in a matter of days. These two changes in access to satellite image data and processing, coupled with general improvements in technology since the turn of the century, make remote sensing one of the most promising methods of monitoring ecosystems on a large scale.

Equipped with NASA and the USGS's satellite data, as well as data from other remote sensors, and Google's processing capabilities, Dr. Murray and many others began working with the Allen Coral Atlas, which processes satellite data of coral reef ecosystems shallower than 20 meters and between

[50] Foo and Asner, *Scaling Up Coral Reef RestorationUsing Remote Sensing Technology*.
[51] Foo and Asner, *Scaling Up Coral Reef RestorationUsing Remote Sensing Technology*.
[52] Foo and Asner, *Scaling Up Coral Reef RestorationUsing Remote Sensing Technology*.

30°N and 30°S to provide a map of the world's tropical corals, including the GBR. The Allen Coral Atlas is managed by the Arizona State University Center for Global Discovery and Conservation Science in partnership with Planet, the Coral Reef Alliance, and the University of Queensland. Their advanced analytic techniques broke open the potential of monitoring and mapping coral reefs and the processes they undergo, like coral bleaching, across the blue, green, red and near infrared spectra.[53] The Allen Coral Atlas website displays data levels such as the benthic map, geomorphic map, satellite reef imagery, and the level of coral bleaching. Satellites are able to detect the whitening of reefs on a week-by-week basis as new satellite images are generated and processed every seven to eight days.[54] Instead of relying on citizen scientists or researchers physically being at a bleached reef soon after bleaching occurs to flag it and respond accordingly (whether that response is indicating to scientists that the reef is an area of interest, a policy response such as limiting further damaging human activities in that area, or even just flagging that bleaching occurred as evidence of the magnitude of the risk of coral bleaching), bleaching is noticed and tracked much earlier and across the entire reef instead of the smaller portions that are physically visited.

Limitations of Remote Sensing and Its Possibilities for the Future

Just as citizen science and artificial intelligence have their limitations in coral reef monitoring, remote sensing has its drawbacks as well. As imagining capabilities improve, the resolution of remote sensing images and thus the specificity of information they provide has increased, but even the best satellites generate 3.125-meter pixels and are not capable of accurately capturing reefs deeper than 20 meters.[55] Despite these limitations, remote sensing remains an incredibly valuable tool in the early stages of identifying bleaching events, identifying areas that require further in-situ monitoring, and tracking ecosystem-wide change. One of the greatest challenges in environmental monitoring is that one instance of monitoring can only tell *what* is there, not *how* it is changing.[56] Because remote sensing data is much more frequent than what the capacities of in-situ monitoring can allow and covers a wider range, it not only tells the status of the entire GBR on a weekly basis, it also effectively tracks how it is changing and the actual process and progression of bleaching.

One promising future application of remote sensing is the creation of a coral bleaching alert system. Such systems already exist for other forms of environmental degradation, most notably the University of Maryland Global Analysis and Discovery lab's deforestation alert system on the Global Forest Watch (GLAD alert system). As new satellite images are processed each week, the alert system automatically flags areas where the forest canopy has changed by comparing the images to historical satellite images of forest cover. With pixels grouped into thirty by thirty-meter squares, this system is accurately able to detect forest cover loss, especially considering that the world loses over an acre of forest every few seconds.[57] These alerts can then be followed up on the ground with the related authorities knowing which precise location needs their attention. This type of monitoring

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53 Allen Coral Atlas Science and Methods https://www.allencoralatlas.org/methods/
54 'Allen Coral Atlas | Atlas'. https://www.allencoralatlas.org/atlas/#5.35/-18.8847/149.9945
55 Alan Coral Atlas Science and Methods https://www.allencoralatlas.org/methods/
56 Scott Bainbridge, Monitoring the GBR: Technology and Solutions, 13 June 2022
57 'GLAD Deforestation Alerts, Explained | Global Forest Watch Blog'.

system allows resources to be most effectively employed to regions of concern, quickening and streamlining the process of creating a policy response. The key difference between the GLAD alert system and the current applications of remote sensing of coral bleaching is that the GLAD alerts are automatic. No individual researcher or research group is analyzing the images to track ecosystem change; the machine learning training sets instead have used technology to make the generation of these alerts automatic for any forest loss. Creating an automatic alert system for coral bleaching would greatly enhance the efficiency of existing platforms like the Allen Coral Atlas as well as its utility to policymakers.

A coral bleaching alert system based on remote sensing data could bring bleaching monitoring in line with the United Nations Convention on Biological Diversity (CBD) 2030 goals. In the past, the CBD has focused on conserving specific species in an effort to protect the world's biodiversity. Recently, according to Dr. Murray, there has been a new focus on instead conserving ecosystems as biodiversity hotspots. As one of the world's most biodiverse ecosystems, rivaled only by tropical rainforests, protecting coral reefs is at the forefront of protecting the world's biodiversity. And because ecosystems cover such vast geographical ranges, the effective monitoring of entire ecosystems necessitates the use of remote sensing data and ecosystem change alert systems. The continued increase in global, freely available, comprehensible, and accessible remote sensing data and visual data displays is crucial for the conservation of key ecosystems, including tropical coral reefs.

Conclusions and Recommendations for the Future of Coral Reef Monitoring

The need for environmental monitoring has increased for researchers and environmental managers as threats to ecosystems and ecological stresses have accumulated, particularly in the face of climate change. In combination with the existing traditional research methods, citizen science, artificial intelligence, and remote sensing provide an exciting and promising future for monitoring coral reef ecosystems. Citizen science provides highly accurate, regionally specific information about benthic cover, biodiversity, and ecosystem health across the Great Barrier Reef. Artificial intelligence augments and expands on the capacities of traditional research methods and citizen science by going beyond the geographic range and ocean depth that people can reasonably frequently visit and study, and increasing the efficiency of traditional research methods by using AI for data analysis. It also further improves the accuracy of citizen science by automatically identifying species and ecosystem types from images that citizen scientists provide. But citizen science and AI still remain limited spatially and temporally, especially across a region as large as the GBR. Employing remote sensing closes these gaps by providing high-resolution, weekly data on the status of the GBR. With a coral bleaching alert system in place, remote sensing could identify bleaching as it is happening and streamline the process of deploying scientists, autonomous vehicles, and other sensors such as heat sensors or cameras in areas of concern where bleaching is actively occurring and flag which sets of citizen science data (what region and what time period) are of the most utility to those who study and manage the reef. Recognizing the strengths and limitations of current monitoring methods, a hybrid system that combines all of the mentioned observation techniques must be developed to integrate these approaches. Taken together, these methods can provide accurate, regionally specific, timely data on coral bleaching - the greatest threat to the future of the GBR and coral reefs worldwide - across the entire 2,300 km stretch of the Great Barrier Reef. As bleaching becomes more frequent and more severe, this type of data is crucial to indicate to policymakers that the GBR is in grave danger due to climate change and that actions to mitigate this threat must be taken now.

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