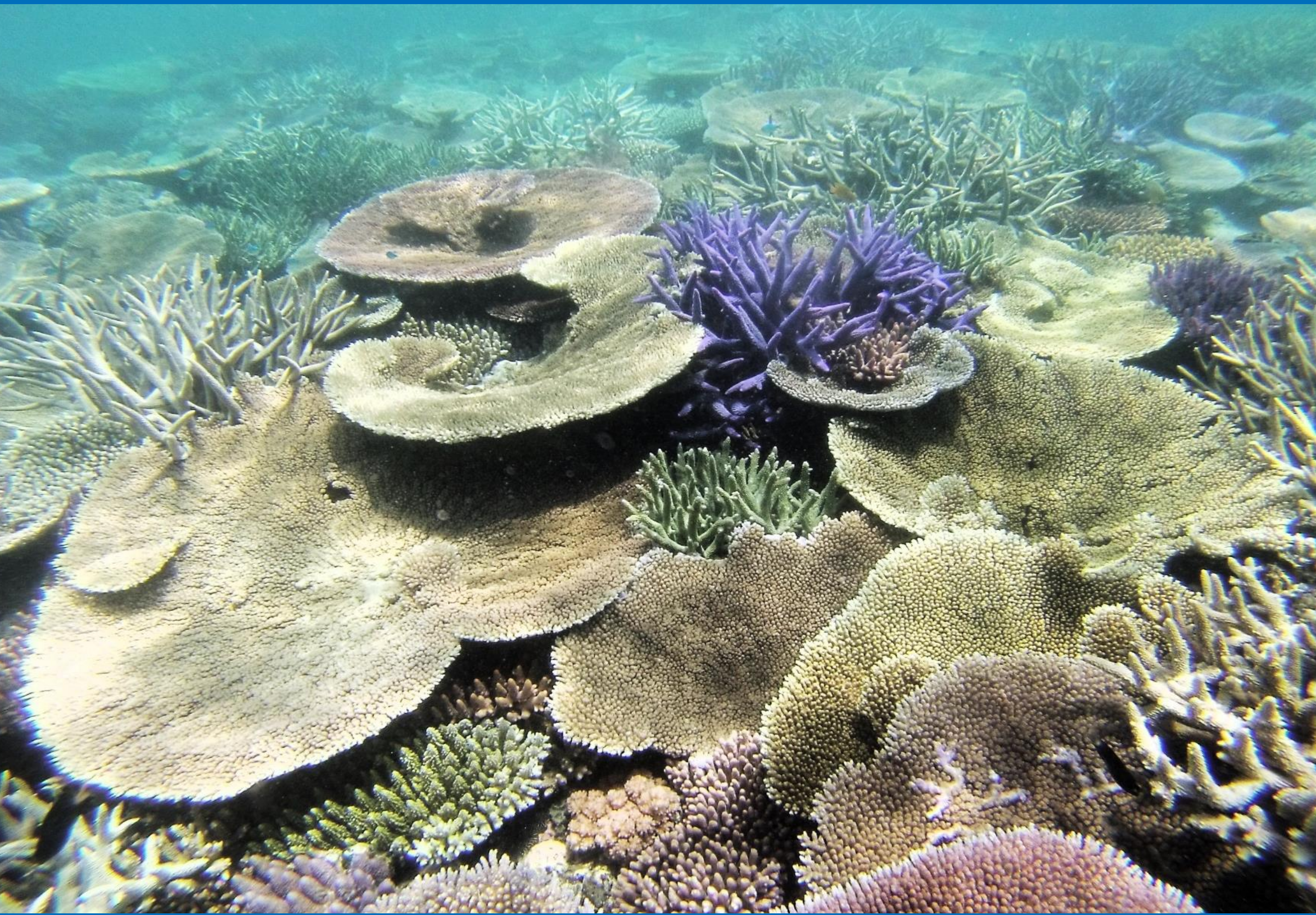
REEF ENCOUNTER

The news magazine of the International Coral Reef Society



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ICRS International Coral Reef Society

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Reef Encounter is the Magazine Style Newsletter of the International Coral Reef Society. It was first published in 1983. Following a short break in production it was re-launched in electronic (pdf) form. Contributions are welcome, especially from members.

INTERNATIONAL CORAL REEF SOCIETY

The International Coral Reef Society was founded (as the International Society for Reef Studies) in 1980, at a meeting in Cambridge, UK. Its mission is to promote the acquisition and dissemination of scientific knowledge to secure coral reefs for future generations.

CORAL REEFS - THE JOURNAL

The International Coral Reef Society also publishes through Springer its premier scientific journal entitled “CORAL REEFS”. The Journal publishes high quality scientific papers concerning the broad range of fields relevant to both modern and ancient reefs. For further details, including the list of editors see here.

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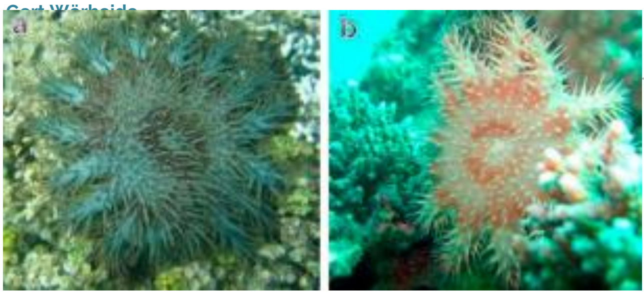
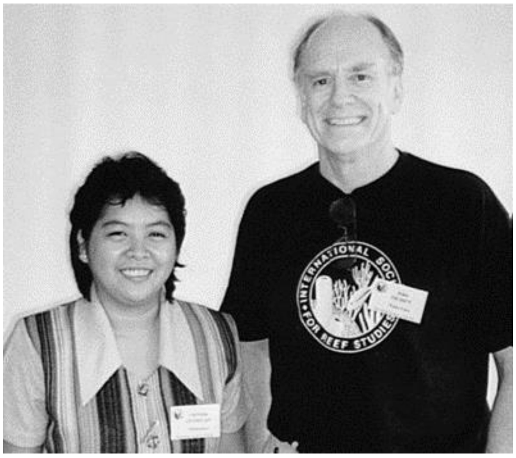


REEF DEPARTURES



ABOUT THE COVER | View of the fringing reef at Lizard Island, mid-shelf Great Barrier Reef, taken in November 2023. (Photo by Terry Done)

EDITORIAL & OFFICERS' REPORTS

PRESIDENT'S MESSAGE

Christian R Voolstra, ICRS President

Dear ICRS Members,

Time flies … it is a reminder that coral reefs are precious, and we need urgent action on (1) reducing carbon dioxide emissions, (2) improving local conditions, (3) implementing active restoration and developing the underlying science to do so efficiently and efficaciously.

The ICRS is the association to promote the acquisition and dissemination of scientific knowledge to secure coral reefs for future generations. We have witnessed tragic bleaching in the Caribbean this year and the bleaching outlook for the coming year is dire. Sometimes it feels hopeless, but looking back on this year I think change happens, although gradually, but things do change.

The ICRS has strengthened ties with ICRI, CORDAP, and the Coral Restoration Consortium to provide a unified and loud voice for the case of coral reefs, which becomes evident through our concerted actions at the COP28.

To strengthen and support our society, and by that the case of coral reefs, we have established a new mentorship & belonging committee to better train the next generation of coral reef scientists, we have set up a sustainability award to champion environmentally conscious meetings, and we have announced in his memory the John Ogden President's Award to support the representation of researchers from developing and low-income countries in society activities and conferences.

We as ICRS remain committed to secure a future for coral reefs and it requires all the voices we have and all the noise we can make, so that things do keep changing in the right direction!

I wish everyone and their families a happy holiday season and a new year of strength, peace, and joy!

Sincerely,

Christian R Voolstra, President, ICRS

EDITORIAL

Rupert Ormond, Editor, Reef Encounter

Dear ICRS Members,

Welcome to another “bumper edition” of Reef Encounter. For this I must again thank all those who have contributed items, from graduate fellowship awardees to senior scientists, as well of course as colleagues in the editorial team who have helped pull everything together.

As this edition documents, this year has seen the struggle to ensure the future of coral reefs intensify. Marine heatwaves have developed within all three ocean regions, with coral bleaching occurring especially in the Caribbean, where stony coral tissue loss disease (SCTLD) has also continued to ravage coral communities. The sorry state of Florida’s coral reefs was documented at the ReeFLorida meeting held this November in Miami; as described in the report by Les Kaufman, Bill Precht, Peter Auster & Peter Glynn (pages 10 & 11), the Florida reef system seems to have degraded into a remnant late-Holocene structure with scattered small hard coral colonies amounting to < 2% substrate cover. Nowhere, perhaps, has the impact of the summer’s mass coral bleaching been more evident than in Mexico, where, as described in Reef Edge articles by Andrés López-Pérez and colleagues (p. 64), and by Guillermo Horta-Puga and colleagues (p. 59), extensive bleaching has occurred on both Pacific Ocean and Caribbean (Gulf of Mexico) coasts. Yet the outlook for 2024 is likely worse, with the recent paper by Ove Hoegh-Guldberg and co-authors[1] concluding that given next year’s anticipated synchrony of rising sea surface temperatures with an El Nino-Southern Oscillation (ENSO) event, coral bleaching and mortality can be expected to be even more severe.

There have however been some exceptions to the overall picture of reef decline. Terry Done, to his evident surprise (as described in his report pp. 31-33), found reefs in the northern Great Barrier Reefs in apparently pristine condition (even if the dominance by fast growing *Acroporas* does look a touch suspicious), and Bill Precht and colleagues report on a haven of diverse healthy corals on Key West in, of all places, the harbor!

Nevertheless, climate change continues apace. October 2023 was the hottest month ever recorded, with mean global temperature >1.5ºC above the pre-industrial norm, and 2023 is now confirmed by the European Union's Copernicus Climate Change Service as the hottest year yet, with a global mean 1.46ºC above the pre-industrial norm[2]. In response ICRS again sent a team of delegates (led by Raquel Peixoto, winner of the inaugural 2023 Rachel Carson Prize for Applied Microbiology – congratulations!) to the UN Climate Change Conference of the Parties (CoP28) in Dubai (UAE), to lobby on behalf of coral reefs (see their report on page 12 & 13). While at the Paris CoP in 2015 the Society was able to play a key role in promoting the 1.5ºC target for maximum temperate rise, influencing decision-makers has become increasingly tenuous, with the total numbers of delegates swelling to >97,000, of whom increasing numbers are fossil fuel representatives apparently lobbying against a full prohibition on the use of fossil fuels anytime soon[3]. It is distressing to hear such publicists referring to the environment as if it was only a minority interest, as if their own health and survival did not actually depend on the safe functioning of spaceship earth! This is a misconception that we must all take every opportunity to correct, with the neighbors, on the high street, in the classroom, and on the beaches, as well as with family and friends.

Rupert Ormond, Editor, Reef Encounter

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[1] O. Hoegh-Guldberg et al., Science 10.1126/science.adk4532 (2023).

[2] https://www.bbc.co.uk/news/science-environment-67607289

[3] https://climate.copernicus.eu/

SOCIETY ANNOUNCEMENTS

Society Grants and Awards

Please submit nominations and applications for the following awards and fellowships offered by the Society to recognize the scientific, leadership, educational, practitioner, and policy achievements of its members.

All nominations and applications must be submitted by 15 February 2024

Please see details of how to nominate or apply on the Society's Website at:

https://coralreefs.org/awards-and-honors/nominations/

Eminence in Research Award: In recognition of a scientist for an outstanding body of research performed over an extended period of time (up to two per year)

Mid-Career Scientist Award: In recognition of excellence in research by a mid-career scientist (ten to twenty years post-PhD) performed over the preceding ~10 years (one per year)

Early-Career Scientist Award: In recognition of excellence in research by an early career scientist no more than 10 years post-PhD (one per year)

ICRS Fellow: In recognition of scientific, conservation, or management achievement, as well as service to ICRS, over a significant period of time.

World Reef Award: In recognition of scientific or conservation achievement by an individual who is a member of an under-represented group of members in the field of reef science or management (one per year)

Coral Reef Conservation Award: In recognition of a regionally or globally significant contribution to the protection of coral reefs (typically one per year)

Ruth Gates Fellowship: In memory of Dr. Ruth Gates, this research grant is available to students and early-career scientist (no more than three years post-PhD; one per year)

Graduate Fellowships: a grant awarded to registered graduate research students to assist in the costs of undertaking fieldwork or visiting laboratories (typically six per year, half to students from developing countries)

Science Communication Fellowship: a grant awarded to an ICRS member at any career stage in any type of position (e.g. academic, NGO, government, private sector, other) to gain science communication skills through a workshop, course, internship, or equivalent experience.

New Award

THE JOHN OGDEN PRESIDENT'S AWARD

Dear ICRS members,

We are very pleased to announce a new award – **The John Ogden President's Award.**

This award was established in honor and memory of Dr John Ogden, who served as ICRS president from 1994-1998. John was a wonderful colleague, advisor, mentor, friend, and inspiration to many coral reef scientists around the world. His work included research in behavioral ecology and the role of herbivores in reef and seagrass communities, as well as protection and conservation of tropical ecosystems. John passed away in 2023. To honor his legacy of inclusivity and collaboration, we are offering two types of awards to be dedicated to support scientists, reef managers, and policy makers from developing countries who are involved in coral reef research and conservation.

The first award is the **Membership Award.** Successful recipients will receive a one-year membership (renewable) in ICRS. This award is currently open until February 2024. In addition, if you are also considering applying for another ICRS award that requires membership (AND you fulfill the requirements for the Membership Award), these awards can be applied for at the same time.

The second award is **The Meeting Attendance Award.** Successful recipients will be provided with funds needed to attend the 2026 ICRS in New Zealand. This award will open in November 2024 and close in February 2025.

ICRS Awards Committee

FOR MORE DETAILS PLEASE SEE: https://coralreefs.org./john-ogden-presidents-awards

SOCIETY ANNOUNCEMENTS

The **European Coral Reef Symposium**

Naples, Italy - 2nd-5th July 2024

A reminder that the next ICRS conference, the European Coral Reef Symposium (ECRS 2024), to be held in the dramatic and unmissable city of Naples, is fast approaching - in particular the deadline for abstract submission.

To make sure that everyone has enough time to prepare, t**he Conference Chairs and Organizing Secretariat have extended the deadline for submitting abstracts for presentation at the conference**.

The new deadline for abstract submission: January 31st (2024)

ECRS 2024 NAPOLI 2-5 JULY

https://ecrs2024.eu/

Thirteen sessions and topic areas are planned, with topic 13 intended as a home for contributions that do not easily fit into any of the previous 12:

1. Lessons from the Past to Inform the Future
2. Coral Reef Structure and Functioning
3. Biology and Ecology of Holobionts in Coral Reefs
4. Global Climate Change and Environmental Stressors
5. Coral Reef Anthropic Pressures, Conservation and Restoration
6. Community-Based Monitoring and Ecosystem-Based Management
7. Shallow Temperate Reefs
8. Mesophotic and Cold-Water Coral Ecosystems
9. Technological and Methodological Innovation in Underwater Surveys and Data Analysis
10. Coral Reefs Under a Socio-Economic Perspective
11. Beyond Corals and Fishes – Evolution and Biodiversity of Neglected Reef Taxa
12. The Ocean Decade: The Science We Need for the Coral Reefs We Want
13. Insights into Further Fields of Coral Reef Research from Around the World

Other key dates are:

Early bird registration – NOW OPEN

March 5th, 2024 (23.59 CET) – Authors' registration deadline

March 20th, 2024 (23.59 CET) – Early bird registration closes

March 21st, 2024 – Regular registration opens

June 25th, 2024 (23.59 CET) – Regular registration closes

July 1st-5th, 2024 – Onsite registration

For detailed information, including of the highlights (opposite page) visit the ECRS 2024 website at https://ecrs2024.eu/

Conference Icebreaker

Meeting point: Stazione Zoologica Anton Dohrn

Tuesday, July 02nd 2024, 06.00 pm

Conference Dinner

Meeting point: Chiostro di Santa Chiara

Thursday, July 04th 2024, 08.00 pm

WORKSHOP AND CONFERENCE REPORTS

Breathing New Life into Florida's Coral Reef

The Frost Science Museum organized and hosted the inaugural ReeFLorida Symposium from 6-9 November 2023 in Miami, Florida. The symposium was the first-annual gathering of practitioners of science, conservation, and education who focus specifically on Florida's coral reef complex. The meeting was informative, provocative, and timely, coming at the tail end of a challenging summer of extreme ocean warming. There were three days of talks on the continuing decline of the reef, its current status, coral culture, reef restoration, and some glimmers of hope for the future. There was a total of 159 meeting registrants, with 43 being students. In total, there were some 49 oral presentations, not including three impactful plenary talks that kicked off each day, as well as an evening keynote lecture that was open to the general public (Fig. 1). There were also 16 posters presented, and six workshops. Needless to say, the meeting was full of timely information with lively scientific discussions and debate surrounding the venue.

Figure 1. Dr. Les Kaufman giving the ReeFLorida evening plenary and public lecture on why we should still have hope for the future of coral reefs on 8 November 2023 at the Frost Museum Planetarium.

Florida's coral reef is experiencing increasing severity and frequency of stressors: thermally induced coral bleaching, coral diseases, poor water quality, and other cumulative human population pressures. The system exhibited high hard coral cover, fish biomass and good esthetic value as recently as the late 1970s. Today, it has degraded to a remnant late-Holocene structure with scattered small hard coral colonies comprising less than 2% of the reef surface area. The most recent heatwave and concomitant bleaching event of 2023 along with the continuing effects of stony coral tissue loss disease (SCTLD) have had a devastating impact on the entire ecosystem. Belated recognition of the fragility of the system spurred heroic efforts in July and August to move entire coral nurseries into deeper, cooler water as well as to land-based facilities to serve as an ark of species and genetic diversity. Multiple presentations were focused on current restoration efforts as well as insights into new approaches and processes that could serve both to address the current crisis, as well as provide signposts for the new paths ahead.

Discussions in sessions and in sidebars in the hallways acknowledged that restoration of corals to reefs is necessary, but not sufficient, to restore coral reef ecosystems. Resources are needed to sustain as well as move beyond total reliance on the few fast-growing species that are the current focus of restoration efforts, acknowledging their diverse genomes and all the complexities of husbandry, out-planting, and maintenance. We need to set our sights on restoring coral reef ecosystems using foundational species to ensure these sites serve as magnets for biodiversity, and cradles for the complex and myriad species-interactions that make these behave as self-sustaining ecosystems in our new and future ocean. This will require looking beyond the reef to the Everglades-Kissimmee system to ensure that the reef system benefits from the regulatory services of clean water and removal of stressors on corals and their associated taxa. We also need to look beyond the invertebrate taxa of the reef, and address species interactions with fishes and links to fisheries management, in order to safeguard the functional role of both predators and herbivores in ecosystem health.   These goals cannot be performed in a vacuum, and they cannot be accomplished in just a few short years. Our priorities need to be focused on the long view. Now, more than ever, we need to join forces to address these common goals.

What does that long view look like? The reality is that it could take centuries to rein in and reverse anthropogenic climate change. Shallow water, tropical coral reefs today exist within a narrow thermal range; this range can be extended by selecting for those coral genets best suited to the future ocean that is coming. Ideally, this strategy would be a practical element of the larger strategy to bridge the “climate change hiatus”, the time between now and a Floridian environment once again hospitable to coral growth and reef accretion. Given the increasing frequency and intensity of some climate-driven anomalies, we could be at this for a very long time. Like certain cancers that are most treatable when they are aggressive, the experience of shepherding out-planted corals through times of climate insult may provide effective learning opportunities. While the situation remains something better than hopeless, there is a critical period during which we might be able to learn how to carry coral reefs and their dependent denizens through our home-grown adversity. In this respect, recent advances in our understanding of coral spawning and settlement, common garden experiments, and even genetic manipulation are fueling dedication and commitment to coral reef conservation by a robust generation of bright, young scientists, many of whom spoke at this meeting. Several others are working in marginal reef environments for coral growth as in Florida, leading to exciting new discoveries that are challenging some of our long-held beliefs regarding reef function and development.

A major theme of the meeting was the great need for outreach beyond the converted, to fully engage the public. The ecological and socio-economic contributions of coral reefs to society need to be integrated into formal and informal education for both children and adults. We must fully engage the stakeholder community in finding solutions and making progress. *And in Florida, as elsewhere, we are!* Much of the work force, with hands in the water, is composed of volunteers, students and interns. We had the sense that the attendants at this meeting “got” all of this. Public taxes and private funds are being spent, and people need to know and get excited about how, and to what end, we are doing this.

The atmosphere at the meeting was one of sober reflection on the catastrophic heatwave that killed corals in record numbers throughout the region earlier this year. There was also a great enthusiasm and energy for the adventure of trying to solve this problem - of keeping coral reefs and the ecosystem services they deliver alive in Florida in some form for now.   The meeting supported the notion that active coral restoration was an essential step in coral reef recovery and survival through the Climate Hiatus. As recommended by Aldo Leopold, our job is to “save all the pieces”. Save all the pieces, but not in a drawer or a cabinet; in nature, actively evolving and adapting. The coral reef habitats that result may for a while look strange and unfamiliar to us, but alive.

Mission: Iconic Reefs, the effort to maintain at least some of Florida’s Coral Reef in a productive form, is a gigantic experiment in adaptive management, laid out in a careful design, its data harvested with technologies both new and old. The challenge, the adventure of it, the knowledge that will result are valuable even if the way forward is at times a bit dark, uncertain, and even dubious.

Les Kaufman, Boston University, Boston, MA 02215
William F. Precht, Dial Cordy and Associates Inc., Miami, FL 33014
Peter Auster, Mystic Aquarium & University of Connecticut, Groton, CT 06340
Peter W. Glynn, Rosenstiel School of Marine, Atmospheric and Earth Sciences, Miami, FL 33149

Dubai Diary – COP28

The International Coral Reef Society (ICRS) delegation worked hard to make waves at the 28th Conference of the Parties (COP28) in Dubai (Nov. 30 - Dec. 13), bringing critical attention to the plight of coral reefs worldwide! The delegation, consisting of Raquel Peixoto, Mariana Rocha de Souza, Anderson Mayfield and Tali Vardi, focused on advocating for ocean conservation and emphasizing above all the importance of decreasing fossil fuel emissions and not exceeding the target 1.5ºC minimum temperature increase above pre-industrial levels. Through presentations, panel discussions, and collaborative efforts with policymakers, we highlighted the urgency of reducing the threats already degrading coral reef ecosystems.

ICRS delegates to COP28, Raquel Peixoto, Tali Vardi and Anderson Mayfield, together with Amy Appril (far left), at the Ocean Pavilion, after the event "Solutions Toolbox to Save Coral Reefs"

The delegation also strengthened their collaboration with RINGO, the association (or constituency) which under the UNFCCC represents Researchers and Independent Non-Governmental Organizations. Through RINGO members we were able to get extra badges to attend particular events, including attendance at a high-level meeting of the RINGO ocean thematic group with Dr. Richard Spinrad, the head of NOAA (the US National and Atmospheric Administration). The delegation's activities included the following:

December 1st. Raquel, Anderson, and Tali were part of a panel held at the Ocean Pavilion. Joined by Amy Appril of Reef Solutions Initiative (Woods Hole Oceanographic Institution) and Meizani Irmadhian from Konservasi Indonesia, they presented a comprehensive toolbox of scientific, financial, political, and community-based solutions designed to save coral reefs. Discussions revolved around the urgent need for climate neutrality, strategies to mitigate reef damage, and the imperative for global coordination in tackling this critical challenge.

December 2nd. In anticipation of the Health day at COP, Raquel contributed to the discussions on "Safeguarding our planet, biodiversity, climate, and One Health" at the Saudi Pavilion. The panel delved deep into the intersections of biodiversity conservation, climate change mitigation, and the One Health concept. The panelists included Princess Mashael Al Shalan, H.R.H. Prince Sultan bin Fahad bin Salman Al Saud, and Princess Hala bint Khaled bin Sultan Al Saud. In addition, Tali and Raquel played leading roles at the Coral Restoration Consortium Story Telling Hub, in the Commonwealth pavilion. The event included several videos documenting past reef restoration efforts, followed by a panel discussion on restoration work at different scales.

December 6th. Focus on Sustainability and Action. Raquel participated in a panel discussion in the Innovation Zone, exploring the vital issue of translating research into tangible impact, and presented her research on coral reef probiotics. The other panelists were Yousef S. Al Hafedh (Saudi Arabia Ministry of Environment, Water and Agriculture), Kate Gibson (Global Director of Society, Diageo), Martin Popilka (CEO of P1 Funds), Raquel On the same day, she joined the Science for Climate Action Pavilion, discussing the pivotal shift from pledges to actionable initiatives for coral preservation, alongside figures such as H.E. Peter Thomson (UN special secretary-general for the Ocean) and H.R.H. Princess Hala (president of the Living Oceans Foundation) .

Raquel Peixoto speaking at the Panel event: Unleashing Essential Commercialization: Converting Sustainability Research into Impact.

Meanwhile Mariana spearheaded a panel discussion at the JUST NORTH & Beyond, a Popup University Pavilion, that also included Shikha Bhasin (RINGO Steering Committee), Bradley R. Colman (President of the American Meteorological Society), Ana Spaldin (Smithsonian Institute), Andriannah Mbandi (South Eastern Kenya University), and Raina Tailingfong (Pacific Island Refugees). The panel delved into the crucial role of scientists in shaping climate policies, particularly focusing on strategies for supporting early career researchers in work towards a just and sustainable future.

December 8th: Anderson attended a virtual event hosted by the Virtual Ocean Pavilion in which he spoke on the importance of science in the "Coral Reef Breakthrough", recently announced by the International Coral Reef Initiative (ICRI). He stressed the significance of the considerable body of knowledge of coral reefs already acquired by the collective membership of ICRS, and pushed for the inclusion of sound scientific practices in coral reef conservation and restoration initiatives (both large and small).

December 9th: Ocean Day. Mariana and Tali participated in a panel discussion dedicated to the conservation of coral reefs in the Red Sea. The session, held at the Green Pavilion, included Sam Teicher, CEO of Coral Vita, as moderator, and other panelists including Ove Hoegh-Guldberg (University of Queensland) and Nicole Trudeau (CORDAP). The discussions revolved around the unique resilience of Red Sea corals to temperature variation, scientific innovations, restoration opportunities, and the critical need to minimize local as well as global stressors to ensure the effective preservation of the region's corals.

On the same day, at the JUST NORTH & Beyond Pavilion, Mariana gave a presentation summarizing potential major ocean-related actions relevant to COP28, and Anderson joined a panel of global mangrove conservation experts at the UK Pavilion to discuss the challenges that coral reef and mangrove ecosystems face in common. The session highlighted the link between mangroves and coral reefs, with the former often serving as nursery areas for organisms that spend their adult lives on the reef, and emphasized the need for more integrative, multi-ecosystem solutions.

Now the COP has concluded we need to consider how effective our efforts have been, and how best, going forward, to maintain a high profile for coral reefs in the face of their rapid global decline. We anticipate a further report on our experience!

Mariana Rocha de Souza
Hawaii Institute of Marine Biology
mrds@hawaii.edu
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Mariana Rocha de Souza speaking at the Panel "Coral Conservation in the Red Sea" in the Green Pavilion.

REEF PERSPECTIVES

CAN REEF FUTURES BE IMPROVED BY CRIMINALIZING ECOCIDE?

Earth's biodiversity, including coral reefs, is under increasing pressure, with continuing loss or modification of habitat and elevated rates of species extinction (Pimm et al. 1995, Turvey and Crees 2019, Ceballos and Ehrlich 2023). If a significant part of nature, be it a species, habitat or ecosystem, is lost or destroyed through wanton or unlawful human actions, **should perpetrator(s) face serious criminal charges under international law?** This question lies at the heart of a recent global legal initiative, **the criminalization of ecocide** (Stop Ecocide International 2023a). In this follow-on essay (see the first part in the **Reef Perspectives** section of the June edition) I briefly explore its history, rationale and process, outline complementary legal initiatives, and the potential application in improving reef futures.

Lyndon DeVantier

Coral Reef Research, PO Box 129, Millaa Millaa, QLD, Australia
Present address: Hangatahua River Orchard, Okato, 4335, Aotearoa New Zealand
(Ldevantier@aol.com)

Indigenous leader Valdelice Veron, of the Guarani-Kaiowá nation, and world-renowned scholar and environmental activist Vandana Shiva (photo Stop Ecocide International)

The term 'ecocide' was coined, apparently, by Arthur Galston, a plant physiologist whose work on plant hormones was adapted and co-opted for military use as Agent Orange, sprayed across large tracts of Vietnam with devastating multi-generational consequences to biodiversity and people (Zierler 2011, Chou 2023, Scriven 2023). In 1972 Olof Palme acknowledged ecocide in his address at the United Nations (UN) Conference on the Human Environment. In the coral reef community, Roger Bradbury and Ann Cameron, along with 35 postgrads from the Zoology Department of the University of Queensland (UQ), were early advocates. In an open letter written more than 50 years ago, 'A Statement of Disenchantment to the Australian Marine Sciences Association (AMSA) Symposium on Pollution in the Marine Environment', Bock et al. (1970) stated:

"Public concern for the environment may be new; the ecocide that gave rise to it is not. The marine environment has been deteriorating for a long time and marine scientists were in a position years ago to inform the public that the crisis was approaching. … Biology can and must provide a basis for an objective assessment of man as a species, but unless we seek for an immediate re-examination of the basic philosophies around which the institutions we foster and represent are built then we will have failed in our duty as scientists and we will have hastened the collapse of the biosphere."

Bock et al. (1970) also noted that the 1970 AMSA Symposium was sponsored by the offshore oil industry, an early example of the widespread corporate strategy of 'buying social licence'. This continues. Indeed, many research institutes, big environmental NGOs, and researchers, including myself, have benefitted from such funding, perhaps rationalizing that the end – conservation actions or research results – justifies the means. However, such pragmatism, sometimes called 'new conservation', can hold contradictions with unintended consequences (Spash 2022, and see Ando et al. 2022, Boyd et al. 2023 for alternative views).

Not just an 'echo chamber'

In the more than five decades since that prescient open letter from UQ postgrads, coral reefs, and natural ecosystems more generally, have continued to decline. Causes vary across scales – local, regional, global – all well documented as our science has expanded and been widely disseminated. Our outreach can be surprising, as the recent inclusion of reef research in a chapter on '*Climate-Induced Migration in the WIO Countries and Its Regional Implication'* (Bhattacharya 2023) illustrates. Bradbury and many others have succeeded in informing decision-makers and society more generally. Indeed, quick internet searches (14th November 2023) on coral reef decline and degradation listed more than 9,550,000 and 7,930,000 results, while reef death yielded an even more astounding 50,400,000 results. Coral reefs are a 'poster child' for climate and ocean disruption, featuring prominently in IPCC reports and mass media. Members of our Society continue to play key roles, documenting ecological status, providing timely warnings and countering disinformation spread by bad actors. None of this is novel.

Giants' shoulders and the lessons of history

Among the earliest of our forebears, Peter Forsskål (Figure 1) worked with colleagues along the Red Sea in 1761. Forsskål made a major taxonomic contribution, albeit posthumously, thanks to Carsten Niebuhr, describing some 26 species of reef corals (Antonius et al. 1990) and 153 species of reef fishes (Fricke 2008). Many of these are considered valid today, including *Lobophyllia (Madrepora) corymbosa* and *Chaetodon auriga*. In addition, Forsskål (1759) wrote a treatise on civil liberty. While reflecting religious views of the times, it still holds relevance with respect to governance, fact versus fiction, and freedom of expression:

"To this liberty, the greatest danger is always posed by those who are the most powerful in the country by dint of their positions, estate, or wealth. Not only do they easily abuse the power they hold, but also constantly increase their rights and strength."

Some 25 years after Forsskål, Scottish economist philosopher Adam Smith (Figure 1), pioneer of the political economy (1776), was also highly sceptical of the motivations, power and political connections of some in the business class, 'mercantilists' in his day:

"The proposal of any new law or regulation of commerce which comes from this order, ought always to be listened to with great precaution, and ought never to be adopted till after having been long and carefully examined, not only with the most scrupulous, but the most suspicious attention. It comes from an order of men, whose interest is never exactly the same with that of the public, who have generally an interest to deceive and even oppress the public, and who accordingly have,

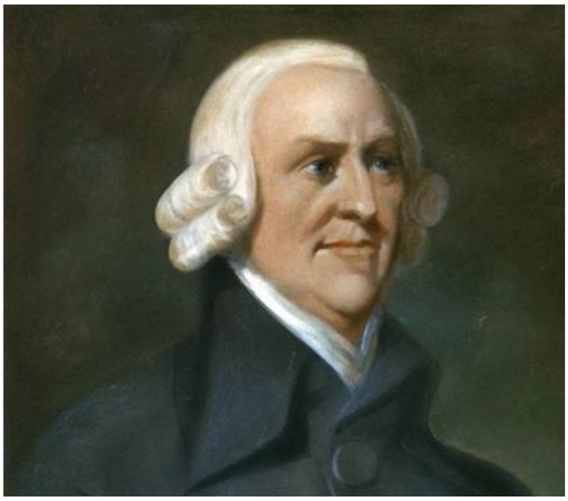


Figure 1. Left. Peter Forsskål (1732-1763). Right. Adam Smith (1723–1790). Photo courtesy of J.H. Romanes 1945, both photos cropped, Wikimedia Commons

upon many occasions, both deceived and oppressed it."

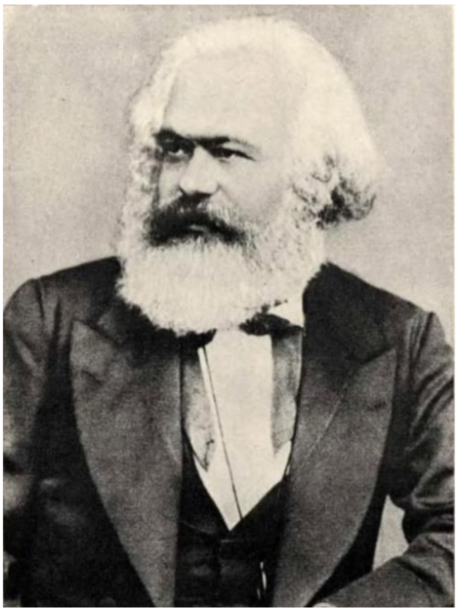
Almost a century later, Karl Marx (1857, Figure 2) stated: *"For the first time, nature becomes purely an object for humankind, purely a matter of utility; ceases to be recognized as a power for itself; and the theoretical discovery of its autonomous laws appears merely as a ruse to subjugate it under human needs, whether as an object of consumption or as a means of production."*

Another, more recent warning, albeit more than 60 years ago, from a very different part of the political spectrum, was given by United States President Dwight Eisenhower (1961, Figure 2), in his farewell address:

"As we peer into society's future, we – you and I, and our government – must avoid the impulse to live only for today, plundering for our own ease and convenience the precious resources of tomorrow. We cannot mortgage the material assets of our grandchildren without risking the loss also of their political and spiritual heritage."

Despite these and many other warnings regarding the limits to growth and socio-ecological impacts (Meadows et al. 1972, Brundtland 1987), our civilization's rapid technological advances continue to be built on increasingly unsustainable consumption of natural resources, with resultant pollution. The consequences are our rapidly increasing exceedance of earth system boundaries, the 'safe and just operating space' for humanity (Rockström et al. 2023, Richardson et al. 2023). Despite well-reasoned pleas to the contrary (e.g., Daly and Farley 2004), mainstream economics has never properly considered these crucial aspects, nor properly accounted for the ecological costs of resource extraction, depletion and pollution, the last usually considered an 'externality' (Helbling 2023). Such accounting is critically needed, along

Figure 2. Left. Karl Marx (1818-1883). Right. Dwight D. Eisenhower, White House (1890-1969). Photos from Wikimedia Commons. Despite their wise words cited above, both men's legacies hold contradictions, beyond the scope of this perspective.



with other key aspects of transition economics (e.g., Tradable Energy Quotas, Fleming and Chamberlin 2016).

Absent these initiatives, our present economic system has continued to create enormous wealth for some, as Forsskål (1759) foretold. There is also, as Smith (1776) warned, abundant evidence of deep-seated malfeasance, of 'predatory delay'– the deliberate prolongation of unsustainable but financially profitable practices, the impacts and costs of which are borne and paid for by others. Tim O'Reilly (see Steffan 2016) makes the case:

"… 'Policy should protect the future from the past, not the past from the future.' Yet in every country on Earth, policies made at the top are still overwhelmingly designed not to meet our planetary crisis at the scale and speed it demands, but to protect the institutions, companies and systems causing that crisis from disruptive change."

Political and corporate realities and unrealities

In political and corporate spheres, some are intent on continuing with business as usual, regardless of the consequences. Indeed, environmental defenders are killed weekly for having the courage to stand in defense of nature (Global Witness 2021, 2023). As climate disruption intensifies, violence against those working to halt environmental destruction is also increasing. This does not imply that all politicians and corporate leaders are villains, but some in positions of power and influence continue to act in highly irresponsible, self-serving manners, via weak integrity laws and the enabling 'revolving door' between politics, lobbying and industry (Wilkinson 2020). Journalist George Monbiot (2023) explained it thus:

"People seem mystified by this apparent perversity. But it's a clear manifestation of the pollution paradox, … essential to understanding modern politics. The most damaging companies have the greatest incentive to invest money in politics (by making donations to political parties, funding lobbyists and junktanks, hiring troll farms and microtargeters and all the other overt or covert techniques). So, politics, in our money-driven system, comes to be dominated by the most damaging companies."

The fossil fuel industry, with many ties to political parties and leaders globally, provides an archetypal case in point, highly relevant to the future of coral reefs. Major spills pollute habitats (International Coral Reef Initiative 2023), while emissions drive heat waves and storms, acidification and deoxygenation, and sea level rise. Collectively, these portend increasing marginality (Guinotte et al. 2003, Hoegh-Guldberg et al. 2007, Couce et al. 2013), leading to irreversible loss in the future habitability of marine ecosystems (Santana-Falcón et al. 2023). Petrochemical derived plastics and other novel entities also increasingly impact biodiversity (Richardson et al. 2023, Ouédraogo et al. 2023). As worthwhile as they are, all of our efforts to address other impacts may be wasted if we continue in failing to address this overarching issue.

Box 1. Perverse subsidies, regulatory capture and shareholder greed

Oil 'megadeals', a global game of monopoly, continue apace (Sheppard 2023). These are financially supported by major international banks, with more than US$150 billion in 2022 (Niranjan 2023) for companies operating or developing 'carbon bomb' projects (Kühne et al. 2022). Globally, perverse subsidies (Myers and Kent 2001) for fossil fuels were calculated at US$5.9 trillion in 2020, increasing to US$7 trillion in 2022 (International Monetary Fund 2023). These are expected to continue to increase. United Nations Secretary-General António Guterres (2023) recently implored: "… stop subsidizing fossil fuels … Our ocean is choked by pollution, plastics and chemicals. And vampiric overconsumption is draining the lifeblood of our planet … No more greenwashing. No more bottomless greed of the fossil fuel industry and its enablers. … I have a special message for fossil fuel producers and their enablers scrambling to expand production and raking in monster profits: If you cannot set a credible course for net-zero, with 2025 and 2030 targets covering all your operations, you should not be in business. Your core product is our core problem."

At the same time, investment in renewable sources, mostly wind, solar and hydro, is increasing rapidly, with a recent analysis suggesting these ultimately can provide humanity with sufficient energy (Jacobson 2023), particularly in a 'post-growth' world (Hickel et al. 2022). This is not to discount the inescapable EROI math, notably the significant resources and energy required for the transition, nor that vexed issue of consumption and the continuing mainstream politico-economic obsession (Frey 1978) with constant, endless growth. As James Hansen et al. (2022) concluded: "There is no indication that incumbent governments are even considering the fundamental actions that are needed to slow and reverse climate change. Instead, they set goals for their future emissions and hope that the collective outcome will be good. When data suggest otherwise, they revise hopes for future emissions downward, all the while knowing – if they have any common sense and technical understanding – that their claims for the expected future emissions are (to put it plainly) hogwash because they have not taken the fundamental actions required to achieve those goals."

The industry holds significant political influence – 'state- and regulatory capture' – drafting or successfully lobbying to amend the very legislation under which it operates. Regularly one of the largest contingents at the annual UN Conferences of Parties (COP) on climate (Michaelson 2022), it is no surprise that governments with state-owned fossil fuel companies include their representatives in IPCC delegations. COP28, held in the United Arab Emirates, has the CEO of Abu Dhabi National Oil Company (ADNOC) as its president-designate. ADNOC recently announced plans to invest $150 billion in oil and gas expansion over five years (Carrington 2023). At the same time, the finance gap for climate change adaptation continues to widen, estimated recently at between US$194 billion and US$366 billion per year, an increase of at least 50% on previous estimates (United Nations Environment Programme 2023a). Impacts on human health have also been downplayed (Haswell et al. 2023). A recent damages estimate tallied extreme events attributable to climate change at US$143 billion per year, the majority (63%) due to human loss of life (Newman and Noy 2023).

Adding 'fuel to the fire', literally, increasing majorities of shareholders are opposed to their companies' meeting emissions targets. Resolutions seeking alignment with the Paris Agreement received less support in 2022 than in 2021 (Halper and Gregg 2023). This highlights a sharp dichotomy dividing those living and working in the 'reality-based community', where solutions emerge from judicious, scientific study of discernible reality (Türk 2023), built on enlightenment principles, from those either unconcerned with, or able to manipulate, perceived reality to suit their desires and preconceptions. Among the latter, obviously, are those focused on gaining wealth unsustainably from extraction of natural resources, be it via fossil fuels, fisheries, forests, industrial agriculture or minerals from rainforests, deserts or deep seas, with little concern for the ecological consequences (Merleaux et al. 2023). Our age of 'extractivism' continues apace. Mining the Moon, Mars, or perhaps an asteroid, is the latest goal of venture capitalists (Space Ventures Investors 2023). It's a simple matter of supply and demand, that is the mantra, cycling back to that vexed consumption issue, as our population continues to grow (Callegari and Stoknes 2023).

Having underpinned the industrial revolution, the fossil fuel industry has enabled development of our global civilization. It has provided unprecedented standards of living for our burgeoning population, particularly middle- and upper-classes, in the process generating most greenhouse gas emissions (Heede 2014, Climate Accountability Institute 2020). Since the 1980s, the industry and its very well-funded lobby have also increasingly undermined climate science and political action, via that self-serving campaign of predatory delay. Despite clear documentation and predictions from its own proprietary research, the industry funded a well-orchestrated campaign of denial, disputing the evidence, downplaying the urgency, and manipulating political processes. Among the wealthiest corporations ever to exist, the companies knew full well of their outsized role in climate disruption since at least the 1980s (Banerjee et al. 2015), probably decades earlier (Revelle et al. 1965); but in their public and political engagement, conspired to deceive (Oreskes and Conway 2010, Supran et al. 2022). Following early obstructionism, fossil fuel producing and exporting nations have repeatedly 'watered down' references to their product as the main cause of climate and ocean disruption (Rich 2019, Pickering 2022, Earth Negotiations Bulletin 2023), aided in their deception by gullible and/or unscrupulous media. Had the fossil fuel industry acted responsibly – they had the finances to do so – humanity could have avoided the past four, and counting, 'lost decades'. Certainly, as individuals, we all contribute to a greater or lesser degree (Bruckner et al. 2022, Chancel 2022), but most of us haven't deliberately set out to deceive. In providing context for criminalizing ecocide, parts of the following may appear polemical, or to 'cut to the chase', see from 'Legal Options: Turning the Tide' section below.

As someone who has argued repeatedly at government hearings against future exploration and mining permits for fossil fuels, I can attest that the industry, whether state-owned or corporate, has no intention of stopping voluntarily (also see Stockholm Environment Institute et al. 2023, and see Box 1). Having made record profits in 2022 (Newsom 2023, Halper 2023), business, and greenhouse gas emissions, are booming (International Energy Agency 2022), capitalizing massively, if unsustainably, on the worsening relation between fossil fuel energy return on energy invested (EROI, Hall et al. 2008). Forecasts indicate that up to US$570 billion will be spent annually in new oil and gas development and exploration to 2030 (International Institute for Sustainable Development 2022, Bousso and Adomaitis 2023). Companies' advertised transition

Figure 3. Left: Floating plastic garbage patch embedded with seagrass and algae, Fiji. Right:. Discarded fishing net entangling soft and stony corals, Bali, Indonesia.

plans are often 'greenwash' (Center for Countering Digital Hate 2022, Tollefson 2022), part of the predatory delay campaign.

Plastics and other 'novel entities'

Petrochemically derived plastics, fertilizers, pesticides and other novel entities (Richardson et al. 2023) are increasingly polluting oceans (Eriksen et al. 2023, Zhang et al. 2023). Plastic production is predicted to triple by 2060 (Kwon 2023), mostly created by major fossil fuel producers (Charles and Kimman 2023). Many reef tracts are increasingly fouled by plastics (Figure 3) and other petrochemicals (Menezes et al. 2023, Richmond and Buesseler 2023). A 2011 reef assessment around Bali, Indonesia, recorded plastics on all 32 reefs surveyed (Turak and DeVantier 2012), reflecting the situation on many reefs across the Coral Triangle, as elsewhere. Seabirds, turtles and other marine life are also increasingly impacted (Charlton-Howard et al. 2023). As with mining, major plastics manufacturers have no intention of 'turning off the tap' (Wei et al. 2020, Bergmann et al. 2023).

Ecological reality and multilateralism: Treaties, targets and (own) goals

Roger Bradbury (1971) had some early, sage advice: *"Individuals and communities must begin to accept the ecological realities of this earth. We must accept, as real, the limitations of our environment and reject economic systems which say otherwise; we must accept, as necessary and vital, the complexity of our ecosystem and reject attempts to simplify it; and we must accept, as essential, the regulation of all organisms within the carrying capacity of this ecosystem and reject, as unecological, those philosophies that advocate continuous, mindless, growth."* Like so many others, Bradbury's warning fell largely on deaf ears in political spheres. So how do those of us who care for the natural world, those good 'doctors', to again borrow from Aldo Leopold (1949), deal with this? With a few widely quoted exceptions, including the 1987 Montreal Protocol (United Nations Environment Programme 2023b, but also see Solomon et al. 2023, Western et al. 2023, Tollefson 2023a), global conventions and treaties fail us, mainly through being aspirational while lacking enforceable 'teeth'. Most of the previous Aichi Targets of the UN Convention on Biological Diversity have not been met (IPBES 2019): *"The negative trends in biodiversity and ecosystem functions are projected to continue or worsen in many future scenarios in response to indirect drivers such as rapid human population growth, unsustainable production and consumption and associated technological development."*

So, a new set of 23 ambitious, largely unenforceable targets is now set (Ainsworth et al. 2022, Obura 2023). A similar situation exists for the Sustainable Development Goals (SDG), agreed on in 2015, that aim to end poverty and achieve equality while protecting the environment. A recent review found it unlikely that any of the 17 goals, and just 12% of the targets, will be met by the 2030 deadline (United Nations 2023, Malekpour et al. 2023, Nature editorials 2020, 2023a,b). SDG 14, to protect marine life, is also failing.

Of relevance to deep sea coral bioherms and sea mount biota, the 'Biodiversity Beyond National Jurisdiction' (BBNJ) High Seas multilateral treaty was adopted at the UN in June 2023. The agreement, open for ratification from 20th September 2023, was signed by 67 states that same day (83 states at time of writing). It will come into force in early 2024 (United Nations Treaty Collection 2023), and provides a broad mandate for any State Party to establish marine protected areas. The Treaty supports existing targets such as the 2022 '30×30' pledge for protected areas from UNCBD COP15 (Ainsworth et al. 2022, Nature Editorial 2023c).

However, such area-based measures must not undermine existing bodies with regulatory powers under the UN Convention on the Law of the Sea (UNCLOS). These include the International Maritime Organization responsible for shipping, 17 Regional Fisheries Management Organisations and the International Seabed Authority responsible for mining. These also include dispute resolution, and failings therein. Although few coral reefs occur on the High Seas, a pertinent example is given by the reef systems of the Spratly Archipelago (Figure 4) (McManus et al. 2010, McManus 2017, Shao 2017). The region is a major trade route, with significant fisheries and fossil fuel reserves, and strategic importance, engendering territorial claims by five littoral nations. To briefly summarize a long and complex process, most claims have been supported by UNCLOS, but China, a State Party to the Convention, has refused to accept the rulings (Miranda and Maljak 2022).

It is not helpful, nor fair, to disparage good intentions and sterling efforts to achieve multilateral treaties (including ongoing work on plastics, United Nations Environment Programme 2022) – these do have an important, if challenging, role. However, I think it fair to say that our current approaches are failing coral reefs and other ecosystems (Willcock et al. 2023). Bert Rölling's (1960) aphorism comes to mind: *'The road to hell is paved with good Conventions'.*

Policy land- and 'seascapes', as emissions, and the temperature rise

Our Society's leadership has provided thorough analyses of the policy 'seascape' (e.g., Kleypas et al. 2021, Knowlton et al. 2021), while also stating that we are living in: *"... a turbulent moment in history where social dynamics, economic organisation, and legal infrastructure are rapidly changing. On the one hand, we have learned that even a dramatic reduction in human activity has not reduced greenhouse gases to the level required by the Paris Agreement, which is itself not adequate to protect coral reefs over the long term. Greenhouse gas emissions have continued to increase even amid the global pandemic ..."* (Knowlton et al. 2021).

These articles also note that actions commensurate with policies have not yet started or are poorly implemented (also see Ivanovich et al. 2023), along with a concomitant decline in the status and function of reefs. Knowlton et al. (2021) called on policy makers and other actors in all countries to heed the collective voice of the coral reef science community. More recently UN Secretary General Guterres (2023) made a similar plea, as has the global medical profession re human health (Abbasi et al. 2023), among many others. To have the desired effect, such calls require a rational, ethical approach from those in power. That has failed to eventuate, despite many decades, indeed centuries, of appeals and warnings. Instead, our global political leadership continues to meet, talk, and struggle to develop, let alone implement, largely toothless treaties, while greenhouse gas emissions, temperature, sea level and ocean heat content, continue their relentless rise (Figure 5).

Approximately half of all anthropogenic emissions since the Industrial Revolution have occurred since 1990 (Renwick 2023, Richie and Roser 2023), year of the first IPCC report. Some two-thirds of coal (64%), oil (63%) and gas (70%) companies exceeded their production budgets from 2014 to 2020, under the

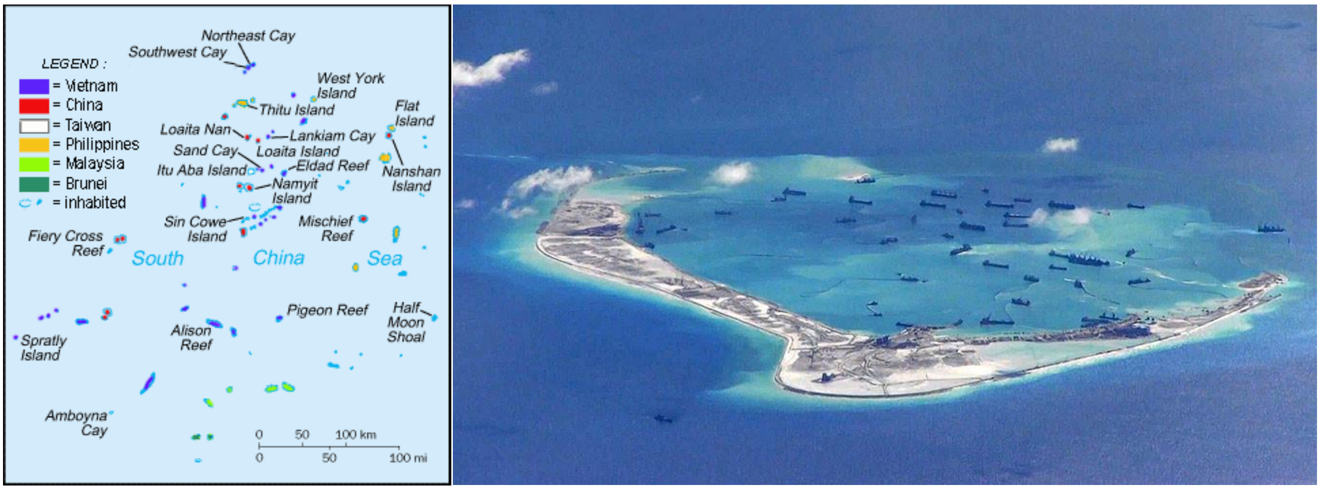


Figure 4. Left: Territorial claims and development in the Spratly Islands (Map courtesy Spiridon Manoliu, public domain, Wikimedia Commons). Right: Subi Reef (photo courtesy United States Navy, public domain, Wikimedia Commons)

IPCC's middle-of-the-road (SSP2-1.9) Paris Agreement-compliant scenario (Rekker et al. 2023, UNFCCC 2023). In 2022, global energy-related CO_2 emissions grew by 0.9% or 321 Mt, to a new high of over 36.8 Gt (International Energy Agency 2023a). For the 11th consecutive year atmospheric CO_2 levels rose by more than 2 ppm. On 3rd February 2023 atmospheric CO_2 exceeded 420 ppm at the Mauna Loa monitoring station for the first time (CO_2.earth 2023). The past 12 months, from November 2022, were the hottest on record, with an average warming of more than 1.3°C above the pre-industrial baseline (1850-1900, Climate Central 2023).

Most of the heat, and some 25% of the emitted CO_2, has been absorbed by the oceans (Li et al. 2023, World Meteorological Organization 2023, Figure 5). Ocean heat uptake has accelerated dramatically since the 1990s, nearly doubling during 2010–2020 relative to 1990–2000 (Li et al. 2023).

1759, Smith 1776). Rather, it is an unintentional aid to those with an interest, vested or otherwise, to deceive. The fossil fuel and petrochemical industries are just two interlinked cases in point, albeit driving the greatest existential threat to coral reefs and other ecosystems. For reefs, many other anthropogenic impacts, at varying scales, are also manifest.

As Sir Maurice Yonge (1978, Figure 6) noted in relation to the nearshore Great Barrier Reef: *"I had the opportunity of revisiting Low Isles, off Port Douglas and the scene of the expedition I led 50 years ago ... It was sad to find the reef surface, then the site of the richest possible array of living organisms and a natural experimental aquarium, now almost entirely dead. This appears to be the effect of sediment brought down by the Daintree River following the clearance of rain forest."* (also see Yonge 1930, 1940, Rogers 1990, Stafford-Smith and Ormond 1992, Fabricius 2005, Turak et al.

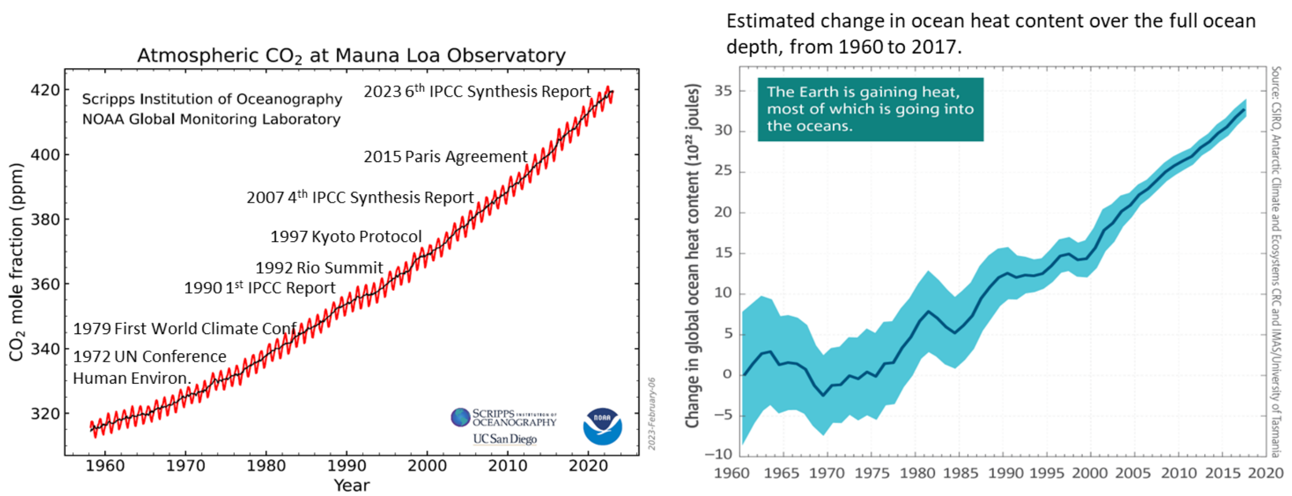


Figure 5. Left. Source graph 'Trends in Atmospheric Carbon Dioxide', NOAA Global Monitoring Laboratory (https://gml.noaa.gov/ccgg/trends/). Right. Ocean heat content, CSIRO (https://www.csiro.au/en/research/environmental-impacts/climate-change/state-of-the-climate/previous/state-of-the-climate-2018/oceans)

Conversely, recent uptake of CO_2 may be declining, with possible further shrinkage as climate change progresses (Müller et al. 2023). Concurrently, sea temperatures continue to rise (Climate Change Institute 2023), fuelling marine heatwaves, with obvious effects on coral reefs and ocean life more generally.

Positives, negatives and wishful thinking

Relying on rational appeals to the better nature of political and corporate leaders is not a successful strategy for engendering necessary change. Indeed, we have long been warned of this folly (Forsskål

2021).

Given the obvious direness of the global situation, it is easy to become pessimistic, cynical, or depressed by the challenge. Throughout human history, society's advance has coincided with, or caused, ecological devastation and extinctions (Flannery 1994). Our 'ability' in these respects has expanded with rapid industrialization and reproductive success. Also, along with the predatory delay by vested interests, there is inherent inertia in our economic system and industrial-military complex, the former widely neo-liberalized or controlled by


Figure 6. Left. Maurice and Mattie Yonge on Low Island, 1928. National Library of Australia. Right. Times have certainly changed! P. Orr wearing the diving helmet used at Low Isles, ca. 1928. (photo by C.M. Yonge. National Library of Australia). Copyright expired on both photos, courtesy of James Cook University (Fielding 2023).

oligarchs, the latter embedded in nationalistic tribalism in some cases verging on xenophobia. Both remain heavily reliant on combustion of fossil carbon.

There is also the powerful desire for continually improved standards of living, along with a widespread sense of entitlement, fuelled by advertising, including a surge in propagandized mis- and dis-information (see Bernays 1928 for early insight). As Susan Murphy (2014) eloquently noted: *"…we have, somewhere in the march of 'civilisation', lost the humble amazement of feeling the earth and ourselves to be a prodigious unearned gift from the universe."* Our increasing biophysical over-shoot is a symptom of a deeper, more subversive modern crisis of human behaviour (Merz et al. 2023). The three main drivers – economic growth, marketing and pro-natalism (the last including government support for a higher birthrate) – directly impact the three 'levers' of overshoot – consumption, waste, and population.

Resulting maladaptive behaviour has been *'catalysed and perpetuated by the intentional exploitation of previously adaptive human impulses'* (Merz et al. 2023), its remedy requiring a shifting of social norms, economics and consideration of intergenerational justice (Raworth 2017, Victor 2023). In their annual World Energy Outlook 2023 report the International Energy Agency (IAE, 2023b) noted that: *"The world is much better prepared than we were 50 years ago. We know what we need to do and where we need to go."* The IAE cautioned, however: *"At the same time, the challenges are much broader and more complex – energy security and climate are interwoven …".*

A case can also be made that we are living at a time of unprecedented humanist progress, and that empirically derived facts will, ultimately, win the day (Barbier 2023, Barbier and Burgess 2023). Steven Pinker (2018) martials significant support for this case, but see Goldin (2018) for critique and Harari (2016) for a wide-ranging, provocative view on these, and other futurist arguments. Forward-looking economists are finally championing post- or beyond growth narratives (e.g., Hickel et al. 2022).

From a naturalist's perspective, Edward O. Wilson's (1984) 'biophilia' hypothesis provides a philosophical underpinning that may resonate with many coral reef scientists, as well as anyone fortunate to spend time in the natural world; or even, vicariously, through the remarkable visual archive of wildlife documentaries. Nature has remarkable adaptive and restorative powers of resilience. International institutions continue to foster engagement among nations, and social norms are changing, with growing awareness of biodiversity loss, climate and ocean disruption, and our breaching of planetary, or earth system, boundaries (Rockström et al. 2023, Richardson et al. 2023, Ripple et al. 2023). There is also, however, significant cognitive dissonance (Festinger 1957), of inconsistent or conflicting thinking and attitudes towards necessary behavioural change.

As posited above, humanity's current multilateral response, founded mainly in international non-binding treaties and 'nationally determined contributions', is demonstrably failing. Can climate- or geo-engineering, with proposals ranging from the well-meaning to the hubristic, help? Some may, notably proposals for significant rewilding (Clover 2022, Jepson and Blythe 2022). Unintentional examples include the return of wildlife following the Chernobyl nuclear reactor incident (United Nations Environment Programme 2020). Intentional examples include the 'Ridge to Reef Rewilding Campaign' (Wood 2023) that includes sites in Ecuador (Galapagos), French Polynesia, Tonga, United States (Midway Atoll) and Palau. Numerous reef restoration efforts are also underway, with different experimental and

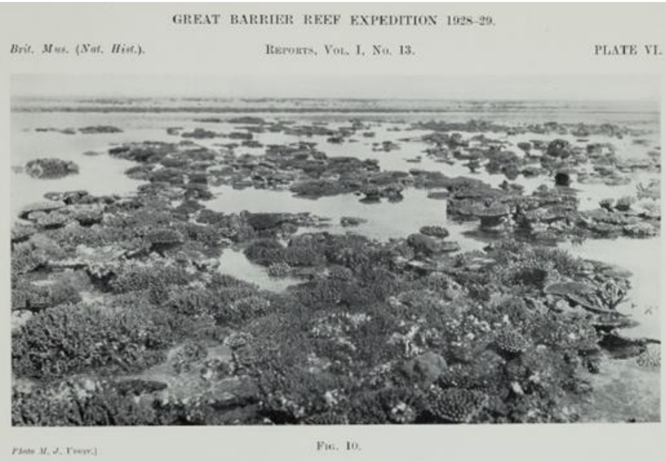


Figure 7. Branching corals, largely species of *Acropora*, exposed during very low spring tides in the sheltered waters of the anchorage at Low Isles." (Yonge 1940, Courtesy Biodiversity Heritage Library http://www.biodiversitylibrary.org).

logistical approaches, funding support and chances of success.

Comparisons of the effectiveness and side effects of four geo-engineering methods, artificial ocean upwelling, ocean iron fertilization, ocean alkalinization (Tollefson 2023b) and solar radiation management, along with afforestation (Keller et al. 2014), suggest that most will not succeed. Even when applied continuously at scale, each method was, individually, either relatively ineffective with limited (< 8%) warming reductions or had potentially severe side effects. Another recent evaluation of the potential for six methods of oceanic CO_2 removal (CDR) and sequestration (Doney et al. 2021) concluded: *"Based on the present state of knowledge, there are substantial uncertainties in all of the ocean CDR approaches. … Amongst the biotic approaches, research on ocean iron fertilization and seaweed cultivation offer the greatest opportunities for evaluating the viability … Out of the abiotic approaches, research on ocean alkalinity enhancement, including electrochemical alkalinity enhancement, have priority over electrochemical approaches that only seek to achieve carbon dioxide removal … ".*

At this point in our emissions trajectory, the role for geo- or ocean engineering or other forms of drawdown and offsetting to compensate for failed mitigation, of reducing emissions at source, appears limited, some would say delusional. With current technology and timeline, removal of sufficient CO_2 via carbon capture and storage, for example, is magical thinking, an unscalable pipedream (Ho 2023), albeit a key component of many Emissions Trading Schemes, widely promoted by the fossil fuel industry as rationale for continuing to pollute (Kusnetz 2023).

Legal options: turning the tide

A more holistic approach to ocean and planetary governance is urgently needed, yet competing interests continue to dominate (Frick et al. 2016, Guerreiro et al. 2023), along with widespread dis-information and fearmongering. With growing awareness, however, recent developments in national and international law are focusing increasingly on ecological governance (Cullinan 2003, Woolley 2016), also known as Earth jurisprudence, Earth law or multi-species justice (Tschakert et al. 2020). These include the UN-supported initiatives 'Towards a Universal Declaration of Ocean Rights' (Earth Law Center 2023) and, where environmental harms also impact humanity, the UN Guiding Principles on Business and Human Rights (Oldring and Robinson 2023).

Advisory opinions on legal responsibilities of nations for climate change have been sought by Small Island Developing States, notably reef-rich Vanuatu and Pacific neighbours, from the International Court of Justice (2023) and the International Tribunal for the Law of the Sea (2023). Recognizing existential risk from the rising sea, the atoll nation of Tuvalu's Constitution Bill stated that: *"The State of Tuvalu within its historical, cultural and legal framework shall remain in perpetuity in the future, notwithstanding the impacts of climate change or other causes resulting in loss to the physical territory of Tuvalu."* (Government of Tuvalu 2022).

Since 2017, more than 2100 climate-related lawsuits have been filed, across 65 jurisdictions, in international, regional, and national courts, tribunals, quasi-judicial and other adjudicatory bodies, including special procedures of the UN and arbitration tribunals (United Nations Environment Programme 2023c). Of these, 17% have been filed in developing nations, including the Coral Triangle nation Indonesia.

Specific coral reef-related litigation is increasing, notably for protection of threatened species. Recent examples include the Center for Biological Diversity's (2023) case under the US Endangered Species Act against the US National Marine Fisheries Service for failing to finalize protections for 12 coral species listed under the Act in 2014. According to the lawsuit, the species have not received the critical habitat designation the law requires. In August 2023, critical habitat was designated for five threatened Caribbean corals, *Orbicella annularis*, *O. faveolata*, *O. franksi*, *Dendrogyra cylindrus* and *Mycetophyllia ferox*, pursuant to section 4 of the Endangered Species Act (NOAA Fisheries 2023a).

Other cases have dealt with damage caused by ship groundings, including on Australia's Great Barrier Reef. In 2010, the Australian government sued the Chinese owner of a bulk coal carrier over unpaid damages from the ship's grounding, which spilled oil and damaged protected reef. The lawsuit sought AU$120 million in damages from the ship's owner for the cost of 'remediation' of the shoal, or alternatively required remediation of the shoal by the ship's owner. Ultimately the owners agreed to pay AU$39.3 million (ABC news 19th September 2016). Similar events have unfolded elsewhere, notably in the Caribbean and Western Indian Ocean (WIO), where ship groundings have occurred for millennia. Increasingly, analyses of financial costs of damage are being used in determining reparations, based on attribution science (Grasso and Heede 2023). In the WIO a standardized assessment and compensation regime has been developed for the Regional Organization for the Conservation of the Environment of the Red Sea and Gulf of Aden (PERSGA 2009), by Egyptian colleagues Mohammed Kotb and Mohamed Abou Zeid.

Whatever one's ethical view on valuation approaches to 'natural capital' and ecosystem services (Schröter et al. 2014, Costanza et al. 2017, Nature editorial 2019, Eddy et al. 2021), even significant compensation payments may be considered simply a cost of doing business. In most jurisdictions, civil law is focused on corporations, not on their leadership. If convicted, companies may appeal the decision and/or the award of costs, keeping cases in the court system for many years. Ultimately, fines can be 'written off'. Further, even substantial verdicts do not necessarily cover all costs of damage (Parenteau and Dernbach 2023). Recent global estimates for extreme events tallied more than US$140 billion annually (Newman and Noy 2023).

A related consideration is the corporate veil (Thompson 1991, Macey and Mitts 2014), which assigns legal personality to companies, providing shelter to leadership and shareholders. For the Deepwater Horizon oil spill in the Gulf of Mexico, fines totalled US$20.8 billion in damages (NOAA 2023b). British Petroleum (BP), the main responsible company, was sentenced to five years of probation – the maximum term permitted under law (EPA 2023). Allegations that BP lawyers vetted 'independent' research on environmental impacts by 'ghost-writing' and 'ghost management' prior to publication remain to be addressed (0'Malley 2023).

No senior executives of BP or any other companies involved were convicted of any crime. BP's fine has been more than recouped. Another pertinent example was the oil spill from the *Exxon Valdez* tanker in Prince William Sound, Alaska, March 1989. The spill affected ~2000km of shoreline, with multi-decadal impacts for wildlife and habitats, local industries and communities. More than 25 years later, marine mammals and birds were classified as 'Not Recovering' or of 'Unknown' status (NOAA 2020). A remarkably litigious series of claims and counter-claims lasting decades ensued from the spill (New York Times 1989, Palast 2008). Throughout, the companies continued doing business, profiting massively from recent global events.

State Investor Dispute Settlement (ISDS) clauses included in thousands of investment treaties and trade agreements enable foreign investors to file arbitration claims if government actions are perceived to harm their interests. More than 1,250 claims have been filed since the 1990s, with awards into the billions of dollars. The 12 largest awards, 11 of which have gone to fossil fuel or mining companies, totalled more than US$95 billion (Tienhaara et al. 2022, Boyd 2023). Clearly, present trade, legal and governance systems could be better directed towards environmental sustainability and the rights of future generations.

Stopping Ecocide

At an international level, a potentially more effective approach is to make widespread environmental destruction, ecocide, a crime on the Rome Statute of the International Criminal Court (ICC). The Statute, adopted in 1998 and entered into force on 1 July 2002, currently has four crimes on its books – war crimes, genocide, crimes against humanity and the crime of aggression. In the 1980s the UN's International Law Commission considered inclusion of an environmental crime within the Draft Code of Crimes Against the Peace and Security of Mankind. Early drafts did include ecocide (Article 26 wilful and severe damage to the environment), but this was dropped, somewhat mysteriously (Gauger et al. 2013), apparently at the behest of several nations. Nevertheless, the Rome Statute does provide a legal framework to prosecute environmental crimes, particularly during armed conflict, albeit with a human-rights, rather than earth-rights focus. The Office of The Prosecutor has not prosecuted such a case to date (Global Diligence 2014), potentially relating to lack of resources and/or issues of admissibility. The continuing war in Ukraine may change that (Leclerc 2023, International Criminal Court 2023).

With respect to the ICC's early achievements, successes and failings, Geoffrey Robertson (2006) noted: *"There is a 'catch as catch can' quality about international criminal justice at this point, but criticism that enforcement is selective should count not as principled objection but rather as a spur to get international justice systems up and running, creating precedents that can be universally applied."*

There is now, belatedly, a rapidly growing international campaign to include a separate crime of ecocide on the Statute. The aim is to redirect governments and corporations to more ecologically sustainable paths and rein in the worst offenders; those committing the most egregious environmental destruction (e.g., Rogers and Adam 2023). This should help to link complicities between multinational companies and states which, in peace time, are the main perpetrators of environmental destruction. This could provide justice to human and non-human victims, including future generations, of environmental crimes. The intention is to set a moral imperative, with a deterrence effect on individuals, companies and governments to respect human rights and planetary boundaries (Dzimballa 2022, Lamont et al. 2023, Oldring and Robinson 2023). Criminal law is primarily preventative, and the intention is that ecocide law will incentivize foresight and precaution (Jojo Mehta, Executive Director, Stop Ecocide Foundation, pers. comm.).

The initiative builds on the 2018 Report of the UN Secretary-General on *'Gaps in international environmental law and environment-related instruments: towards a global pact for the environment'* (UN Doc A/73/419). It also focuses on the relevant provisions of the 1992 UN Convention on Biological Diversity and the 1992 UN Framework Convention on Climate Change (Sands et al. 2018, Boyle and Redgwell 2021). A draft legal definition, composed by a distinguished international panel of jurors with expertise in criminal, environmental and climate law, from as far afield as Bangladesh, Ecuador, France, Mauritius, Norway, Samoa, Senegal, Sierra Leone, the UK and USA, was published in June 2021 (www.stopecocide.earth/legal-definition).

The draft definition

The Panel drew on existing precedents and authorities in international treaty and customary law, the practice of international courts and tribunals in criminal law, and approaches reflected in the Rome Statute. Hence the draft definition uses wording and terms, where appropriate, that are already included in the Statute.

"1. For the purpose of this Statute, "ecocide" means unlawful or wanton acts committed with knowledge that there is a substantial likelihood of severe and either widespread or long-term damage to the environment being caused by those acts.

2. For the purpose of paragraph 1:

a. "Wanton" means with reckless disregard for damage which would be clearly excessive in relation to the social and economic benefits anticipated;

b. "Severe" means damage which involves very serious adverse changes, disruption or harm to any element of the environment, including grave impacts on human life or natural, cultural or economic resources;

c. "Widespread" means damage which extends beyond a limited geographic area, crosses state boundaries, or is suffered by an entire ecosystem or species or a large number of human beings;

d. "Long-term" means damage which is irreversible or which cannot be redressed through natural recovery within a reasonable period of time;

e. "Environment" means the earth, its biosphere, *cryosphere, lithosphere, hydrosphere and atmosphere, as well as outer space."*

Including an appropriate, overarching definition, and recognising it as an autonomous crime, opens pathways for universal jurisdiction and unifies current environmental law, replacing soft with hard law (Dzimballa 2022, Oldring and Robinson 2023). With no retroactive powers, it is intended to act as a deterrent as much as a prosecutorial tool, providing guidance at the highest levels of government and industry. The major difference from most present legal approaches is removal of corporate and government veils that have enabled leaders to avoid criminal prosecution. Writing in relation to the perpetrators of other crimes already included on the Rome Statute, Robertson (2006) noted:

"This legal principle draws practical support from consideration that crimes … will be deterred only if would-be perpetrators … are given pause by the prospect that one day, under a different regime or in another country, they may be called to account." And: *"They made no secret of their fears …of the indignity that would attend their appearance … in the Hague dock. What exercised them most was the humiliation of being tried in another country, under the world's gaze … This fear of suffering the indignity of international criminal justice seems widely shared … the prospect of trial at the Hague can have real deterrent effect."*

As the process progresses, the draft will undergo significant scrutiny by an international study or working group. Along with evaluation of lawfulness, wantonness and the balancing of perceived benefits versus harm, the scaling of damage is of particular relevance. This is captured in the definition by the words severe, widespread and long-term, as these relate to an ecosystem or species. For coral reefs and bioherms, spatial scales could vary from the local, with extirpation of an endemic species, to the regional, through destruction of a unique biota, such as on a chain of sea mounts or reef tract, to the global, with major reduction or loss of entire suites of species across their ranges. The definition includes consideration of recovery, hinging on interpretation of 'long-term' and 'reasonable period of time'. For reefs, our understanding of recovery is relatively well advanced in respect of coral cover, less so for most individual species and community composition (e.g., Done 1988, Tomascik et al. 1996), or for other taxa, except for a few other macro-invertebrates, some fishes, marine mammals and algae. These deficiencies are compounded by the cumulative, synergistic and antagonistic effects of a rapidly changing disturbance regime. For deep sea coral bioherms, our understanding is even less developed (Clark et al. 2022):

" … recolonisation and regrowth of deep-sea corals on previously heavily trawled deep-sea features can …take place but … recovery is slow, with the first detectable signs of coral recruitment and regrowth occurring approximately two decades after the cessation of trawling. While such observations of the early stages of recovery of coral-dominated seamount communities are encouraging, full recovery to … pre-disturbance status is by no means certain and would still be likely to take centuries, rather than decades."

Inclusion of a fifth crime against peace in international law

To have ecocide included on the Rome Statute requires four steps:

1. Proposal. Any state which has ratified the Rome Statute (ICC) may propose an amendment. There are currently 123 "States Parties".
2. Admissibility. This requires a majority of those present and voting at the next annual assembly of the ICC to agree that the amendment can be considered.
3. Adoption. This requires at least a two-thirds majority of States Parties (currently 82/123) to vote in favour of the amendment. It is likely to take place at a Crime Review Conference, where the final text of the amendment will be discussed and agreed amongst States Parties.
4. Ratification. States Parties can then ratify (officially submit their agreement) and must enforce the law in their own country one year later.

Inclusion of ecocide in the Statute would build on the existing crime of 'widespread, long-term and severe damage to the national environment' during armed conflict. It would acknowledge that most such damage now occurs during peace time (current conflicts notwithstanding). For nations that are not ICC member states, leaders may be subject to prosecution for crimes committed within member states, and similarly for corporations. Selection of specific cases will be at the discretion of the ICC Prosecutor, considering the definition and interpretation of relevant keywords – illegal, wanton, severe, widespread, long-term. Referrals are also possible from States Parties or the UN Security Council, the latter able to refer situations in non-State Parties (Kendall and Nouwen 2013). Prosecutions could happen at the Hague or, where appropriate, in affected States.

Recent developments

At time of writing, the Stop Ecocide movement had 38 national teams and provisional support for its consideration at the ICC from 29 nations, including reef-rich Vanuatu (a champion of the concept), and New Zealand, host of the next International Coral Reef Symposium. A growing number of non-ICC nations, nine at time of writing, have also indicated support (Jojo Mehta, pers. comm.). In 2023, the Parliamentary Assembly of the Organization for Security and Co-operation in Europe called on parliaments of its participating States to enshrine the concept in national and international law. Additional support was forthcoming from the Nordic Council. Following the European Parliament's Legal Affairs Committee's unanimous vote, the Parliament agreed in November 2023 to enshrine ecocide in law as a new offence, stating: *'Member States shall ensure that any conduct causing severe and either widespread or long-term or irreversible damage shall be treated as an offense of particular gravity and sanctioned as such in accordance with the legal systems of the Member States.'*

In recent months ecocide bills have been proposed or progressed in the EU, Brazil, the Netherlands, Belgium, Spain (Catalunya) and Mexico. *"Leaders across the globe are beginning to wake up to the very real dangers we face, and a strong legislative direction of travel is emerging."* (Jojo Mehta pers. comm.). Personal support for the initiative is also growing, including from the UN High Commissioner for Human Rights, Volker Türk, and science and conservation luminaries Jane Goodall and Sylvia Earle. Perhaps we, as a global community, may finally heed those prescient warnings of Peter Forsskål and Adam Smith, and act as the ecological doctors Aldo Leopold proposed.

National adoption and application

Several nations have included ecocide law on their statutes, unsurprisingly including Vietnam, given the legacy of Agent Orange. Ecuador, another coral reef hosting nation, recognized Rights of Nature in a 2008 Constitutional amendment, and criminalized ecocide in Article 247 of the Organic Integral Penal Code, with specific protections from industrial fishing for the Galapagos Marine Reserve. In Ecuadorian law, Nature, or Pachamama, has the Right to maintain and regenerate its cycles, structures, functions and evolutionary processes; and to be restored, with restoration separate from compensation to people. Additionally, *"the State shall apply preventative and restrictive measures on activities that may lead to the extinction of species, the destruction of ecosystems and the permanent alteration of natural cycles"* (Art. 71-74) (Stop Ecocide International 2023b).

In 2017, a Chinese vessel was caught with over 6,000 dead sharks in the Galapagos Marine Reserve. In its judgment, the Ecuadorian Supreme Court ruled that the captain and crew were to receive prison sentences and fined more than US$6 million, noting that Nature, as a subject of Rights, is entitled to complete reparation from the crime, and that the amount necessary in compensation depends on both the material and immaterial damage (Eco Jurisprudence Monitor 2023). The court also noted the roles that sharks play as apex predators and the serious ecological impacts of their removal. Scope of protection was amplified through both the legal recognition as a subject of Rights, and through penalization of a crime against Nature, just as the violation of the Right to Life is penalized by law.

More recently, in February 2022, Panama introduced a Rights of Nature Law, providing an ecocentric perspective of environmental protection, including restoration and regeneration of life cycles. It was recently employed in a Supreme Court decision regarding failings of a mining company to prevent environmental damage. In August 2023, Chile modified its Penal Code on economic crimes to incorporate a new section 'Attacks against the environment'. The amended code includes several elements of the draft international definition, while emphasising prevention, as well as risk of decadal prison terms (Stop Ecocide International 2023c).

Due process: Victimhood, judgement, and verdict

If/when ecocide becomes the fifth crime at the ICC, our members may be called upon as expert witnesses, as has already occurred in civil litigation elsewhere (e.g., Blattner et al. 2023). Successful implementation at the ICC will require appropriate assessment of victimhood (both human and non-human), damage and reparations. On representation for non-human victims "… *an 'oracle' effect [will be required where a] spokesperson gives voice to the group … thereby* *speaking with all authority of that elusive, absent phenomenon"* (Kendall and Nouwen 2013). And *"… the role of victims in the ICC's representational practices goes beyond being represented in court proceedings. More indirectly and abstractly, actors both within and outside the ICC have invoked victims' interests as a telos [fulfilment] of the work of the ICC – sometimes together with other ends such as "the rule of law" or "ending impunity"* (Kendall and Nouwen 2013).

As to the verdict, the ICC has a two-stage process, consisting of judgement on culpability and then sentencing, with detailed sentencing submissions and decisions aimed at providing fairness (Windridge et al. 2018). The ICC allows for filing of separate sentencing briefs, once the parties know the crime and the mode of liability for which an accused has been convicted. This two-stage process enables detailed investigation of sentencing arguments, consistent with rules that allow for either Prosecution, Defence or the Trial Chamber itself to request a separate sentencing hearing (Windridge et al. 2018). The Trial Chamber will determine the appropriate sentence, considering gravity of the crimes and the convicted person's role. It can impose up to 30 years or life imprisonment (ABA-ICC Project 2023). The Trial Chamber can also issue fines and/or forfeiture of proceeds, property, or assets derived directly or indirectly from the crimes. If the sentence and/or other punishment issued by the Trial Chamber is appealed by the Office of the Prosecutor or the convicted person, the Appeals Chamber has the power to uphold, reverse, or amend the sentence and/or other punishment issued.

Damages and reparations: Potential for inclusion of IUCN Red lists

With respect to reparations for a coral reef or bioherm ecocide, PERSGA's (2009), or similar, approaches to damage assessment may provide a template, modified to include individual species' International Union for the Conservation of Nature (IUCN) Red List categories for risk of extinction (IUCN 2023a). These are Near Threatened (NT), Vulnerable (VU), Endangered (EN), Critically Endangered (CR) or Extinct in the Wild (EW). Also relevant is the IUCN Red List of Ecosystems (RLE), applicable at local, national, regional and global levels (IUCN 2023b). The RLE evaluates whether ecosystems are not currently facing significant risk of collapse (Least Concern), or are Vulnerable, Endangered, Critically Endangered or have reached the final stage of degradation (Collapse, CO). RLE provides evidence-based assessments of the risk of ecosystem collapse, measured by reductions in geographical distribution or degradation of the key processes and components.

It has been employed for the Meso-American Reef system (M-AR, Bland et al. 2017) and Western Indian Ocean (WIO, Obura et al. 2022). For the M-AR: *"The overall status of the ecosystem is Critically Endangered (plausibly Vulnerable to Critically Endangered), with notable differences among Red List criteria and data types in detecting the most severe symptoms of risk."* For the WIO: *"… coral reefs are vulnerable to collapse at the regional level, while in 11 nested ecoregions they range from critically endangered (islands, driven by future warming) to vulnerable (continental coast and northern Seychelles, driven principally by fishing pressure)."*

Damage / reparation assessments for potential ecocides on such reef systems, or indeed other marine or terrestrial ecosystems for which RLEs have been completed, could use a scaled factor in calculations, based on the RLE score, for increasing risk. Hence, a simple, potential damage assessment formula for a reef-based ecocide could include the following:

$$\text{Reparations / Damage} = A \times LC \times D \times RP \times V \times \boldsymbol{\Sigma} RL \times RLE$$

where: A is the area damaged (ha), LC is the percent cover of living coral or other taxon (as proportion from 0 to 1); D is percent damage in the area (as proportion from 0 to 1); RP is the estimated number of years required for recovery; V is the assigned, case-specific financial value of one ha; ΣRL is the sum, for all species impacted, of their IUCN Red List category where NT =1, VU = 2, EN = 3, CE = 4, EX (wild) = 5; and RLE is the IUCN Ecosystem Red List score where NT = 1, VU = 2, EN = 3, CE = 4, CO = 5. Both the species and ecosystem Red List categories could be scaled (e.g., logarithmically) in the equation. Additional parameters that address species habitat structuring or keystone roles could also be included, where relevant.

An analogous approach could be adopted for threatened species in other ecosystems, such as rainforests, for which IUCN Red List assessments have been completed. Each case will, of course, be unique, and the levels of information available will differ. Hence any formulaic approach will need flexibility to meet specific circumstances.

Box 2. Potential future regional-scale ecocide scenario on a Caribbean reef tract

Scenario: Major oil spill causing mass death of shallow water sessile species, along with additional death and abandonment by motile fauna in a large section of a reef tract (e.g., Figure 8). The shallower reef zones of an MPA (500ha) were heavily impacted, along with 7,000ha of the adjacent reef system. The spill plume spread to a neighbouring country, also heavily impacting 3,000ha of reefs there. Legal assessments determined the incident resulted from negligence, potentially both unlawful and wanton. Ecological assessments concluded that damage was severe, widespread and long-term. Both impacted nations had ratified relevant Conventions (United Nations Environment Programme 2023b,d), are States Parties to the Rome Statute, and referred the alleged ecocide to the ICC Prosecutor.

Biological evidence:

Prior surveys had reported an average coral cover of 20% in the Reserve and 10% on the broader reef tract, comprised of 45 species of reef-building coral, 40 species of gorgonians and other octocorals, 15 species of sponges, among other habitat forming taxa. The spill reduced average cover in the reserve to 2% and on the broader reef tract to 1%. It had also likely affected subsequent recruitment and recovery, as coral larvae are sensitive (e.g., Nordborg et al. 2022).

Species present ranged in RL score from Least Concern (e.g., *Montastraea cavernosa*) to Critically Endangered (e.g., *Dendrogyra cylindrus*). For *D. cylindrus*, the reserve was one of the last remaining healthy patches of the species in the wild, where significant resources had been devoted to its care.

Additional impacted taxa included 100 species of reef fishes, five species of cetaceans, and numerous crustaceans, molluscs, echinoderms and algae. Only some of these had Red List assessments (e.g., Caribbean reef shark *Carcharhinus perezi* listed as Endangered), so the overall RL scores (summed at 750 for the Reserve and 450 for the broader reef tract) for the incident were considered conservative. The ecosystem has been assessed as Critically Endangered, with an RLE score of 4. Financial values per ha were set, highly conservatively in this example, at US$1,000 for the Reserve and US$500 for the broader reef tract (c.f., PERSGA 2009 for ship grounding, where values were set per square metre at US$300 for national parks and US$120 elsewhere, rates that would make reparations astronomical for widespread impact).

Reparations / Damages equation: A x LC x D x RP x V x ΣRL x RLE

For the MPA: 500 (ha area impacted) x 0.2 (20 % average coral cover) x 0.9 (90 % damage) x 20 (years to recovery) x 1000 (US$ value per ha) x 750 (ΣRL score) x 4 (RLE score) gives a damages value of US$5.4 billion. For the broader reef tract: 10,000 (ha area) x 0.1 (10% average coral cover) x 0.9 (90 % damage) x 20 (years to recovery) x 500 (US$ value per ha) x 450 (sum RL score) x 4 (RLE score) gives a damages value of US$16.2 billion. Additional reparations for human impacts to fisheries, tourism, and health of nearby coastal dwellers were calculated at US$400 million. In this example, total reparations would be assessed, conservatively, at US$22 billion, a sum comparable with fines for the Deepwater Horizon oil spill in the Gulf of Mexico. The difference is that in this scenario, there would also be serious individual criminal liability and jail time for corporate leadership, if a conviction at the ICC was upheld.

Figure 8. Example of major oil spill (left, partly obscured by cloud) impacting Caribbean Sea coastline. Photo from Envisat satellite, CC BY-SA 3.0 IGO, via Wikimedia Commons

Concluding remarks

The case made in these two Perspectives is that our traditional approach to sustaining coral reefs and other natural ecosystems is not succeeding at a pace commensurate with impacts. Some corporate actors, aided and abetted by pliable politicians, continue to profit unconscionably, perpetrating what may be the legalized crime of the millennium against our biosphere. Some of the main perpetrators of those harms have no intention of changing their destructive behaviour; their geo-political power remains formidable, and hence a different approach in directing behaviour is warranted. As Geoffrey Robertson (2006) noted: "*… fear of suffering the indignity of international criminal justice seems widely shared … the prospect of trial at the Hague can have real deterrent effect.*" This initiative, although no panacea, could be a key future tool in deterring and addressing harms, and a significant aid in improving the future for coral reefs.

> "Humanity, and our cohabitant species here on Earth, simply cannot afford any more decades of 'business as usual'. Yet it is clear [..] that this is what is intended. Looking ahead, I wonder whether humanity will rise to the challenge that we have created, over roughly two and a half centuries [..]"

Some 50 signatory nations to the Rome Statute host shallow water coral reefs and/or deep water coral bioherms (Spalding et al. 2001, Tong et al. 2023). Our Society has representatives in many, if not all, of these nations. If this initiative resonates, well-intentioned engagement with relevant government agencies can help to garner support. There is also an opportunity to show support at https://www.stopecocide.earth/scientists.

My personal view: Without such international criminal law effectively deterring those in industry and politics causing and enabling ecocide, powerful bad actors will continue to 'game the system' (Rich 2019), as foretold by colleagues past and present (Forsskål 1759, Bock et al. 1970), privatizing profits while socializing, indeed 'planetizing' losses. Humanity, and our cohabitant species here on Earth, simply cannot afford any more decades of 'business as usual'. Yet it is clear, as outlined above, that this is what is intended. Looking ahead, I wonder whether humanity will rise to the challenge that we have created, over roughly two and a half centuries, albeit with the seeds of our unparalleled success and failings planted long before (e.g., Ardrey 1966 and subsequent critiques). These next few decades will surely tell the tale. Perhaps a future scholar may stumble on this essay in the electronic 'cobwebs' of a long-outdated but still operable computer, belatedly realizing, as I did, that we have long been warned about both our profligacy and the need for just governance. Perhaps those may finally have been addressed, as this Perspective has advocated.

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References

To save space in the circulated (Low Resolution) pdf version of Reef Encounter, the many references cited in the article are included only in this High Resolution pdf version, in which the reference list may be found on pages 73-80.

Alternative versions are downloadable from the ICRS website at https://coralreefs.org/society-publications/reef-encounter/.

REEF CURRENTS

Telling tourists about the state of the Great Barrier Reef

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In November 2023, I was presented with an opportunity to talk to tourists about the current state of the Great Barrier Reef and its prospects in the context of climate change. It was the 25th anniversary of the 1998 *el Niño* that wrought so much coral reef bleaching globally and initiated such devastation at regular intervals in this century's opening decades. With a few dozen middle-aged to older tourists, some of whom were expressly along to 'see the Reef while we still can', I joined the cruise prepared to have to apologize: 'you should have seen it in the good old days' sort of thing.

To the contrary, we snorkeled over some of the most beautiful and, to my eye, 'ecologically healthy', shallow reefs I have seen for a long time. As a guest lecturer on the cruise, I faced a bit of a dilemma – how could I reconcile the apparently great state of the corals, fishes and invertebrates and the reef structure itself – with the gloomy prognoses I was about to deliver in my closing lecture 'Coral reefs and climate change'. The lecture is a somber affair, covering rising sea-level, increased severity and broader distribution of cyclones, ocean acidification, coral bleaching, and cumulative effects.

But based on what we had seen together, I was convinced that these reefs, at this time, were 'doing OK' ecologically. What was it that led me to this conclusion? Was I simply being fooled by the beauty? I don't think so. Having spent my working life with some great reef ecologists and geomorphologists, I had been mentally ticking boxes for 'reef health' as I snorkeled about that, frankly, I was not expecting to see. Among corals, for example, across a range of reef habitat types, we almost always saw high coral cover, reasonable composition and diversity, a wide mix of coral ages and sizes (years to centuries) and evidence of strong settlement and growth. And hovering over some classic reef margins, I saw several spectacular examples of vigorous reef-building, where, constrained by sea level, the reef had been 'backstepping' across its own shallow back-reef terrace for millennia.

Fortuitously, the cruise visits a cross-shelf series of reefs, the likes of which whose structure and dynamics I had followed for about three decades while a researcher at the Australian Institute of Marine Science (AIMS – see links below to AIMS monitoring data for three of these reefs). I wasn't diving, so was able to roam about and look at the shallow reefs as a snorkeler – say the top 4 m. The pictures here, taken using my GoPro from the surface or just below, are not in any sense a random sample of the state of corals on the reefs we visited. Rather, they are pretty shots that I could use to tell a bit of natural history to the guests. It was very easy to snap off lots of pictures of the shallow reefs like these. Yes, I did look for attractive composition, but no, I did not have to swim more than a few fin-strokes across such coral-dominated scenes to get another shot. There are links below where you can see more of the reefs represented in these four images.

Fitzroy Island: Inshore fringing reef (Fig. 1)

This scene at about 3 m below low tide is an easy 40 m snorkel off a sheltered beach on the northern side of Fitzroy Island. This type of scene is seen by

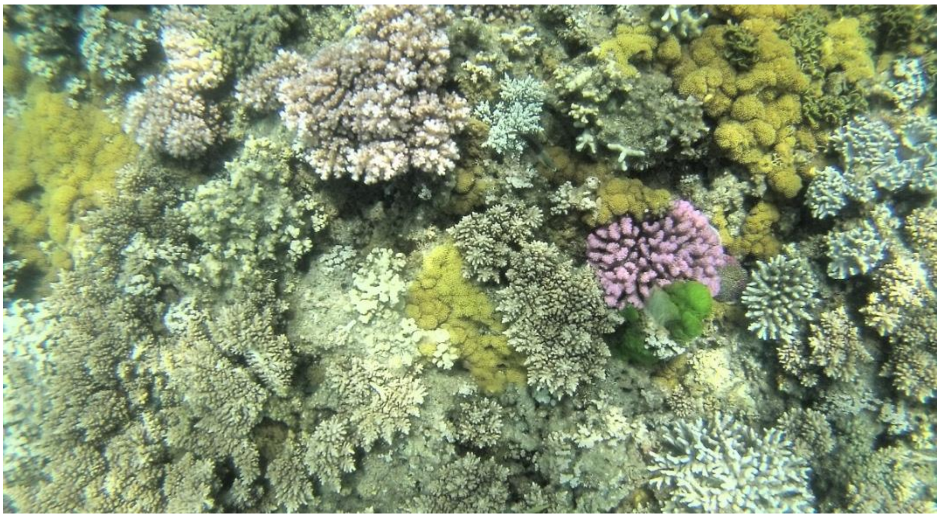

Figure 1. Fitzroy Island: Inshore fringing reef

lots of tourists who make the day trip from Cairns to this no-take, no-touch area. There is a nice variety of common nearshore soft corals and hard corals of delicate form of a size that suggests they are only a few years old. Nearby are massive *Porites* up to several metres tall, whose ages are decades to centuries. See more images at https://1drv.ms/f/s!Ah0IPTbzqn4sjJc1rbHx_Gt7opCGwA?e=8uXHK6

Figure 2. Lizard Island: Mid-shelf fringing reef

Lizard Island: Mid-shelf fringing reef (Fig. 2 and cover)

The scene in figure 2 was taken near a long-term photo study site (Lizard 5) that my AIMS team maintained at Lizard Island from 1981 to 2005. A high cover of typical mid-shelf corals of the same composition (primarily *Acropora* spp. and *Pocillopora* spp.) and similar sizes was destroyed by Cyclone Nathan in 2015, so the story here is one of strong settlement, growth, and survival over the last eight years. The pale colours of the *Acropora* plates may represent minor bleaching at the beginning of an *el Niño* summer, which will potentially be very hot. See more images at: https://1drv.ms/f/s!Ah0IPTbzqn4sjJc1rbHx_Gt7opCGwA?e=8uXHK6

Ribbon Reef No. 9: outer-shelf reef (Fig. 3)

This backreef margin is typical of GBR Ribbon Reefs in having a solid intertidal reef-flat margin that drops vertically in some places, and steps down in others onto a sand and rubble talus a few metres (~5 – 12 m) below. These habitats are mostly protected by the 500 m wide reef from the prevailing swells and waves from the Coral Sea but are occasionally bashed from the south by big seas that build up behind the GBR reef-tract. The centuries to millennia-long process of active reef accretion across its own backreef is evident, the margin being dissected by gullies and crevices that are accretional rather than erosional features, and the precipice edge being studded by large *Porites* heads that have died on top (micro-atolls) and been occupied by species more tolerant of exposure to air at extreme low tides. There are numerous outcrops down slope and in gullies that clearly have been nucleated by fallen heads or chunks of reef dislodged from above. See more images at https://1drv.ms/f/s!Ah0IPTbzqn4sjJc1rbHx_Gt7opCGwA?e=8uXHK6

Figure 3. Ribbon Reef No. 9: outer-shelf reef

At an ecological timescale, the large sizes of the more ephemeral corals and the prevalence of crustose coralline algae as substrate-builder suggest the site has not been physically damaged (storm waves) or biologically damaged (crown-of-thorns starfish; coral bleaching) for a long time (a decade or more). There were abundant and diverse fishes representing all the major feeding guilds, probably contributing to the apparent vibrancy of the reef, despite the reef being in a management zone that does allow some fishing ('Habitat Protection Zone'). Apart from the occasional damselfish territory (*Stegastes nigricans*), there was little standing biomass of turf or fleshy algae, there being lots of grazing fishes (especially Scaridae and Siganidae) seemingly cropping it off as fast as it grows.

Osprey Reef: Coral Sea (Fig. 4)

This large reef lies some 200 km beyond the outer reaches of the GBR and is subjected to extremely strong wave forces that can attack from any side. This image was chosen to illustrate how the shoulder (break in slope between a solid reef flat and a precipitous wall) has been heavily colonized by what appears to be a single cohort of digitate *Acropora* colonies and *Pocillopora* that, judging by their sizes, would have settled as larvae around 2019 or 2020. This event is consistent with anecdotal accounts that the reef had been 'trashed' by coral bleaching and storms not long before then. Like the Ribbon Reef back margin, the reef is built, and the reef surface is coated thickly, by crustose coralline algae that has promoted the strong coral settlement. Barring bleaching, continuation of current rates of growth in these corals should lead to more crowding, more top-heaviness, and more vulnerability to dislodgement in coming years, where these corals will end up over the cliff or as rubble in the gullies throughout this site. 'That's how reefs are built', I tell my guests.
(see other images at https://1drv.ms/f/s!Ah0IPTbzqn4sjJc1rbHx_Gt7opCGwA?e=8uXHK6)

My prognosis

I had joined this cruise with a little trepidation about what I would see. But what I did see was beautiful, and I was able to follow up my gloomy corals and climate change talk with the idea that these reefs, in November 2023, were 'doing OK' ecologically, based on my observations alluded to above and shared with the guests. We had travelled hundreds of kilometers across, along and beyond the northern GBR that, at each place visited, exhibited an encouraging mix of old growth corals (those *Porites* are tough!) and that 'flush of youth' represented by strong settlement and growth of a rich variety of corals over recent years. Clearly, coral larvae arrive at these reefs in a flood, not a trickle. And the settled corals have survived and grown at rates that indicate on-site environmental and ecological conditions are OK. The old-growth

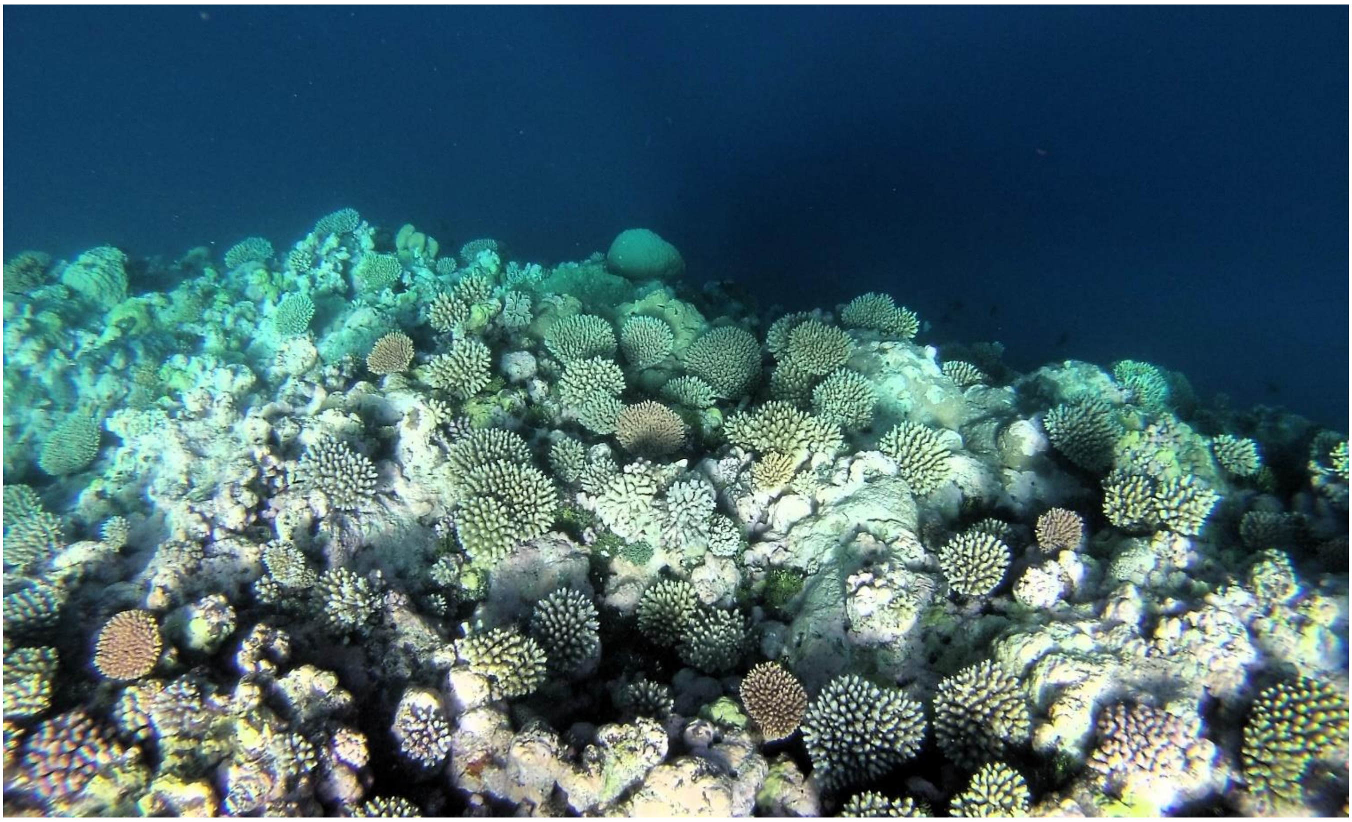

Figure 4. Osprey Reef: Coral Sea

corals are surviving well and buttressing the growth of reef around themselves and providing settlement space for other types on their bald heads where they break the surface. The fields of corals that surround these big old corals are primarily pre-teens and teenagers. How will it be next year? How about in another 5 years? And I know, it's not just about corals: in shallow and deep reef habitats alike, restitution of the full suite of biodiversity and abundance dependent on living coral will likely take a long time – could it be years or decades? Or will the whole progression of reef ecosystem recovery be interrupted by the next storm, heatwave or outbreak of crown-of-thorns starfish?

I don't think I did adequately reconcile the apparently great state of the reefs with my 'Coral reefs and climate change' talk. I did mention the devastation currently being wrought on coral reefs elsewhere, and I did manage to refrain from telling my guests 'she'll be right'. But I did not have to apologize that 'you should have seen it in the good old days'. Lucky me: these were good old days for these reefs.

Links

Go Pro Images - all sites November 2023: https://1drv.ms/f/s!Ah0IPTbzqn4sjJc1rbHx_Gt7opCGwA?e=8uXHK6
AIMS monitoring:
Fitzroy Island: https://apps.aims.gov.au/reef-monitoring/reef/Fitzroy%20Island/benthic.
Lizard Island: https://apps.aims.gov.au/reef-monitoring/reef/Lizard%20Isles/benthic
Ribbon Reef No. 9: https://apps.aims.gov.au/reef-monitoring/reef/Ribbon%20Reef%20No.9/manta
1981 – 2005 photo-transect images: Lizard Island: https://apps.aims.gov.au/metadata/view/2f88a3b9-9f9c-4eb7-ae50-14f47d6b8b26 .
Great Barrier Reef Zoning Plan Definitions: https://www2.gbrmpa.gov.au/access/zoning/interpreting-zones.

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The Decline and Resurrection of an Urban Reef

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Coral biologist Huang Danwei has one piece of advice for scuba divers and explorers of the reef: Never ignore your cuts.

In 2009, he was cut by coral while on a dive trip to the Philippines as part of his research into coral diversity. Then a PhD student at the Scripps Institution of Oceanography, he ignored it and hoped the cut would heal on its own, but the wound festered and he ended up having to spend a week in hospital upon his return to his hometown of Singapore. He eventually recovered after being administered a cocktail of antibiotics. But that encounter with the hidden world of coral microbes would not be his last.

Now an associate professor at the National University of Singapore (NUS), Dr Huang counts among his research interests a desire to learn more about the tiny things that most people don't see or immediately think about when they look at a coral reef. "Every organism is an ecosystem," said Dr Huang, who is deputy head of the university's Lee Kong Chian Natural History Museum. "The microscopic life - the microbes that live in the coral - all contribute to the functioning of the ecosystem."

Among the most well-known of coral microbes are their symbiotic zooxanthellae, single-celled algae that provide the coral with nutrition. But the coral microbiome comprises more than just these photosynthetic organisms. In the last 20 years or so, research has uncovered a much greater diversity of coral symbionts (Blackall et al. 2015, Galand et al. 2023), said Dr Huang. The natural bacterial mix in coral (part of the community of microorganisms, including bacteria, and viruses that constitutes what is known as the coral microbiome) also includes pathogens that are known to cause disease in humans – including microbes from the *Staphylococcus* genus (Svoboda 2021). Yet for the

Figure 1. An aerial view of the Sisters' Islands in Singapore. The Sisters' Islands are two islands separated by narrow but deep channels. They are part of the Sisters' Islands Marine Park, the country's first and only marine park. Photo: National Parks Board

coral, its microbiome is also part of its defence against external threats, including potentially harmful bacteria (Shnit-Orland 2009, Peixoto et al. 2017) and dangers that are more pernicious, like the rising sea surface temperatures brought about by climate change.

In the human world, some relationships fall apart at the first sign of trouble. Yet, for other couples, each helps the other through tough times, enabling them both to thrive. So too in the coral world these fortuitous couplings exist, with specific pairings between coral and microbiome conferring the organism with more resilience against heat stress (Doering et al. 2021). "Depending on the association between the coral and its microbes, the coral can be more resilient to stress," said Dr Huang, who also leads the Reef Ecology Laboratory at the NUS department of biological sciences.

Dr Huang wants to find out what these pairings are. Under a research grant he received under the Marine Climate Change Science Programme, launched in 2021 by Singapore's National Parks Board (NParks) (see Fig.1), Dr Huang and his team will play matchmaker, looking for the best matches between the coral animal and its microbes, which allow the holobiont (the combination of coral plus microbiome) to survive in an ocean set to boil (IPCC 2023). Dr Huang's research joins a body of other research projects starting up in Singapore that aim to look at how coral reefs can withstand the impacts of climate change. Indeed, even the name of the programme his research is funded under provides a clue – the previous iteration of the Marine Climate Change Science programme had been known as the Marine Science Research and Development Programme. This focus on climate resilience marks a new chapter in the story of Singapore's coral reef science journey, which previously had a large focus on how reefs can bounce back after loss or degradation due to coastal development.

"This change is something that is reflected globally as well," mused Dr Jani Tanzil, the facility director at Singapore's St John's Island National Marine Laboratory, citing conversations she had with other coral reef researchers around the world at conferences, including the recent Asia Pacific Coral Reef Symposium held in Singapore in June 2023. "Coral reefs are still facing many local threats, like coastal development, urbanisation and sedimentation. But now they also have to deal with climate change."

Climate change, caused by an ever-thickening blanket of greenhouse gases in the atmosphere, is a global problem. Countries will gather in Dubai from November 30 to December 12 for COP28, the United Nations climate change conference that aims to galvanise climate action and call on nations to taper down the use of fossil fuels to limit global warming. But it may take some time yet for global politics – and national policies – to catch up with what the science clearly points to. In the interim, research efforts that look into increasing the resilience of Singapore's remaining coral reefs, which are clinging on despite the odds, will be paramount if they are to have a fighting chance of survival in a planet on fire.

Figure 2. Corals growing along Singapore's urbanised East Coast. Photo: Jonathan Tan

A Story of Loss and Hope

The history of Singapore's coral reefs could be, depending on how you look at it, a tragedy or a glimmer of hope. Over 60 percent of coral reefs in the city-state have been lost over the years. Due to the reclamation and coastal development works undertaken in the country's budding phase, many reefs were buried, with the remaining ones made "more compact and shallow due to chronic sedimentation and unstable bottom rubble that is easily moved about by currents" (Ng et al.2013). Yet, despite the losses, life persists in the nation's turbid waters (Fig. 2).

National University of Singapore Emeritus Professor Chou Loke Ming, a pioneer in Singapore's marine science and conservation community, saw first-hand the impact of the country's early coastal works. "In the 1960s, the water was clear. Standing on the boat, you could look down and see corals all the way down the reef slope, to depths of 10m or more. I was so taken by their beauty," he recalled. Today, coral life is now mainly found in shallower waters, at depths not exceeding 5 metres.

As a young professor in the university in the 1970s, Prof Chou saw that coastal reclamation work was not the only threat confronting the fledgling nation's reefs. "Coastal development was in full swing, and the live aquarium trade was also thriving," he said. A zoologist who began his career studying house lizards, Prof Chou recalled the days he spent observing the small reptiles by Clifford Pier, a former landing port in Singapore which is now an esplanade full of bars and restaurants. The scurrying reptiles were not the only things he saw; he also observed people bringing in corals to shore "by the boatload". "It was such a loss. I watched the splendour of the reef decline, watched it go. It was such a pity," he remembered.

In 1977, Prof Chou started the Reef Ecology Laboratory at NUS, and studied various types of reef life from tropical fish to nudibranchs. In 1989, the lab also started testing the feasibility of deploying man-made structures - including hollow concrete cubes and tyre-pyramid modules - to improve fish stocks. These were installed at a depth of 15m, and showed a "significant increase in fish abundance and species richness" (Low et al. 1999).

The lab also conducted reef surveys, with Prof Chou and his colleagues recording species diversity and abundance at various sites. But back then, there was no standardised survey method, making it hard to compare results across sites in Singapore or even the rest of the region, he said. In the late 1980s, Prof Chou was among the marine biologists from Southeast Asia who took part in the ASEAN-Australia Coastal Living Resources Project. That effort resulted in the development of standardised sampling protocols to "promote national and international cooperation, comparative studies of ecosystems and a support base for the more inexperienced students beginning work in this field" (Australian Institute of Marine Science 1997). For Singapore, it also resulted in a useful database of information on Singapore's coastal resources, including mangroves, coral reefs, and soft-bottom benthic communities (Chou 1991).

These developments laid the groundwork for the next phase of marine research efforts in the country: How to bring a dying seafloor back to life.

Healing a Reef

In Singapore, mitigation measures usually involve the relocation of entire coral colonies away from sites due to be filled in to locations where they can, hopefully, attach and grow.

One of the earliest recorded relocation efforts was in the early 1990s, when a local environmental group, the Nature Society (Singapore), called on over 400 volunteers to help move coral colonies and reef invertebrates from sites in the southern part of the country due to be reclaimed to the nearby Sentosa Island. Barely 10 per cent of the translocated corals survived due to various factors, including an inappropriate choice of recipient site - the area was often subjected to surge and heavy sedimentation - and improper methods in securing fragments to substrate that caused the smaller corals to be washed away easily (Ng et al. 2013). That episode, however, had a silver lining in that it led to improvements in coral relocation techniques and subsequent mitigation projects (Ng et al. 2013).

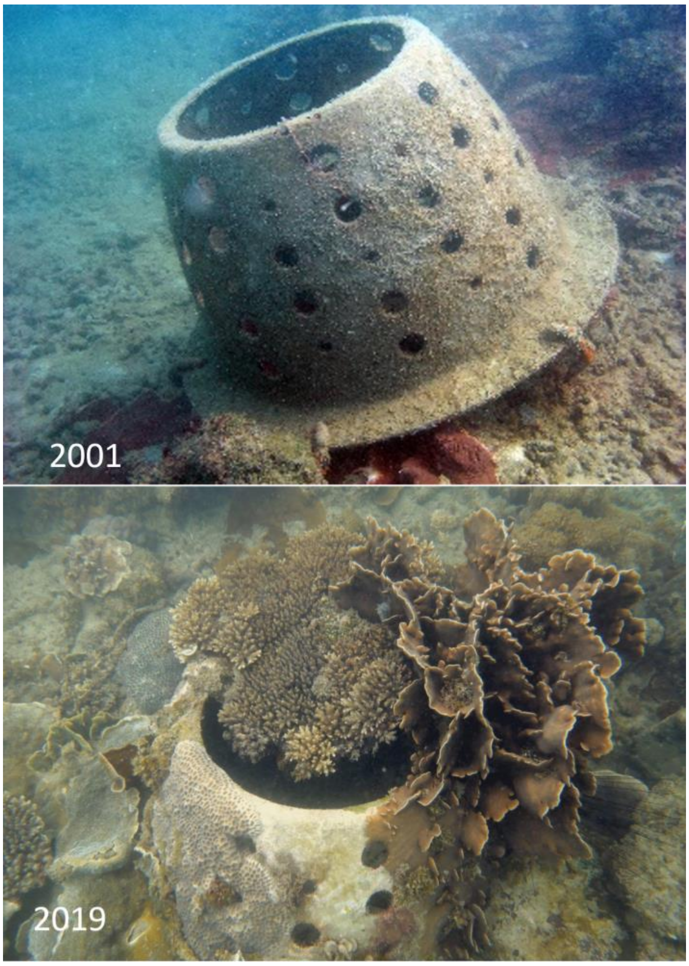

Figure 3. The REU deployed in Singapore under the NUS-STB project, pictured in 2001, when it was first deployed, and in 2019. Photo: Reef Ecology Laboratory

In the early 2000s, there was a global shift toward taking a "gardening approach" (Mbije et al. 2010) for reef restoration, said Dr Tanzil, the facility director of Singapore's St John's Island National Marine Laboratory. Inspired by the forest restoration efforts on land, the global coral community reasoned that a two-step protocol – "gardening" small colonies in nurseries and then transplanting them to damaged areas – could improve the chances of rejuvenating a reef. In Singapore too the movement took off, with coral research coalescing around two parallel approaches: The development of artificial reefs for reef restoration, and the use of coral nurseries.

Dr Tanzil, also a senior research fellow at the NUS Tropical Marine Science Institute, started her career as a research assistant in Prof Chou's Reef Ecology Laboratory in 2004. By that time, she had been volunteering for the lab for two years and had been trained in various reef survey methodologies. One of her first projects was to monitor coral recruitment on the reef enhancement units (REU) deployed in Singapore's southern islands under a collaboration between NUS and the Singapore Tourism Board (STB) (Fig. 3). That effort, which began in 2001 – about a decade after Prof Chou's lab first deployed concrete modules and tyre pyramids in Singapore – had a different focus. Instead of acting as fish aggregation devices, the REUs were being tested for their ability to encourage natural coral recruitment at the "bald" spots in a degraded reef to promote coastal tourism (Ng et al. 2013), such as through leisure boating and snorkelling.

The earlier experiments with concrete modules and tyres found that the deployment of such structures required the use of barges. But due to the turbidity in Singapore's waters, structures to enhance coral growth had to be deployed in shallow areas where there is higher light penetration. The use of barges in such shallow waters is risky as it could damage the marine environment as the vessel runs the risk of running aground.

Fibreglass structures were used under the NUS-STB project instead, as they were light enough for scuba divers to install and still provided a sturdy surface for corals to grow on. The REUs were deployed 3m underwater on various reefs. Coral recruits – defined as corals less than 5cm in diameter – were detected on the REUs within the first year, recalled Dr Tanzil. The researchers also found that the recruitment rates on the REUs were higher compared to those on adjacent rubble areas, likely because the REUs provided a stable structure and were regularly maintained, with algae and sediment removed, she said.

Prof Chou said that that project had focused on the natural recruitment of corals, although fragments were attached to the REUs if researchers came across them on the seafloor. Dr Tanzil mused: “At that point, we had no nursery, we just took corals of opportunity - what we called broken coral fragments on the seafloor - and attached it to the artificial reef frame using epoxy.” But this was soon set to change.

By the mid-2000s, the coral gardening concept in Singapore was picking up steam. The first coral nurseries were established in the nation’s southern waters to test if in-situ nurseries would be successful given the turbid conditions. That study showed that such nurseries were useful in providing coral nubbins (small fragments taken from adult corals) with a stable substrate to grow on, although survival rates were low at about 30 per cent (Bongiorni et al 2011). Around that period, NUS was also involved in a project funded by the European Union to restore denuded reef areas in Indo-Pacific countries, including Singapore, Philippines and Thailand, using the gardening approach. The project aimed to establish underwater coral nurseries adapted to different Indo-Pacific areas, before outplanting the nursery-grown colonies onto degraded reefs (European Union 2014).

Context in coral restoration is of the utmost importance, said Dr Karenne Tun, another protégé of the Reef Ecology Lab under Prof Chou. She first worked as a research assistant at the lab in the late 1980s, and was involved in the surveys of corals, mangroves and the soft-bottom benthic communities under the ASEAN-Australia initiative. She later moved to Penang, Malaysia, for three years when she took on the role as regional coordinator for East Asia for the Global Coral Reef Monitoring Network, before returning to Singapore in 2007 to pursue a PhD at NUS while concurrently working as a marine biologist at environmental consultancy Danish Hydraulic Institute (DHI).

Now the director of the terrestrial, coastal and marine branches at NParks’ National Biodiversity Centre, Dr Tun said coral restoration techniques must be tailored to local contexts. For example, in countries where the waters are clearer, coral fragments can be transplanted directly onto degraded reefs and thrive. In Singapore, the chances of this being successful was lower due to the rubbly nature of the seafloor that made it difficult for the juvenile corals to gain a foothold. The size that coral fragments should grow to before transplantation is also different in Singapore, she said. “In other countries, nubbins about 1 or 2cm long can be transplanted and survive. But we found that in Singapore, fragments that grow to at least 10 cm long stand a better chance of survival,”.

Eventually, the research paid off, with higher coral survival rates in subsequent translocation exercises. In 2013, the Maritime and Port Authority of Singapore (MPA) funded a project to move corals from the Sultan Shoal, southwest of Singapore, to protect them from the impact of the Tuas Terminal development. Larger coral fragments were transplanted directly to the three recipient sites off Singapore’s southern coasts, while smaller ones were moved to nurseries. Over 80 per cent of corals survived the move (Lim, 2015) – a marked improvement from the low survival rates from the effort in the early 1990s.

Waves of Change

As the knowledge base of coral restoration science in Singapore accreted, concerted efforts to protect the nation’s marine biodiversity also began to take shape. Coral reef scientists in Singapore are continuing to push the frontiers of coral reef science and restoration, from growing corals on plastic toy blocks to maximise yield (Fig 4), to translocating nubbins to deeper, light-limited waters where almost all corals have vanished.

At the same time, what was once an endeavour among academics, gradually expanded to become more inclusive, involving government agencies, the private sector and civil society. “Blue plans”, developed by marine conservationists, scientists, and volunteers, were published in 2001 (Lai 2018) and 2009 (Singapore Blue Plan 2009), calling on the

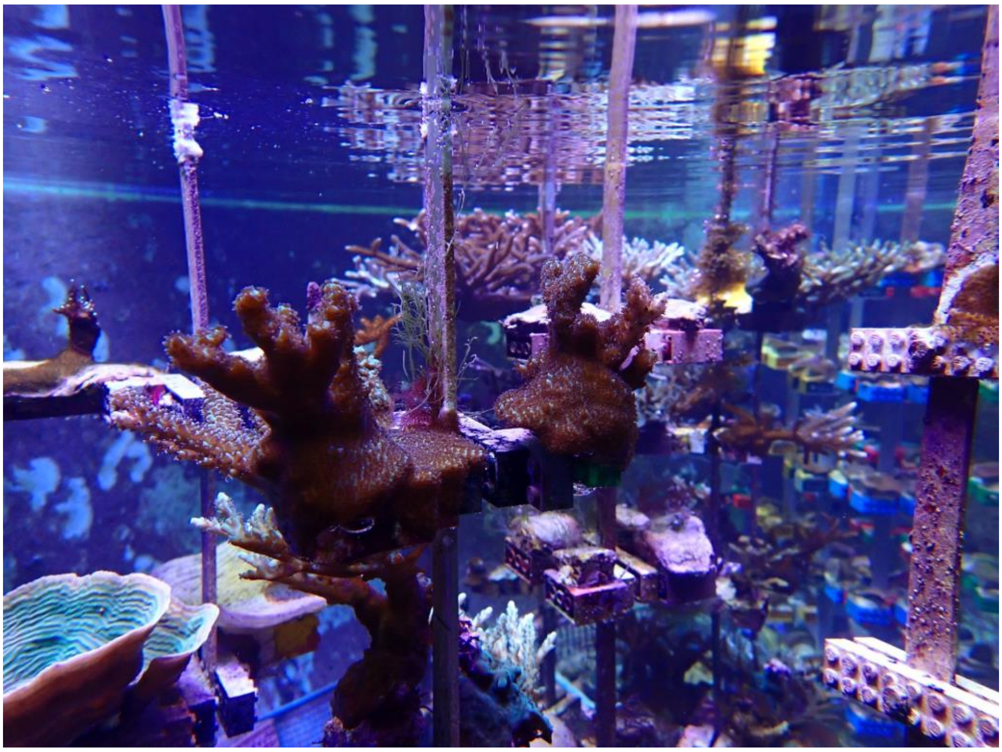

Figure 4. Coral nubbins growing on plastic toy blocks in Singapore. Photo: Lionel Ng

consultant to consultant. Previously, there was no locally standardised methodology in the EIA process for how such surveys should be conducted. Most recently in June 2023, NParks announced its most ambitious coral restoration plan to date: to grow small corals in nurseries and plant 100,000 of them over at least 10 years at degraded coral reef sites or sites that could potentially support coral habitats (NParks, 2023).

From the 1980s until today, there has been a sea change in Singapore's efforts to bring its dying reefs back to life. For Prof Chou (see Fig. 5), whose publications charts the progress of coral reef science in Singapore – from baseline mapping to artificial reef deployment and nursery development – the current research frontier looks at how these important habitats can be made more resilient in the face of climate change. This includes the work

Government to protect Singapore's marine treasures. In 2014, the country designated its first marine park – the Sisters' Islands Marine Park (NParks 2014) – which modelling that simulated coral larvae dispersal patterns had shown to be Singapore's "mother reef", seeding coral larvae to other marine habitats (Chang 2015).

A community group, Friends of the Marine Park, was also established to promote stewardship and responsible use of the area. The most recent edition of the blue plan - which outlines six recommendations, including improved laws to protect marine environments and formalised management systems for these areas – was published in 2018 (Lai 2018).

NParks also rolled out biodiversity impact assessment guidelines for marine areas in 2020 (NParks, 2020), helping to set minimum standards for such studies which had previously differed from

Figure 5. Emeritus Professor Chou Loke Ming pictured in his office in NUS in July 2023. Photo: Audrey Tan

that Dr Huang Danwei – another one of his protégés, to whom he handed the reins of the Reef Ecology Lab when he retired in 2014 – is doing on the coral microbiome, as well as other projects looking into green-grey coastal infrastructure to protect the country from sea-level rise.

In November 2022, Prof Chou was named an ASEAN Biodiversity hero for his pioneering work on coral reef restoration and management. The award recognises passionate individuals in ASEAN who have dedicated their lives to protecting diversity. Asked for his advice for the next generation of marine biologists, he said: "Don't give up. You may feel like you are alone, fighting the system. But you are not alone, there are many people out there with you. Not all of them are scientists, but they are also with you in advocating for marine conservation."

Having watched the decline of the country's reefs, Prof Chou is still optimistic for their future and believes in the potential for their resurrection. "When I first started in coral reef research, many people were talking about how coral reefs are fragile, break easily, and unable to handle large disturbances. But that's not the case for our reefs, and going forward, with new technology and new science, anything is possible."

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REEF RECRUITS

Towards understanding the impacts of marine heatwaves on coral gamete formation, reproduction and epigenetic inheritance

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Background

Phenotypic plasticity, or the ability for a single individual to produce a range of phenotypes in response to environmental conditions, can facilitate rapid beneficial acclimatization to assist in coral survival (Huey et al. 1999, Putnam and Gates 2015, Coles et al. 2018). Acclimatization can occur through the modulation of gene expression to create phenotypic or functional changes (Eirin-Lopez & Putnam 2019). Epigenetic modifications, defined as heritable changes to gene expression not involving changes to DNA sequences (Eirin-Lopez & Putnam 2019), can regulate gene expression, induce phenotypic change, and thus play a vital role in coral response to environmental change.

Studies in model organisms have consistently shown that environmental factors (i.e., stress, diet, pollutants, etc.) can elicit changes in organism reproduction and offspring phenotypes. This can occur through epigenetic modifications during gametogenesis (the sexual reproduction process where haploid gametes are created from diploid germ cells through meiosis with recombination) (Bourc'his et al. 2001, Skinner et al. 2019). Epigenetic inheritance is mediated through epigenetic alterations that can occur within the sperm or egg and are passed down to offspring (Lacal & Ventura 2018). Epigenetic modifications during gametogenesis can therefore change offspring phenotypes (Maamar et al. 2021). By investigating epigenetic modifications during gamete development and subsequent inheritance, we can further understand the consequences for reproductive capacity under ocean warming.

My research investigates the influence of marine heatwaves on coral gametogenesis by tracking the impacts of exposure to high temperature on physiology, maternal provisioning, epigenetic inheritance, and performance of offspring. Initial studies indicate that maternal provisioning (e.g., proteins, lipids, carotenoids, and fatty acids) contribute to the resilience of early coral embryos to stress (Strader et al. 2018, Van Etten et al. 2020), but these studies have primarily focused on mature gametes. Despite the critical importance of gametogenesis in facilitating epigenetic inheritance and offspring phenotypes, only a single study in corals has focused on molecular mechanisms (i.e. transcriptomics) underlying the process of gametogenesis (Chiu et al. 2020) and no studies have tracked epigenetic state across the full cycle of gametogenesis. This work will be a critical contribution for our capacity to understand the implications of marine heatwaves on parental effects and function of reefs of the future.

My research aims were to (1) determine the effects of marine heatwaves on gene expression and DNA methylation of *Acropora pulchra* throughout gametogenesis and early embryonic development; and (2) characterize the relationships between maternal provisioning and epigenetic inheritance that can lead to environmental memory in offspring resulting from parental thermal stress exposure. Pursuant to these aims, we tracked physiological, histological, and molecular characteristics in 40 *A. pulchra* colonies monthly for a year and exposed 24 *A. pulchra* colonies to a simulated marine heatwave with the intention of characterizing subsequent maternal provisioning, epigenetic state, and performance of offspring.

Methods and Study Site

All field and laboratory research took taken place at the University of California Berkeley Richard B. Gump Research Station (Gump station) in Mo'orea, French Polynesia, site of the National Science Foundation Mo'orea Coral Reef Long-term Ecological Research program. There in December

2021 we tagged 40 *Acropora pulchra* colonies on the North Shore backreef (Fig.1).

Tagged *A. pulchra* colonies were then sampled each month from December 2021 until spawning in October 2022 for molecular and physiological metrics. We deployed sensors to measure temperature and light intensity continuously. These data provide us with the environmental conditions these colonies were exposed to from the onset of gametogenesis until spawning. During each monthly sampling, we sampled one fragment (12-15 cm) for physiological metrics, histological processing, and sampled two biopsies (1-2 cm) from each fragment for molecular analyses. We then characterized physiological metrics including chlorophyll concentration, symbiont density, total protein, tissue biomass of the coral host and algal endosymbionts, surface area, and color score (i.e., bleaching index).

To test how maternal provisioning and epigenetic inheritance is affected by thermal stress, we split distinct genotypes of *A. pulchra* colonies (n = 12) found within our site into two halves and exposed the replicates to either an ambient or marine heatwave diel exposure (Fig. 2A) for four weeks. The experimental heat stress mimicked what *A. pulchra* colonies would naturally see in Mo'orea during warmer months. To determine an ecologically relevant marine heatwave scenario we analyzed historical temperature data from the Moorea Coral Reef Long-term Ecological Research database (Leichter et al. 2004) into the heatwaveR (v.0.4.6.9001) package in RStudio (v.2022.07.1) (Schlegel and Smit 2018). During the experimental period, we collected physiological (photosynthesis, dark respiration, chlorophyll concentration, symbiont density, host and symbiont tissue biomass, total protein, surface area, and color score (a proxy for bleaching)) and molecular samples at five distinct timepoints (initial, after acclimation period, after heatwave ramp period, after nine days of a heatwave, and after a six-day decline period). Following exposure, these colonies were sampled as above and returned to their original location on the reef to recover for ~ six months (from May until October) until spawning in October2022 (Fig. 2A).

After the recovery period, these coral colonies were brought back to the laboratory two weeks prior to the full moon in October (2022), which is the known spawning period for *A. pulchra*. During spawning, colonies were contained in static individual containers and checked for the release of bundles (i.e., containing sperm and egg, which breakdown, and release gametes into the water column) each night (Fig 2B). Once spawning was observed, bundles were collected. Coral eggs and sperm were then separated, and a portion of the sperm and eggs were collected for parental baselines of egg size, eggs per bundle, and for transcriptome and DNA methylation analysis. The gametes from individual crosses of spawning colonies within parental

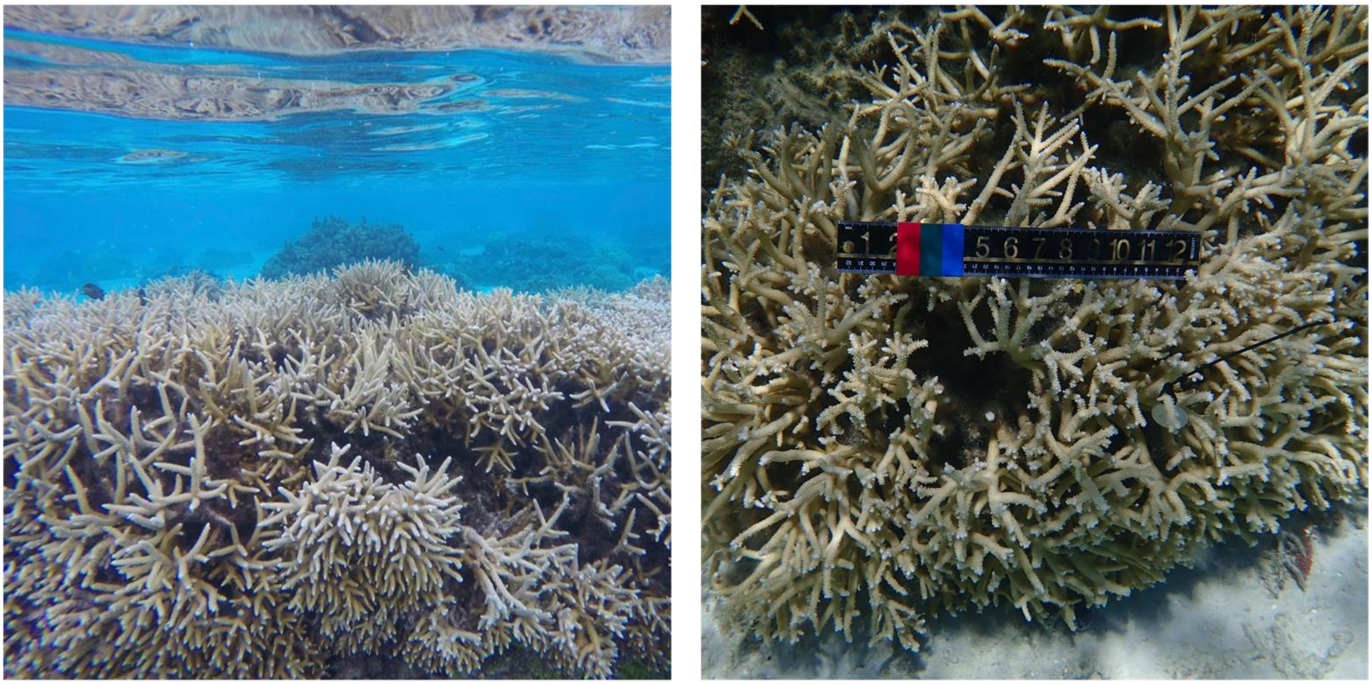

Figure 1. Patches of *Acropora pulchra* thickets on the North Shore backreef of Mo'orea, French Polynesia and a close-up tagged *A. pulchra* colony for timepoint sampling.

exposure treatment were reared into swimming larvae in flow-through conical tanks (Fig. 2B). To understand how larval metabolism is impacted by parental exposure treatment during a heat stress, we also measured respiration rates on swimming larvae (7 days post fertilization) of field collected wildtype, ambient, and heatwave exposed parental treatments.

Reared larvae from known parental exposure treatments were then subjected to a reciprocal thermal stress ramp experiment for fifty-two hours (Fig. 2C) to test how parental treatment influences offspring performance under subsequent stress. The thermal ramp was controlled by Neptune Systems® Apex temperature controller systems which increased the thermal ramp exposure from 26.8 °C to 32 °C over the first 12 hours, which was then held constant at 32 °C for the following 40 hours. To assess thermal performance of the larvae, individual larvae were counted every 6-8 hours for survivorship. Larval samples were taken at the beginning and end of the thermal stress to test for the same physiological and molecular parameters described above. Biopsies are currently being processed for analysis of gene expression (RNA-seq) and DNA methylation (Whole Genome Bisulfite Sequencing).

Research Undertaken

For Aim 1, we have characterized the physiological (bleaching index, chlorophyll content, symbiont density, surface area, host and holobiont total protein, and tissue biomass) and environmental (continuous light intensity and temperature) conditions at our site for the past year. Further, we have begun to process the histological samples to characterize gametogenic timing and reproductive state in our *Acropora pulchra* colonies during the entire gametogenic period. Physiological analysis reveals seasonal variation in symbiont metrics and biomass metrics. During the austral summer in Mo'orea, when rainfall is higher and more frequent and temperatures increase with the thermal maximas occurring in the April and May months, we see symbiont densities, chlorophyll-*a*, chlorophyll-c2 content, host protein, and holobiont protein are at their lowest during this seasonal period (data not shown). While during the austral winters in Moorea bring cooler temperatures and less rain, we see a peak in symbiont densities in August and a peak in chlorophyll-*a* during June. We also see peaks in host and holobiont protein and chlorophyll-c2 content in January, which is the beginning of austral summer in Moorea, characterized by large storms. Histological data indicates that oogenesis starts as early as December

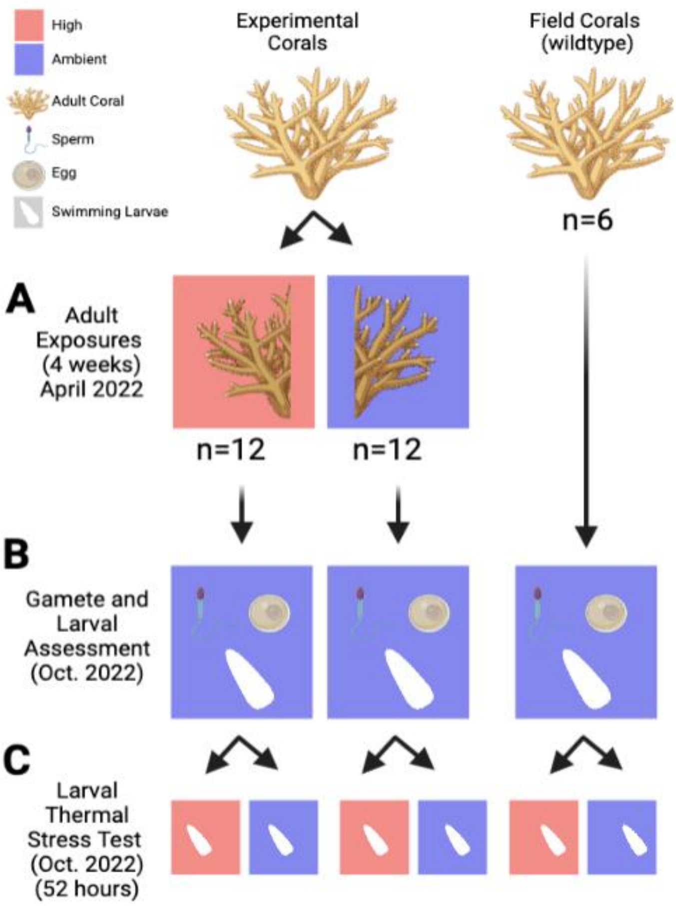

Figure 2. Experimental design for cross-generational epigenetic inheritance work A) Experimental heat wave exposure of the corals for 4 weeks from April 21 to May 21. Adults were these replaced to their collection reef and re-collected immediately prior to spawning in October 2022. B) Gamete and larval samples were collected for assessment. Swimming larvae were also exposed to a thermal stress test (52h) at ambient temperature or a ramp from 26.8˚C to 34˚C over 12 hours and held for 40 hours. Swimming larvae respiration rates were also compared at 27˚C and 30˚C seven days post release.

and spermatogenesis in *A. pulchra* follows ~five months later, with spermaries becoming visible in May, five months before release in October 2022 (data not shown).

For Aim 2, we have characterized physiological performance of *Acropora pulchra* coral fragments during our marine heatwave exposure. Over the course of the heatwave, the corals in the heated treatment showed declines in color and photosynthesis and respiration (Fig. 4), as well as in symbiont densities and chlorophyll content (data not included). This may have implications for corals maintaining metabolic homeostasis under a heatwave and consequences for their offspring. We then tested the parental baselines of egg size, eggs

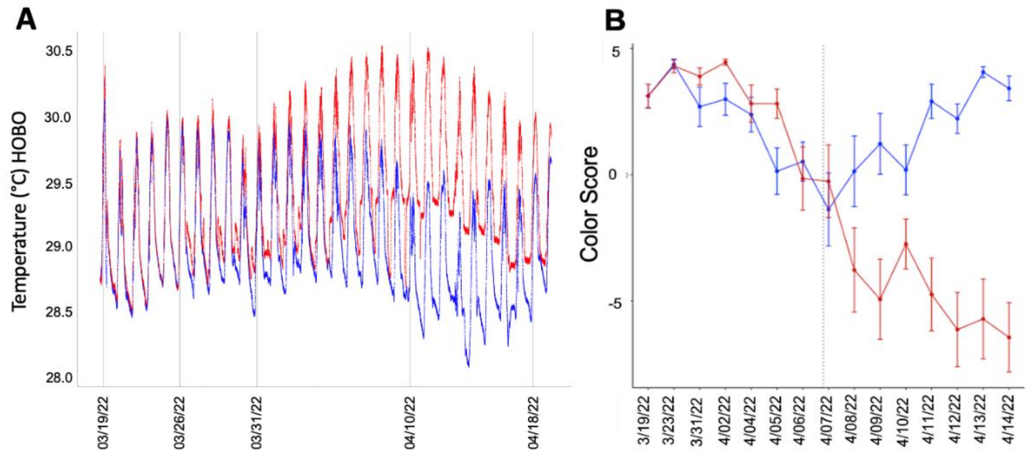

Figure 3. A) Schematic of daily mean of temperature treatments and sampling timepoints. B) Exposure of the *Acropora pulchra* fragments to the heatwave resulted in a substantial separation in color score, a photographic proxy for bleaching, by ~3 weeks of exposure.

per bundle, and fertilization success for each treatment group and collected samples for

transcriptome and DNA methylation analysis. We also measured respiration on live larvae and collected samples (n=3) for total protein, symbiont densities, DNA methylation, and transcriptome analysis. Gametes from the heatwave parental history had significantly larger egg size (p = 0.018) and higher percent fertilization success (p=0.020) than the offspring from the ambient parental history. There were no differences due to parental treatment between the stages of development when sampled 4 hpf (p>0.05). Adult coral colonies that have experienced the marine heatwave treatment did not have significantly higher respiration rates at 30°C compared to 27°C, however they had higher thermal performance in a reciprocal thermal stress event (data not shown).

We have analyzed data collected during the October 2022 spawning event. Thus far, we have found that offspring from parental colonies that had previously experienced a marine heatwave had significantly higher survivorship (20% greater) under thermal stress compared to offspring from ambient colonies and 25% higher survivorship compared to offspring from wildtype colonies. These results demonstrate that offspring of parents challenged by thermal stress exhibit enhanced fitness through parental provisioning of energetics or molecular regulation that can act as "environmental memory". As climate change continues to threaten reef persistence, it is critical that we understand mechanisms of cross-generational acclimatization, which will improve our capacity to forecast coral reef reproduction.

It is intended that our further research will improve our understanding of how marine heatwaves associated with climate change may influence coral acclimatization patterns across generations. Our data will: 1) provide a high frequency time series of physiological, histological, and molecular responses of corals during gametogenesis; 2) provide critical knowledge on epigenetic mechanisms of environmental memory; and 3) elucidate

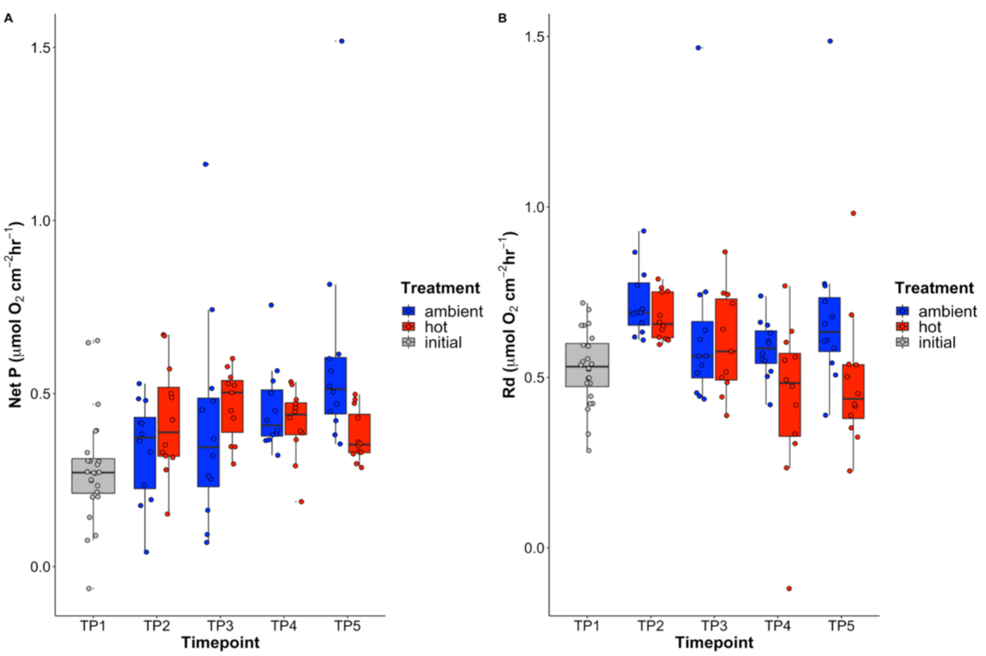

Figure 4. Boxplots representing mean (±SE) of A) net photosynthetic rates (μmol O_2 cm^{-2} h^{-1}) at each of the five timepoints (initial, after acclimation period, after heatwave ramp period, after nine days of a heatwave, and after a six-day decline period) which were initially enhanced as temperature increased, but the sustained heat wave exposure resulted in significantly reduced photosynthesis by the final time point. B) Similarly, dark respiration rates (μmol O_2 cm^{-2} h^{-1}) at each of the five timepoints were initially simulated but were significantly reduced by time point 5 relative to the rates at ambient temperature.

implications for offspring performance due to parental thermal history. It is anticipated that these results will be useful for both mechanistic understanding of reproduction, as well as for informing forecasts of the contributions of cross-generational acclimatization and offspring performance on reefs of the future.

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Examining the role of trophic plasticity in coral acclimatization

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Background

Rapid urbanization in coastal cities has significant consequences for the surrounding marine environment. Urban development is a direct threat to over 60% of the world's already vulnerable coral reefs (Burke et al. 2011). With more than 2.5 billion people living near reefs, corals are facing unprecedented pressure from human activities, including local stressors such as nutrient pollution and increased turbidity (Heery et al. 2018; Jones et al. 2020). Coastal runoff and dredging can directly cause elevated turbidity within the water column, increasing sedimentation on reefs and critically reducing light availability in coral ecosystems (reviewed in Rogers and Ramos-Scharron 2022). The influx of excess nutrients from agricultural and industrial waste and sewage drives eutrophication, causing harmful algal blooms, macroalgae overgrowth, and localized hypoxia (Nicholson et al. 2011). In particular, high levels of dissolved inorganic nitrogen (DIN) are known to reduce calcification and lower bleaching thresholds (Silbiger et al. 2018, Burkepile et al. 2020), and can cause symbiont proliferation within the holobiont, placing an energetic burden on the host and disrupting the symbiosis (Wooldridge 2010, Morris et al. 2019). With corals facing threats from a multitude of concurrent local and global stressors, there is a pressing need to better understand coral resistance and the factors that affect coral survival.

Nutrient acquisition is essential to coral health, and the ability to draw from various energetic sources may increase a coral's resistance to stressors (Conti-Jerpe et al. 2020). Corals are mixotrophic organisms that rely on autotrophic nutrition produced by their algal symbionts, but they are also heterotrophic and can actively feed from a wide range of food sources (reviewed in Houlbrèque and Ferrier-Pagès 2009). An emerging body of research suggests that a coral's trophic strategy is a fundamental mechanism for tolerance to environmental stressors. Certain species can supplement 100% of their metabolic needs through feeding when bleached (Grottoli et al. 2006), and corals have been shown to increase heterotrophy when exposed to conditions such as ocean acidification or light limitation (Anthony and Fabricius 2000, Edmunds 2011). This suggests that trophic plasticity, or the ability to use a range of nutritional sources by shifting between autotrophy and heterotrophy, may be a critical determinant of a species' capacity to resist specific chronic and acute disturbances (Seeman et al. 2012).

The capacity for nutritional flexibility is species-specific (Radice et al. 2019, Sturaro et al. 2021); however, comparisons across species are limited. The exact mechanisms that differentiate species reactions to stressors such as nutrient pollution or turbidity remain unclear, yet insight into these processes is necessary to predict how coral communities will shift under future pressures. Previous findings indicate that coral genera vary from low to high trophic plasticity, with certain genera shifting their trophic strategies in response to seasonal fluctuations in light and temperature while others remained fixed (Chei et al. *in prep*). This study expands on this work through examining trophic plasticity as an acclimatization mechanism to tolerate changes in water quality. Three coral genera were transplanted to sites of contrasting water quality, varying primarily in turbidity and inorganic nitrogen, with the aim of elucidating trophic responses to anthropogenic stressors, as well as investigating differences across genera.

Methods

Coral fragments of three genera (*Acropora, Porites,* and *Platygyra*) were collected in Hong Kong from Sharp Island (22°21'55.3"N 114°17'19.7"E). Using scuba, we identified 40 individual colonies of each genus for sampling to ensure sufficient replication, accounting for possible mortality. Six fragments (~5cm^2) were broken off from each parent colony using a hammer and chisel, and all fragments were placed into individual bags. On the surface, fragments were divided into six bins and attached to PVC and plastic mesh nurseries (Fig. 2) with zip ties. The nurseries were returned to Sharp Island where they remained for an acclimation period of seven days.

Nurseries were deployed at six sites differing in water quality, as determined from DIN, turbidity, and chlorophyll *a* data provided by the Hong Kong Environmental Protection Department (EPD; https://cd.epic.epd.gov.hk/) (Fig. 1). Bluff Island (22°19'27.4"N 114°21'13.5"E), Ninepins (22°15'30.8"N 114°21'0.3"E), and Pak Pai (22°18'12.3"N 114°18'34.2"E) represented low impact sites (LIS), and Lo Chau (22°12'27.2"N 114°13'18.6"E), Deepwater Bay (22°14'25.9"N 114°10'43.3"E), and Sham Wan (22°11'21.1"N 114°8'9.7"E) represented high impact sites (HIS). 40 fragments of each coral genus were deployed at every site at the beginning of Hong Kong's wet season (May) to account for the effects of seasonality. The frames were placed at reef-level (3-5m) in areas adjacent to coral communities. Rebar was used to secure the nurseries and elevate them from the seafloor to reduce the likelihood of sediment accumulation. (Fig. 2). After six months, the fragments were retrieved, rinsed thoroughly with deionized water, and transported to the laboratory on ice where they were frozen at -20°C until further processing.

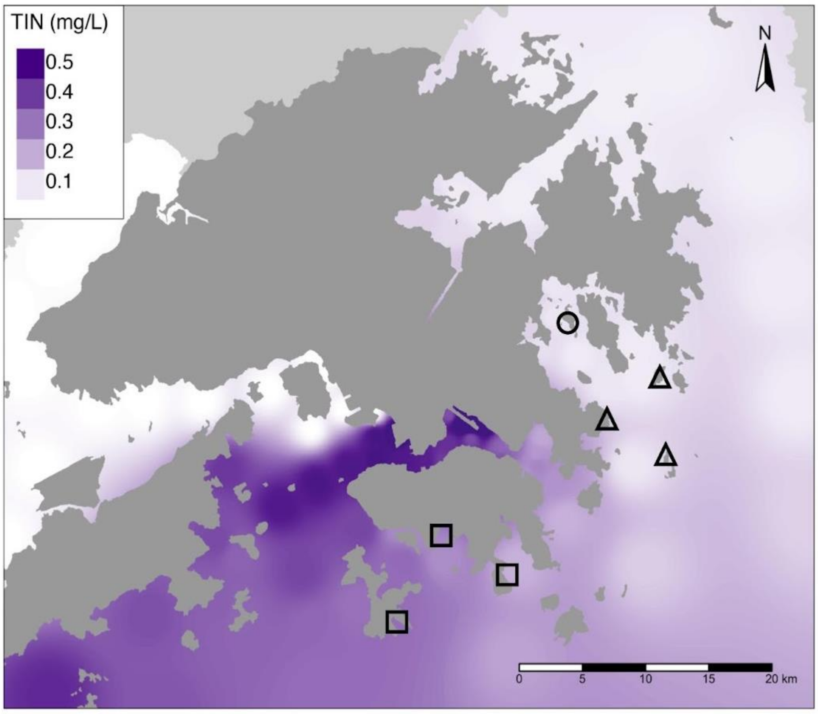

Figure 1. Interpolated map of average total inorganic nitrogen (TIN) values in Hong Kong from 2010 to 2020. Western data were excluded as they exceed the range of coral distribution. The shapes indicate study sites: the circle represents the collection site, triangles represent low impact sites (LIS), and squares represent high impact sites (HIS). All data are provided by the Hong Kong Environmental Protection Department (EPD).

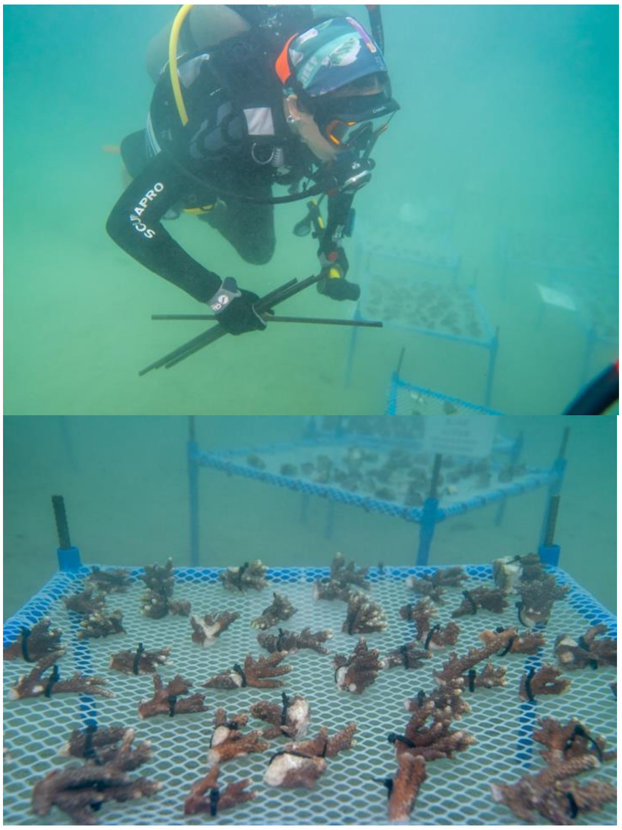

Figure 2. Above: Emily Chei securing coral reef nurseries during the sampling acclimation period. Belowt: PVC nursery with attached *Acropora* fragments at the beginning of deployment. Images courtesy of Alexander Reshikov.

About 30 samples of each genus from each site for each genus and site were processed to ensure sufficient replication for statistical analyses (Syveranta et al. 2013). For each sample, coral tissue was defrosted and removed from the skeleton using a pressurized airbrush (Single Action Internal Mix Airbrush, Paasche, Kenosha, WI, USA) containing deionized water, and the resulting slurry was homogenized for 30 seconds using a Tissue-Tearor (Model 985370, BioSpec Products, Inc., Bartlesville, OK, USA). For ten samples from each genus and site, two 0.5mL aliquots of homogenate were taken for symbiont counts and chlorophyll assays. The remaining homogenate was separated into host and symbiont fractions via centrifugation and freeze dried overnight (Kim et al. 2021). All samples were combusted and analyzed for carbon and nitrogen stable isotopes at the University of Hong Kong's Stable Isotope Laboratory using an elemental analyzer (Eurovector EA3028, Pavia, Italy) coupled with a stable isotope ratio mass spectrometer (Nu Instruments Perspective, Wrexham, UK) (Conti-Jerpe et al. 2020).

A Bayesian statistical model [Stable Isotope Bayesian Ellipses in R (SIBER)] was applied to all stable isotope data (Jackson et al. 2011). Ellipses were fitted to plotted $\delta^{13}C$ and $\delta^{15}N$ values of paired hosts and symbionts, and Bayesian estimates for standard ellipse area (encompassing 40% of the data; SEA_B) and major ellipse area (encompassing 95% of the data; MEA_B) were measured to estimate isotopic niche area (a proxy for trophic niche). For each site, the amount of overlap between host and symbiont ellipses (Conti-Jerpe et al. 2020) and distance between ellipse means (centroid distance) (Turner et al. 2010) were used to assess the amount of resource sharing within the symbiosis. A novel index, Host Evaluation: Reliance on Symbionts (HERS) (Guibert and Conti-Jerpe et al. *in prep)* was used as a quantifier of trophic strategy combining SIBER overlap metrics into a single numerical score, and the magnitude of trophic plasticity was calculated by taking the absolute value of the difference between low impact sites (LIS) and high impact sites (HIS) for each genus.

Preliminary Results and Discussion

Comparing the isotopic niches of corals from LIS and HIS revealed distinct differences, both across taxa and between sites. Overlap of standard ellipses was not observed for any genus or site, and only *Porites* and *Acropora* exhibited partial overlap of major ellipses (Fig. 3). HIS *Acropora* had the greatest overall ellipse overlap and lowest centroid distance, suggesting that these corals had the greatest amount of resource sharing between host and symbiont and were the most autotrophic. Lower ellipse overlap for LIS *Acropora* may be a result of thermal stress at these sites, as slight bleaching of *Acropora* was noted at Bluff Island during the transplantation period. Temperatures during the wet season can reach upwards of 30ºC, well outside of the temperature range for optimal performance (McIlroy et al. 2019). At LIS, heat stress may have contributed to a shift toward heterotrophy for *Acropora,* whereas higher turbidity at HIS could have had a shading effect that reduced the impact of temperature during the wet season (Cacciapaglia and van Woesik 2015).

Conversely, *Porites* had greater centroid distance and lower ellipse overlap, and thus more separation of host and symbiont ellipses, at HIS than LIS. *Platygyra* also had greater centroid distance at HIS sites, although it did not exhibit any overlap of host and symbiont niches. Separation of host and symbiont niches at HIS signals greater host reliance on heterotrophic nutrition (Conti-Jerpe et al. 2020) for both *Porites* and *Platygyra*. Additionally, host ellipse area was greater at HIS compared to LIS. Because carbon and nitrogen stable isotopes are representative of an organism's nutritional resources, larger isotopic niches indicate greater variation between individuals within a population and a wider use of resources than smaller niches (Sturaro et al. 2021). These results may reflect increased *Porites* and *Platygyra* heterotrophy at these sites, either due to availability of resources given higher turbidity and chlorophyll-a or because of an effect of trophic plasticity aiding acclimatization to poorer water quality at HIS.

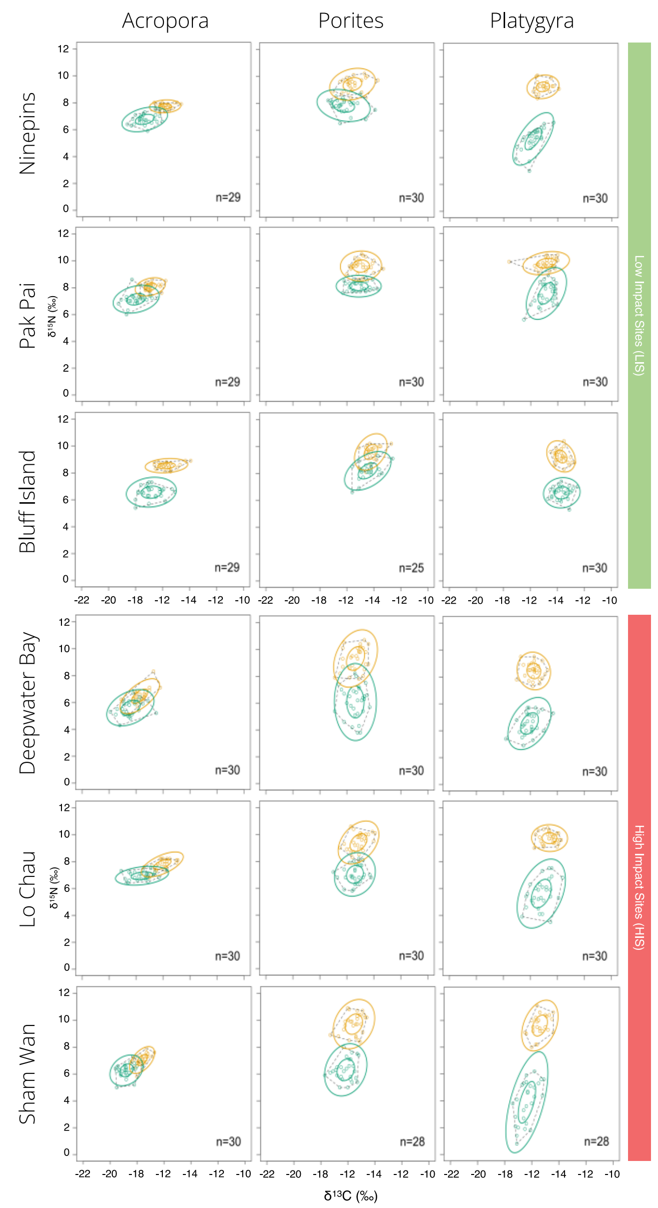

Figure 3. SIBER analyses of paired host (yellow) and symbiont (green) $\delta^{13}C$ and $\delta^{15}N$ stable isotope values for each genus and site. Dots represent individual samples, and ellipses encompass 40% (SEA_B; inner ellipse) and 95% (MEA_B; outer ellipse) of the data.

Trophic strategy and trophic plasticity were notably different across genera, and variations were consistent with observations from previous studies (Conti-Jerpe et al. 2020, Chei et al. *in prep*). *Acropora* was the least heterotrophic genus as evidenced by the greatest ellipse overlap and smallest overall niche area of both host and symbiont, and coral hosts were the most nitrogen depleted across all sites with mean $\delta^{15}N$ values of 7.5±0.7‰ (Fig. 3). *Porites* and *Platygyra* showed greater trophic fractionation and had consistently higher $\delta^{15}N$ mean host values of 9.5±0.6‰ and 9.3±0.6‰, respectively, suggesting that these genera are more heterotrophic than *Acropora*, particularly *Platygyra* with no ellipse overlap observed at any site and the greatest overall centroid distances. When comparing trophic strategies between LIS and HIS, *Acropora* had the largest magnitude of plasticity, followed by *Porites* then *Platygyra* with the lowest magnitude of plasticity. These findings suggest that trophic plasticity varies between genera, and certain corals may adjust their trophic strategy to acclimate in differing environments while others do not.

Concluding Remarks

Results provide further evidence for the importance of heterotrophy in corals and demonstrate that environmental conditions influence trophic strategy. Additionally, clear distinctions across coral genera emphasize the need for multi-species comparisons of trophic plasticity. Data analyses are ongoing with the aim of identifying specific water quality or climatic factors that may explain differences between each site and genus, and symbiont density and chlorophyll-a data will be collected to assess any physiological changes. This study will provide a new perspective for discussing reef susceptibility near urban centers, and it may be valuable for informing restoration efforts at impacted sites. Future work will include using compound specific stable isotope analysis to identify specific nutritional pathways and further elucidate the mechanisms of trophic plasticity.

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Hidden diversity of soft corals on Mozambique coral reefs

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Background

Research on the ecological status of coral reefs points to the continuing degradation of these ecosystems (Fine et al. 2019, Obura et al. 2022). Recent studies by Obura et al. (2022), combining indicators of change in historical ecosystem extent, ecosystem functioning, and projected sea temperature warming, have shown that Western Indian Ocean (WIO) coral reefs are vulnerable to collapse at a regional level. The study predicts that reef systems extending from the Seychelles to the Delagoa region off the coast of Mozambique and South Africa are at risk of becoming functionally extinct by 2070, causing a huge loss of biodiversity and threatening the livelihoods and food sources of hundreds of thousands of people. The ecology and distribution of coral reefs in the WIO are well known, however, the precise area of reef habitat has not yet been accurately determined. Moreover, the coral fauna of some regions is much better known than in others (Sola 2019); further, some groups are more heavily studied than others, soft corals, for example, being often forgotten (Coll et al. 1995, Lasker 2003, Gabay et al. 2012, Ateweberhan et al. 2013, Pupier et al. 2018).

Previous taxonomic inventories of Indo-Pacific soft corals include those of the South Red Sea, South Africa, Taiwan, Southern Japan, Guam, Hong Kong, the Great Barrier Reef and other parts of Australia, Hansa Bay in North New Guinea, New Caledonia and the Mariana Islands (Fabricius et al. 2007). However, there are still significant gaps in our understanding of the distribution ranges of soft

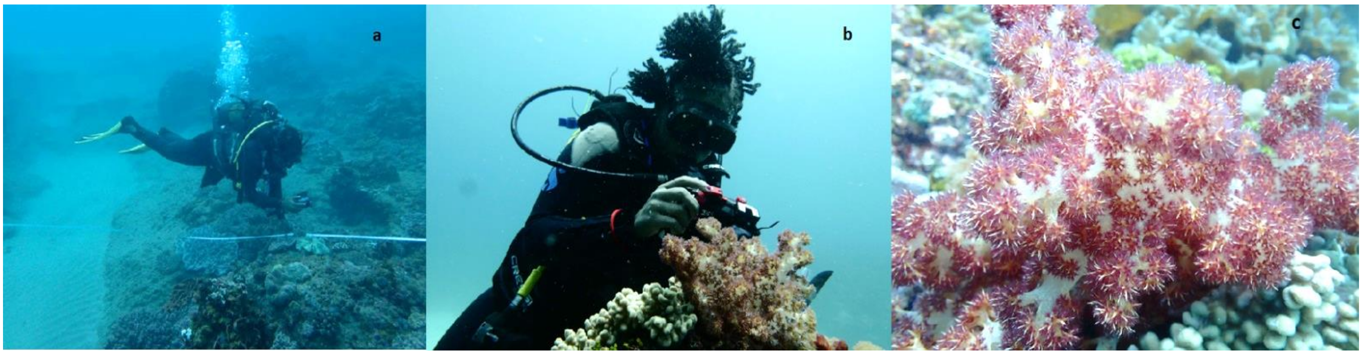


Figure 1. a) Fieldwork at Ponta de Ouro, b) Photographing soft coral *Dendronephthya cf. mutabilis*, c) Close-up of soft coral *Dendronephthya cf. mutabilis*

corals, and their taxonomy remains controversial and mostly unexplored at a global level. Many previous inventories focused on subsets of families or octocoral growth forms (McFadden et al. 2006; Fabricius et al. 2007, Etsebeth 2018). Furthermore, often taxonomic revisions of known species cannot be made due to the poor state of the literature. Instead, detailed revisions exist only for significant genera, including *Sinularia*, *Sarcophyton*, and *Lobophytum* (Dautova 2011). In recent decades molecular approaches have revealed that the taxonomy of much of the tree of life is in crisis. The result has been significant revisions at all taxonomic levels in many coral groups (Huang et al. 2014). Nevertheless, progress has been slow in some of the most ecologically significant and species-rich groups due to the lack of molecular markers that provide resolution at the species level (Etsebeth 2018). For scleractinian corals, taxonomy has been successful in reconstructing accurate phylogenies. However, for soft corals, many of the morphological characters traditionally used for classification in these taxa have now been shown to be discordant with molecular phylogenetic evidence. Furthermore, the lack of accurate estimates of soft coral biodiversity makes it difficult or almost impossible to assess or manage their biodiversity effectively (McFadden et al. 2009, Etsebeth 2018). My project aimed to investigate the biodiversity and distribution of soft corals in Mozambique, to contribute to the development of appropriate management and conservation policies.

Study area

The study was carried out along the Mozambique coastline, comprising the three biogeographic regions, North, Center, and South. The reefs in Mozambique are characterized by their large extent, high biodiversity, and aesthetic appeal (Pereira 2000); they consist of fossilized dunes and rocky beaches colonized by coral to varying degrees. The surveys were carried out on reefs at Vamizi Island, Pemba, Mossuril, Memba, Nuaro, and Mozambique Island (northern region), Ilhas Primeiras e Segundas (central/north region), and the Bazaruto Archipelago and Ponta de Ouro (South region).

Methods

Octocoral samples were collected using SCUBA or snorkel from at least three stations at each of a total of nine reefs across the north, center, and south of Mozambique. Octocoral relative abundance was estimated visually as rare, occasional, common, or abundant (see Fig.1). The colonies were photographed underwater before sampling, and following collection fixed in 70% ethanol and stored at room temperature for morphological investigation. Tissue subsamples (1cm^3) were excised from the lobe region of each sample using a sterile scalpel, placed directly into cryofuge tubes with 96% ethanol, and stored at -80°C.

Morphological Characters

Soft corals were classified according to their morphological features and the form of their sclerites (Fabricius & Alderslade 2001). For the investigation of sclerites, small (less than 1mm^2) tissue samples were removed from the surface and interior of the polyp, and the surface and interior of the stalk (or base) of the colony and dissolved in 10% NaClO. After 10 minutes, the supernatant and organic debris were discarded and the sclerites were carefully and gently rinsed 4–5 times in distilled water to remove excess bleach and debris and viewed under a microscope (Fabricius & Alderslade 2001, McFadden et al. 2006, Aharonovich & Benayahu 2011, McFadden et al. 2014) (see Fig. 2).

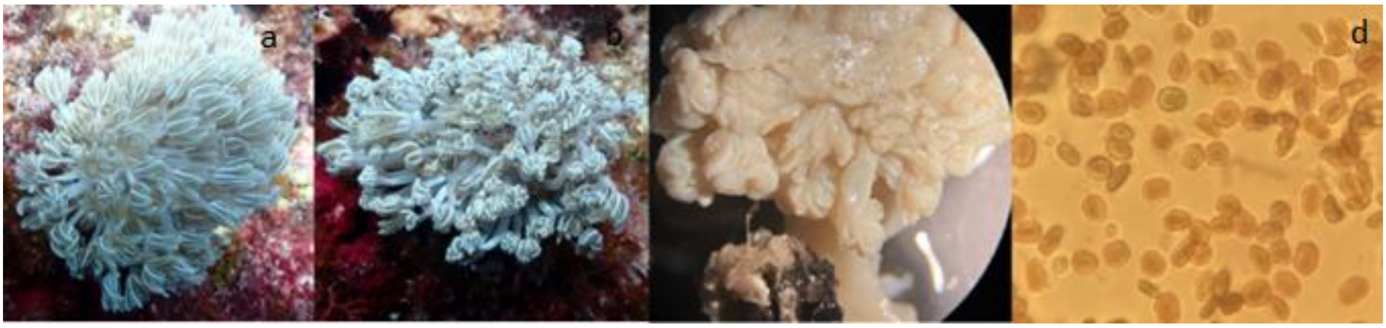
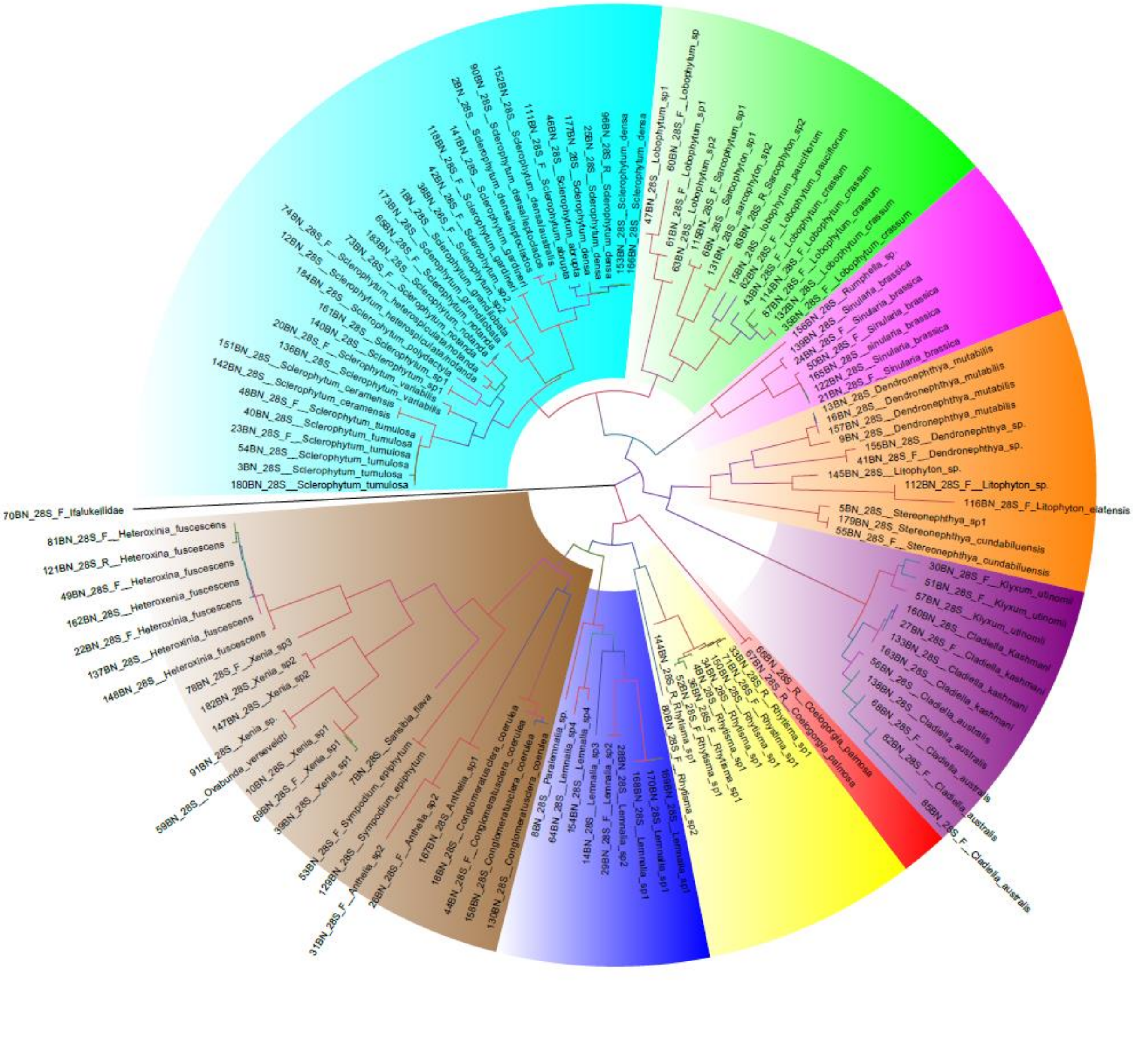


Figure 2. a and b) *Heteroxenia fuscescens* in situ, b) with the polyps contracted, c) *Heteroxenia fuscescens* preserved sample, d) *Heteroxenia fuscescens* sclerites.

DNA Extraction

DNA was extracted from tissue samples using the Qiagen DNeasy® kit, according to the animal tissue protocol and the manufacturer, modified and optimized for the genomic DNA extraction from the soft coral group. Approximately 2 mg of tissue was cut from a polyp of each sample with sterilized scissors and dried on sterile paper. We amplified the octocoral DNA using primers 28S-F and 28S-R (McFadden et al. 2009). Pairwise measures of genetic distance among sequences were computed using MEGA v.5 and a neighbor-joining tree was constructed to visualize relationships (McFadden et al. 2006).

Figure 3. Phylogenetic relationships of the soft coral species collected in Mozambique based on their 28S sequences. Numbers on main branches show percentages of bootstrap values (> 50%) in maximum likelihood analysis.



Summary Results

A total of 184 soft coral specimens were collected, and identified to the species level, through morphological characterization and the use of molecular markers (28S) to infer phylogenetic relationships. The preliminary results indicate the presence of 57 species of soft coral distributed among 23 genera, including 24 unidentified species from 12 separate genera (*Sclerophytum*, *Lobophytum*, *Sarcophyton*, *Litophyton*, *Stereonephthya*, *Dendronephthya*, *Rhytisma*, *Xenia*, *Lemnalia*, *Paralemnalia*, *Anthelia*, *Ifalukella*) (see Fig. 3). *Sclerophytum* was the group with the highest number of species, followed by *Lobophytum* and *Lemnalia*. *Xeniidae* was the family with the largest number of genera, including *Xenia*, *Heteroxenia*, *Sansibia*, *Conglomeratusclera*, *Anthelia*, *Sympodium*, and *Ovabunda*. Currently, we are analyzing all the samples using the mitochondrial marker (mtMutS) to combine them with the 28S marker for more precise taxonomic identification.

Concluding Remarks

This study provides an update of the national list of soft coral species found in Mozambique, with the addition of 11 genera and 10 species (still to be confirmed) compared to the study conducted by Benayahu et al. (2003) which listed a total of 53 species (in 12 genera) for the entire coast of Mozambique. New records are reported in Mozambique for the genera *Dendronephthya*, *Scleronephthya*, *Liptophyton*, *Sansibia*, *Coelogorgia*, *Klyxum*, and *Rumphella*. We did not encounter the genus *Briareum*, which was reported by Benayahu et al. (2003). However, there are still more samples to analyze.

Bibiana Nassongole

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The effects of ocean acidification on the chemosensory behavior of a common marine parasite

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Introduction

Chemical cues play critical roles in the dynamics of aquatic ecosystems, with nearly all organisms relying on chemical signals in at least some aspect of their life cycles (Hay 2009). These signals can be particularly important in aquatic ecosystems. In water visual signals can be disrupted by environmental factors such as turbidity and increasing absorption of light waves with depth (Brönmark & Hasson 2012). Acoustic signals, which can travel as far as chemical signals, are much shorter-lived and can get lost in complex aquatic soundscapes (Nummela & Thewissen 2008, Cox et al. 2018). Chemical signals can influence many fitness-related behaviors including food-, mate- and habitat-finding, as well as predator avoidance (Brönmark & Hassan 2012).

In recent decades ocean acidification has been occurring at an unprecedented rate. Ocean pH is projected to decline by 0.08 to 0.37pH units by the year 2100 (Cooley et al. 2022), with similar declines expected to affect freshwater ecosystems (Leduc et al. 2013). Invertebrates are particularly susceptible to such changes, ocean acidification having been shown to negatively impact the ability of aquatic invertebrates to detect and respond to chemical signals (Kroeker et al. 2014, Zupo et al. 2015, Roggatz et al. 2016). However, these negative effects are variable, with some types of organism suffering more severe effects than others.

Although chemical cues are important to all aquatic organisms, research into the chemosensory behavior of smaller organisms has been limited compared to that into larger, more charismatic forms. This discrepancy persists even though small organisms dominate biodiversity and biomass metrics in aquatic ecosystems and are critical to ecosystem function (Hudson et al. 2006, Knowlton et al. 2010). Numerous factors have led to this group remaining understudied. They are often difficult to collect, rear, and observe. Their small size has resulted in an assumed lack of influence or importance in aquatic ecosystems. Further, the majority of small organisms are parasitic (Hudson et al. 2006), though can be broadly divided into two categories (endo- and ectoparasites) based on their location on or within the host. Endoparasites, that attach to the inside of their host, are largely transmitted passively via consumption (Goater et al. 2014). Conversely, ectoparasites attached to the surface of their host must typically find at least one new host during their life cycle (Hopla et al. 1994).

On tropical coral reefs, among of the most common ectoparasites are gnathiid isopods, a family of isopod crustaceans which occur over a wide range of depths, from the littoral zone to the deep sea. They are temporary blood-feeding parasites of a wide variety of fish (Hendrick et al. 2023). They are unusual among aquatic parasites in that they are parasitic only during their three larval stages and must locate to a new host to feed during each of these stages (Smit & Davies 2004). *Gnathia marleyi* (Fig. 1), which occurs in the northeastern Caribbean is one of only a few gnathiid species to have any aspect of its chemosensory behavior investigated. Both field and laboratory studies have indicated that it is reliant on chemical cues when detecting and locating to a new host (Sikkel et al. 2011,

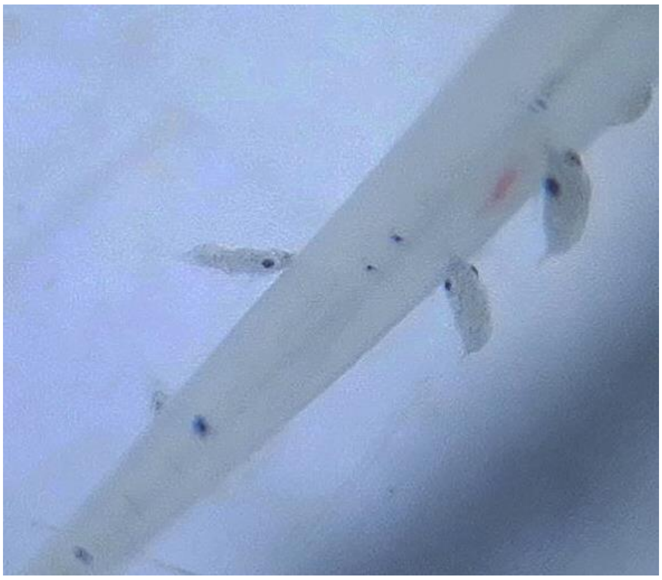

Figure 1. Juvenile *Gnathia marleyi* parasitizing a larval fish.

Vondriska et al. 2020). However, the experiments demonstrating this were undertaken under previous conditions of pH and using outdated instrumentation. Consequently, this present study was undertaken to determine whether increasing ocean acidification to the extent projected by Cooley et al. (2022) will affect the chemosensory host-finding ability of the species, and potentially of other parasitic gnathiids.

Research Undertaken

Gnathiid & Fish Collection. Work on the project was (and will continue to be) conducted at the Environmental Analysis Laboratory at the University of the Virgin Islands, St. Thomas, United States Virgin Islands. Gnathiids were collected from nearby John Brewers Bay using lighted plankton traps modified from those described in Artim & Sikkel (2016). These traps shine white light over an area of reef and are left over night when they attract a variety of zooplankton, including gnathiids. Fish were collected from the same location using modified cast nets.

Initial Behavioral Trials. For this project a novel aquatic olfactometer (Fig. 2) was implemented (see Vondriska & Sikkel (2023) for full description). Briefly, the new design allows an aquatic organism under study to move freely around an arena while at the same time being exposed to chemical cues from up to four separate sources. This olfactometer greatly improves on the forms of aquaria (i.e. channel flumes, Y-tubes) typically used in previous chemosensory research. In control trials, unconditioned (i.e. untreated) seawater was allowed to flow from all four inlets. In host trials, water conditioned with the chemical cues of a French grunt (a common host of gnathiids) was allowed to flow in from a single inlet, with control water flowing from the remaining inlets. Water was conditioned by placing a single host fish in 10 L of aerated water for at least 2 hr. For each trial, an individual gnathiid was placed in the center of the choice arena and allowed to move freely for 10 min while its movements were tracked. All trials were recorded under infrared light and later analyzed using EthoVision XT behavioral tracking software.

Ocean Acidification Trials. To simulate projected ocean acidification parameters, seawater used in a portion of the trials was acidified by injection of CO_2 and pH levels maintained using an aquarium pH controller. pH levels in Brewers Bay range from 8.0 to 8.2 depending on sampling time and location.

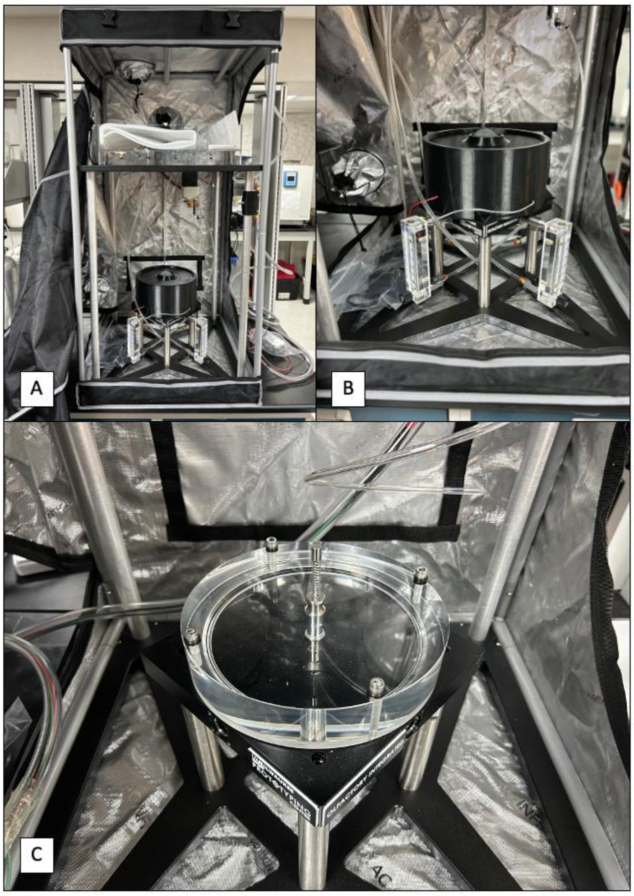

Figure 2. Example of a newly developed aquatic olfactometer. A) Overview of the entire olfactometer, B) Main testing instrument of the olfactometer. Choice arena is covered with a light blocking cover, and C) Choice arena covered with glass cylinder to create watertight seal within arena. Photo Credit: Clayton Vondriska.

Therefore, in the acidification trials the pH was lowered to 7.8, to reflect the likely pH projected by 2100. Control and host trials were then run as in untreated seawater.

Summary of Results

Gnathiids typically adopt a “sit and wait” approach to host-finding, spending the majority of their time stationary, but showing occasional short bursts of high-speed movement. Therefore, the animal’s activity level can serve as an indicator of its response to the olfactory cue. Preliminary results indicate that *Gnathia marleyi* shows similar amounts of activity regardless of acidification level. The response of individuals under both control and experimental conditions was highly variable. Nevertheless, individuals were found to have moved similar distances regardless of whether they were exposed to current or future projected pH. Under all conditions the test gnathiid showed a similar frequency of “high activity” events, in which it moved more than one body length.

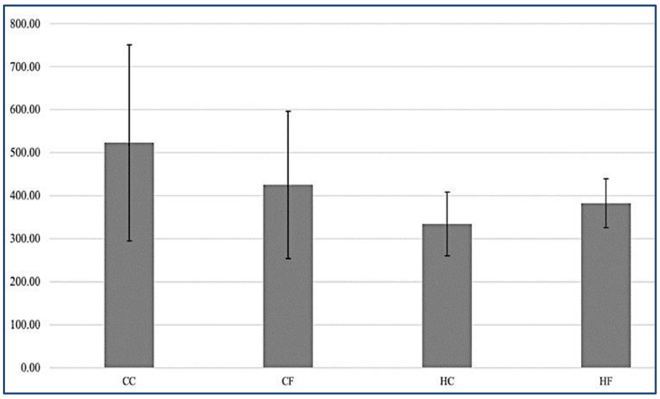

Figure 3. Average distance moved (mm) throughout behavioral trials under various conditions. "CC" = Control Cue, Current pH Conditions; "CF" = Control Cue, Future pH Conditions; "HC" = Host Cue, Current pH Conditions; "HF" = Host Cue, Future pH Conditions. Error bars indicate

Concluding Remarks

Preliminary results from this study are encouraging in that, based on the results of the above experiments, *Gnathia marleyi* appears to be resilient to the effects of ocean acidification. These results also raise the possibility that additional cues (visual, thermal, etc.) may also be important in host-finding behaviors. However, whereas previous work on the chemosensory behavior of gnathiids had been conducted under well-lit conditions shadows or vibrations caused by the researcher might have influenced the behaviour of the animals, this novel design of olfactometer eliminated the need for an observer to be present, leaving the gnathiid with only chemical stimuli to respond to. Additional trials are being conducted to better understand the role of chemical cues in host- and mate-finding, settlement, and predator avoidance behaviors, under both current and future acidification conditions.

Ocean acidification is an imminent issue that will likely affect many aquatic organisms in a variety of ways. However, most small organisms have yet to have aspects of their behavior studied under current conditions, let alone likely future ones. As previously stated, small organisms make up a significant portion of biodiversity and biomass and so can be key players in ecosystem dynamics. Testing how their behavior is influenced by acidification will be essential for understanding how coral reef ecosystems will respond to environmental changes that appear unavoidable.

Clayton Vondriska

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REEF EDGE

Precht et al.

Surprisingly diverse and rich coral assemblage found in an unlikely location in the Florida Keys

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Introduction

Starting in October of 2021, while diving within Key West Harbor, we observed an extraordinary assemblage with thousands of coral colonies comprised of some 25 different stony coral species living on emplaced rock rubble, concrete slabs, steel and cement bulkhead structures, as well as on wharf/pier footings and pilings (Figs 1 & 2). Similar observations by other researchers and environmental consultants have been made over the years throughout the harbor (CSA 2004, TES 2007, 2020), including on the bulkheads fronting the US Navy Mole Pier, US Navy Truman Annex, and the US Coast Guard Station Key West (US Navy 2003, 2004). Despite being located in an active shipping and military port that has been in use for well over a century, these unique habitats comprise some of the healthiest and most robust coral assemblages presently found within the entire Florida Keys National Marine Sanctuary.

We noted that the oldest known structures had the largest coral colonies, many exceeding 1.5 meters in diameter. Based on size and previously published growth rates, we infer that the ages of many of the larger colonies are likely to exceed 100 years in age. We also noted a preference for substrate type with concrete slabs and limestone boulders having the highest coral cover followed by steel, and ultimately with treated wood pilings having the fewest and smallest corals. In addition to stony corals, these man-made habitats are also replete with a rich and diverse benthic community comprised of octocorals, sponges, ascidians, bryozoans, hydrozoans, and macroalgae.

We found that the corals within the harbor are generally in excellent condition with few colonies revealing partial mortality. This was surprising based on the known disturbance history that corals have experienced over the past few decades regionwide (Ruzicka et al. 2013, Manzello 2015, Toth et al. 2019). While minor levels of coral disease were noted during a few of our visits, the disease prevalence (all diseases) has always been quite low (<<3%). For instance, stony coral tissue loss disease (SCTLD) is known to have impacted the reefs off Key West in 2019 (Muller et al. 2020, Precht 2021), but most of the highly susceptible corals to SCTLD within Key West Harbor were apparently blind to the passage of this disease outbreak and presently dominate these unique assemblages. These include multiple scores of colonies of *Dichocoenia stokesii*, *Diploria labyrinthiformis*, *Pseudodiploria strigosa*, *Pseudodiploria clivosa*, *Colpophyllia natans*, *Montastraea cavernosa*, as well as three Endangered Species Act-Listed corals in the *Orbicella* species complex (see Fig. 3). Rippe et al. (2019) found that corals in offshore environments in the upper Florida Keys suffered significantly more mortality from the SCTLD than corals in nearshore environments and hypothesized that exposure to more extreme environmental conditions

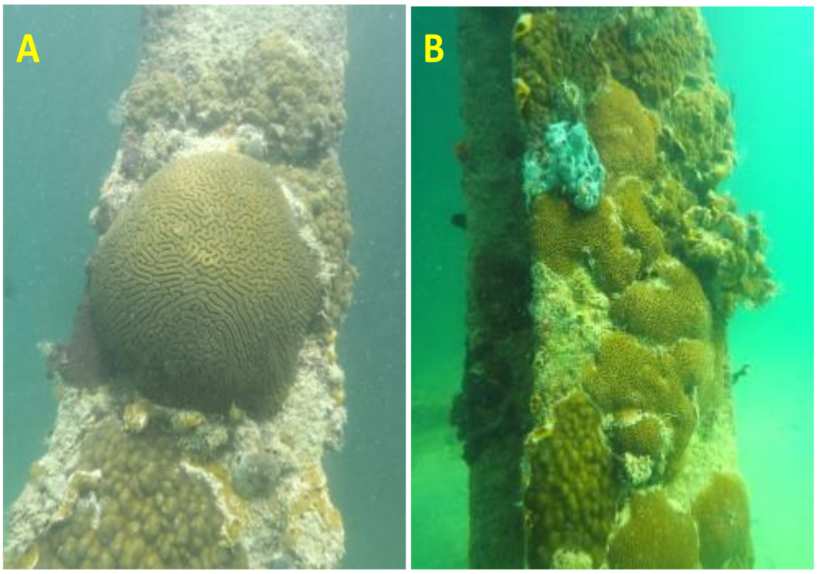

Figure 1. Underwater photographs of corals attached to pilings under Pier B within Key West Harbor. Photo on left (A) is a piling with a large colony of *Diploria labyrinthiformis* surrounded by colonies of *Porites astreoides*. Photo on right (B) is a piling covered with a diverse assemblage of stony corals, sponges, and other benthic invertebrates. Photos taken on April 19, 2023.

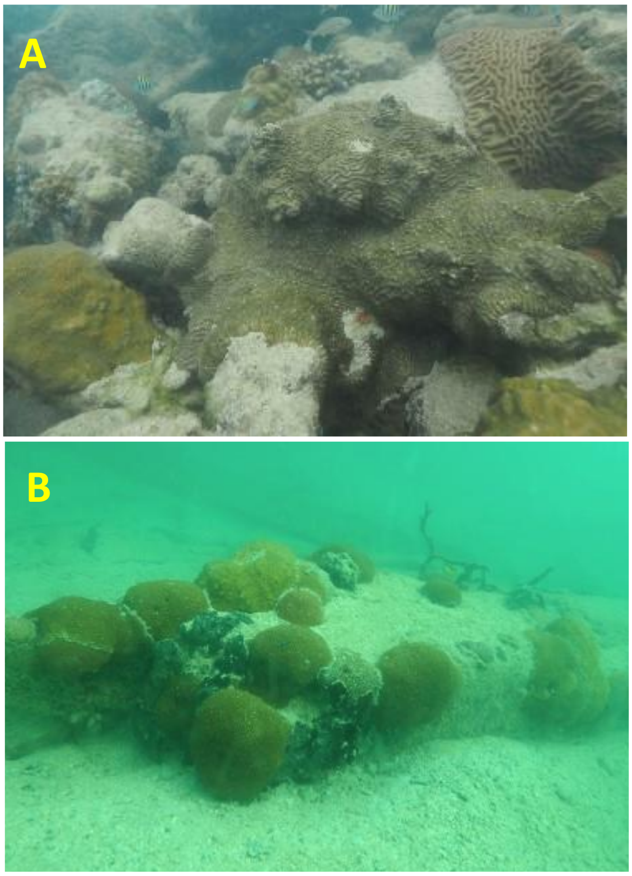

Figure 2. Underwater photographs of corals living on emplaced structures within Key West Harbor in the area adjacent to Pier B. Photo on left (A) is a diverse coral assemblage living on limestone boulders. Photo on right (B) is a concrete slab covered with numerous large stony corals. Photos taken on April 19, 2023.

nearshore may have increased the resilience of corals to this disease.

The observations of a rich, diverse, and relatively disease-free coral community within Key West Harbor are similar in many respects to recently published reports of healthy coral colonies being found in unique urban environments within the interior portions of Port Miami (Rubin et al. 2021, Enochs et al. 2023). The question that begs further research is why? Are these "super" corals? If so, what are the keys to their resilience and persistence in these highly dynamic, altered environments? The answer to these and other questions posed by these enigmatic corals could yield clues to the survival of all corals in an ever-changing world impacted by man.

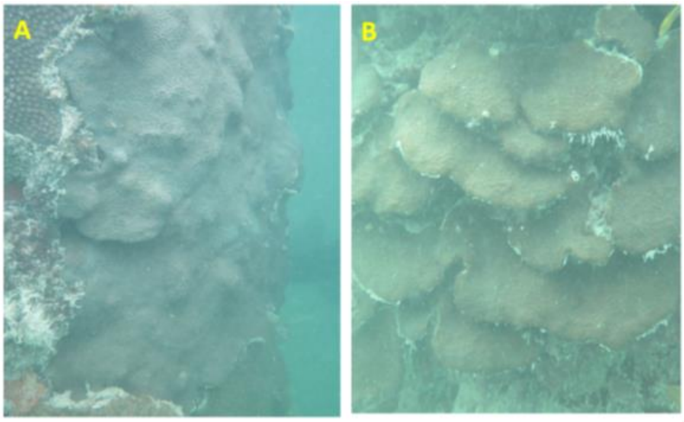

Figure 3. Underwater photo of extremely large colonies of the ESA-listed corals *Orbicella faveolata* (A), and *Orbicella annularis* (B) living on the pilings under Mallory Pier. Based on the size of these colonies and their known growth rates, the conservative age of these corals is 75 - 100 years. Photos taken on October 11, 2021.

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Wörheide

A new species of crown-of-thorns seastars from Red Sea: *Acanthaster benziei*

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Tropical coral reefs are among the most endangered hyperdiverse ecosystems on Earth. In addition to climate change, coral-eating crown-of-thorns seastars (CoTS; *Acanthaster* spp.) pose one of the biggest threats to coral reefs in parts of the Indo-Pacific. Up to 40 cm in length, CoTS feed mainly on the polyps of fast-growing stony corals. Sometimes, CoTS occur in so-called mass outbreaks, whereby the seastars propagate at a rapid rate and many thousands of individuals cause extensive coral mortality over large areas of coral reef. Such mass outbreaks have become increasingly frequent over recent decades, but their exact causes are still debated. In any case, CoTS mass outbreaks have contributed significantly to the decline in coral cover over the last few decades, for example on the Great Barrier Reef (De'ath et al. 2012).

Crown-of-thorns seastars are widely distributed throughout the Indo-Pacific region. They get their name from the large venomous spines that protrude from their arms. Based on regional morphological differences, various species had been described in the past, and the complex taxonomic history of *Acanthaster* species spans more than 300 years (reviewed in Haszprunar et al. 2017, Haszprunar and Spies 2014). Until recently, all were lumped together as the first species described in the genus, *Acanthaster planci,* because it was long assumed that it was distributed from the Red Sea and the Indian Ocean over the entire Pacific. However, in 2008 DNA barcoding data showed that *A. planci* is subdivided into four strongly diverging genetic lineages/clades (Vogler et al. 2008). These four clades were proposed to represent four species, each with a distinct and largely non-overlapping distribution across the Indo-Pacific region: one from the Red Sea, one from the southern Indian Ocean, one from the northern Indian Ocean, and one from the Pacific Ocean (Vogler et al. 2008) (see Fig. 1). Haszprunar and Spies (2014) dug into the original literature and species descriptions, aiming to allocate species names to these four genetic clades. They concluded that *A. planci* is the valid name for the northern Indian Ocean species, *Acanthaster mauritiensis* (de Loriol 1885) for the southern Indian Ocean species,

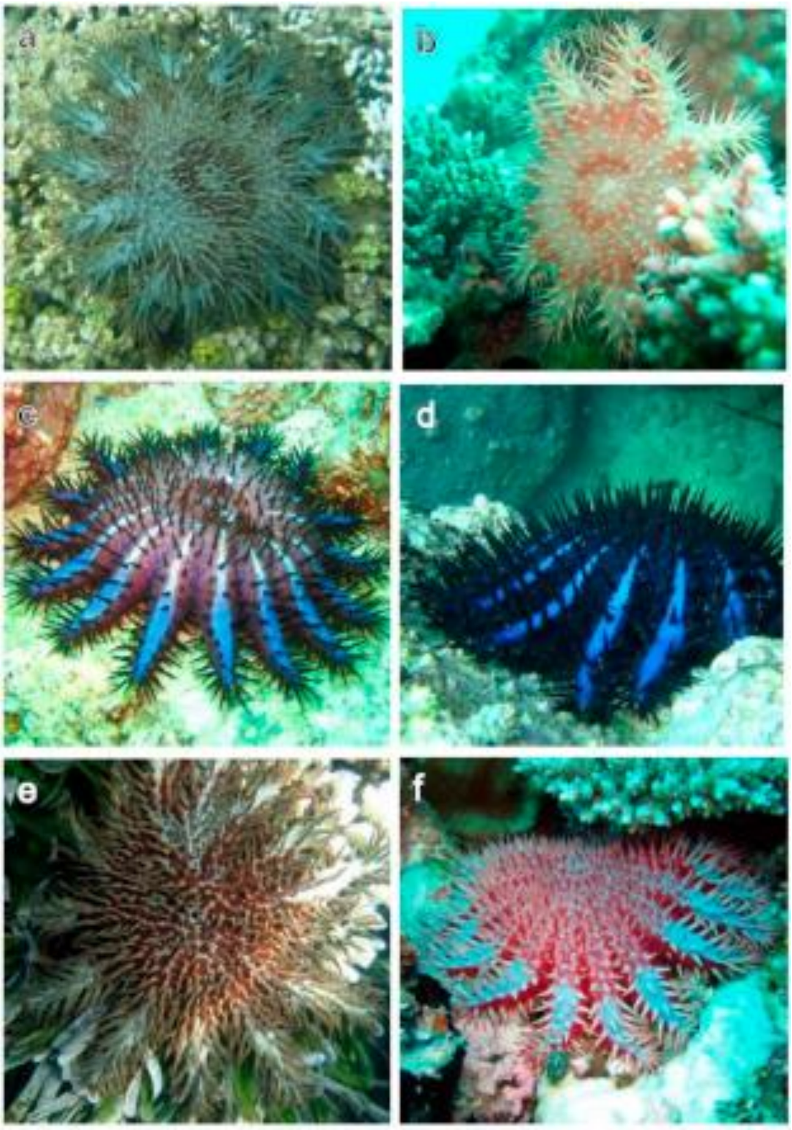

Figure 1. Typical color morphs found in the sister-species: (a) West-Pacific species, Fiji (*Acanthaster solaris* (Schreber, 1793)) (Fiji, credit Nina Yasuda); (b) Red Sea species, *A. benziei* Wörheide et al., 2022 (Thuwal area, Saudi Arabia, credit Jessica Bouwmeester), (c) and (d) Northern Indian Ocean species, i.e., the true *Acanthaster planci* (Linnaeus, 1758), (c) UAE (credit: Maral Shuriqi); (d) Oman (credit: David Mothershaw), (e) and (f) (Southern Indian Ocean species, i.e., *Acanthaster mauritiensis* de Loriol, 1885, (e) Kenya (credit: KevRansom), and (f) Chagos Archipelago (credit: Anne Sheppard). Figure from Haszprunar at al. (2017).

and *Acanthaster* cf. *solaris* (Schreber 1793) for the Pacific Ocean species [see Haszprunar et al. (2017) for an in-depth discussion of species name allocation], but no previous species name was available for the Red Sea, meaning that this was a species new to science.

In an integrative taxonomic study, using morphological investigations and genetic analyses, Wörheide et al. (2022) have now demonstrated that the crown-of-thorns seastars native to the Red Sea form a distinct species, which has been given the name *Acanthaster benziei*. This underlines once again the importance of the Red Sea as an ecosystem with a unique fauna and numerous endemic species. The new species name honors John Benzie, Professor at University College Cork (Ireland), who, with his comprehensive collection and groundbreaking genetic studies, undertook pioneering work on crown-of-thorns seastars in the 1990s.

A. benziei represents the first new species of crown-of-thorns seastars in several decades. Although particular distinctive features had already been observed in crown-of-thorns seastars from the Red Sea, such as a tendency to a more nocturnal lifestyle and a possibly lower toxicity of the spines (reviewed in Uthicke et al. 2024), its distinction as a separate species was still unclear. Nonetheless, the new study now confirmed clear differences between *A. benziei* and the other species of the "*A. planci"* species complex. In particular the diagnostic sequences in the mitochondrial DNA as well diagnostic morphological features, such as a lower number of arms and thinner, differently shaped spines, support the separation of *A. benziei* as a species new to science.

The new knowledge of this distinct CoTS species *A. benziei* from the Red Sea now allows a new appreciation of its biology, ecology, and toxicology and a comparison with the other *Acanthaster* species. In the past, a lower tendency for mass outbreaks in Red Sea crown-of-thorns seastars was observed. Mass outbreaks that devastate reef are known primarily from *Acanthaster* cf. *solaris* in the western Pacific and regularly cause major damage, for example to the Great Barrier Reef, whereas the phenomenon appears to be less severe in the Red Sea. Future investigations may show whether species-specific characteristics are a contributing factor. Most data that have been gathered to date on the biology and ecology of crown-of-thorns seastars comes from *Acanthaster* cf. *solaris* from the western Pacific and have been transferred to other geographic regions of the Indo-Pacific, because a widely-distributed single CoTS species was assumed. By clearly distinguishing the various species of coral-eating crown-of-thorns seastars across the Indo-Pacific and their specific geographic range, more detailed comparative research, for example into the dynamics of mass outbreaks, one of the multiple stressors that affect tropical reefs, can be carried out. Ultimately, this is a step in the direction of better management of reef ecosystems.

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First Report of Mass Bleaching in the South-western Gulf of Mexico

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Horta-Puga et al.

Since the onset of the industrial era, the atmospheric concentration of carbon dioxide (CO_2), the main greenhouse gas, has increased from 280 ppm in the early 1800s to 417 pm in the 2020s. Concomitantly, average global temperatures have risen up to 1.5 °C above those of the 19th century (IPCC 2021). Climate change has now become the main global threat to all ecosystems, but especially to coral reefs (Hoegh-Guldberg 1999; Pandolfi 2015). In general, if seawater temperatures increase by more than about 1.5 °C or more above the monthly average of the warmest month (boreal or austral

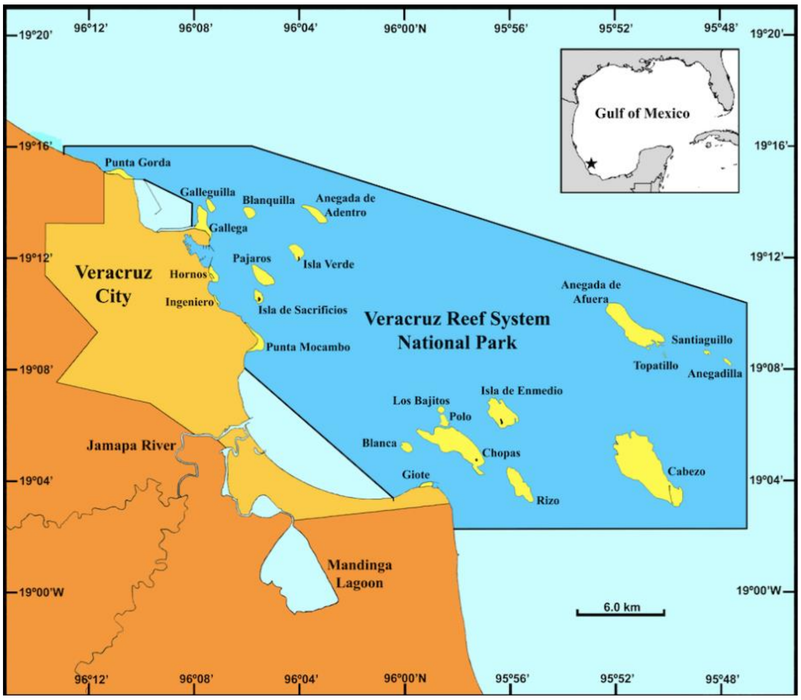


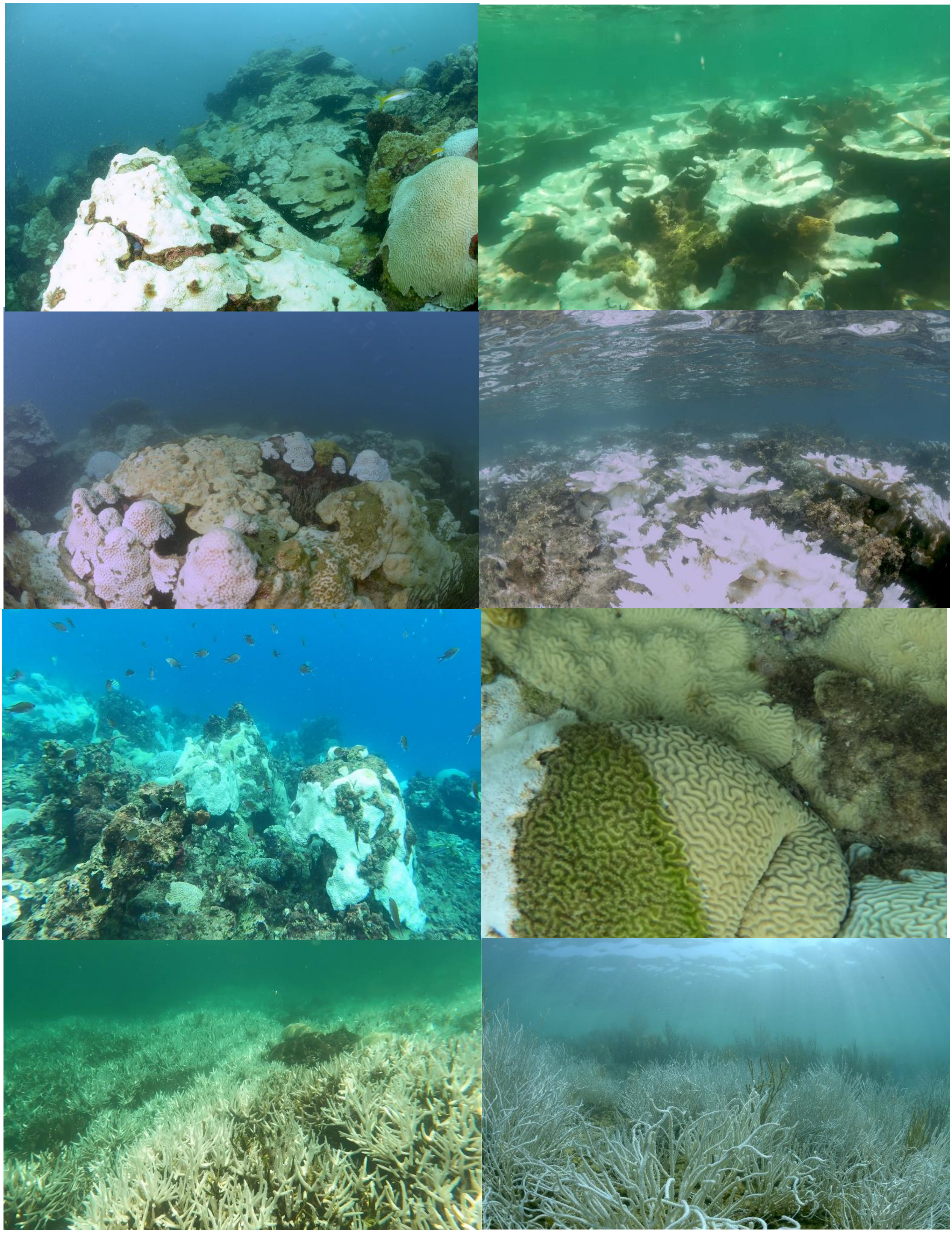
Figure 1. Veracruz Reef System, Southwestern Gulf of Mexico.

summer), the coral's zooxanthellae are expelled from its tissues, due to disrupted photosynthesis (Glynn and D'Croz 1991). As a result, the corals first pale, and subsequently turn completely white (i.e. they bleach). Although their appearance may seem awesome to our eyes, as the corals receive no more organic nutrients from their endosymbiotic partner, unless temperatures are reduced they soon die (Glynn 1996).

Yonge and Nicholls (1931) reported reef-wide coral bleaching for the first time as consequence of high temperatures on the Great Barrier Reef (Oliver et al. 2009). Glynn (1983, 1984) documented from the Eastern Pacific the first well known record of mass bleaching, during the 1982-1983 El Niño event. Since then, and frequently associated to El Niño, mass bleaching across the Pacific Ocean was recorded in 1998, 2010 and 2015 (Heron et al. 2016). Three mass bleaching events severely affected the Great Barrier Reef in 2016, 2017 and 2020, with the extent of bleaching damage to the reefs extending successively southwards to more temperate zones (AIMS: https://www.aims.gov.au/). If sea surface temperatures (SSTs) rise in the years to come, as very probably they will, marine heatwaves will become more frequent, and so bleaching events occur worldwide (Hughes et al. 2018).

Widespread mass bleaching in the western tropical Atlantic reefs has been recorded earlier. In the 2005 bleaching was reported at several localities in the Caribbean, including the Mesoamerican Reef System in Mexico (Wilkinson and Souter 2008, Eakin et al. 2010). Fortunately, in this regional bleaching event the reefs of the southwestern Gulf of Mexico remained unharmed. This year (2023), global daily mean sea surface temperatures (SSTs) in tropical and temperate latitudes (60° N-60° S) have been the highest on record. Since mid-March, global daily SST has been a further 0.1-0.3 °C above the historical records for the 1981-2022 period (Climate Reanalyzer: https://climatereanalyzer.org/). Since El Niño conditions are underway, it seems probable that in the central and eastern Pacific Ocean above average SSTs will last at least until early 2024 (NOAA, Climate Prediction Center: https://www.cpc.ncep.noaa.gov/). Most recently, SSTs have been >29 °C and Bleaching Alert Level 2 in effect across the western and central Caribbean, the Gulf of Mexico and the eastern Pacific, since at least late June (NOAA, CRW: https://coralreefwatch.noaa.gov/index.php). These conditions have evidently triggered mass bleaching on both sides of tropical America, in the eastern Pacific from Mexico to Ecuador, and in the western Atlantic in Florida, Bahamas, Cuba, Costa Rica, Panama, Colombia, and other parts of the Caribbean (AGRAA: https://www.agrra.org/coral-bleaching/). Unfortunately, among those reef areas, the southwestern Gulf of Mexico has not avoided the effects of the warmest summer on record. In the Veracruz Reef System, local scuba divers and fishermen reported the sight of "white corals" in late August. In consequence, in mid-September (11th-14th) we surveyed three reefs off Veracruz City. Extensive coral bleaching was observed on both the reef flat, and the leeward (W) and windward (E) slopes of each of the Anegada de Adentro, Blanquilla and Isla Verde reefs.

Figure 2. *Colpophyllia natans*, Anegada de Adentro Reef, windward slope, 9-12 m. (see rear cover)



Figures 3–6 (left hand column from top down) and **7-10** (right hand column from top down). 3: Anegada de Adentro Reef, windward slope, 9-12 m. 4: Anegada de Adentro Reef, leeward slope, 9-12 m. 5: Blanquilla reef, windward slope, 6-9 m. 6: *Acropora cervicornis*, Isla Verde Reef, leeward slope, 2-5 m. 7: *Acropora palmata*, Isla Verde Reef, reef flat, 1-2 m. 8: *Acropora palmata*, Anegada de Adentro Reef, reef flat, 1-2 m. 9: *Pseudodiploria strigosa* partially bleached and diseased. Soft coral *Erythropodium caribaeorum* bleached to the left. Isla Verde Reef, reef flat, 1 m. 10: The horny coral *Pseudoplexaura* bleached. Isla Verde, leeward slope, 2-5 m. Identification by Miguel Ángel Lozano, Universidad Veracruzana, Mexico.

To evaluate the extent of the damage to the hermatypic coral communities, we completed >100 video-transects (2 min per transect) of the reef substrate. The full results of these surveys will be published after the processing of the video imagery. However, based on the visual estimation of the bleached sites, our preliminary results indicate that the following coral species were severely affected (>60% bleached): *Acropora palmata, Acropora cervicornis, Colpophyllia natans, Montastraea cavernosa, Porites astreoides, Porites porites*, and *Pseudodiploria strigosa*. Species moderately affected (30-60% bleached) were: *Orbicella annularis, Orbicella faveolata, Millepora alcicornis*, and *Siderastrea siderea*. The proportions of bleached corals were greater on the reef flat and leeward slopes than on the windward slopes; they were also greater on shallow (< 7m) areas than on deeper ones. Other symbiont-bearing species, like the soft coral *Erythropodium caribaeorum*, the horny coral *Eunicea flexuosa*, and colonial anemone *Palythoa caribaeorum*, had also bleached. A possible side effect on bleached corals was an increased prevalence of Black-Band Disease on *Pseudodiploria strigosa*. As of September 30th, SSTs were still above the bleaching thresholds for many species, while the reef seemed more like a snowy landscape, with almost all corals at shallow depths (1-12 m) either quite white or very pale.

This is the first time that mass bleaching has been recorded in the western tropical Atlantic and in the eastern tropical Pacific simultaneously. We fear that the long-term effects on Mexican reef ecosystems will be catastrophic, since the reef substrate cover of live corals is usually no more that 20% (Horta-Puga et al. 2021).

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Versión en español

Primer Reporte de Blanqueamiento Masivo en el Suroeste del Golfo De México

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Desde el inicio de la era industrial, la concentración de bióxido de carbono (CO_2) en la atmósfera, el gas de efecto invernadero más importante, se ha incrementado desde 280 ppm a inicios del siglo XIX, hasta 417 ppm en la década de 2020s. Al mismo tiempo, las temperaturas promedio globales se han elevado hasta en 1.5 °C con respecto al siglo XIX (IPCC 2021). El cambio climático es ahora la principal amenaza global para todos lo ecosistemas, pero en especial para los arrecifes de coral (Hoegh-Guldberg 1999, Pandolfi 2015). En general, si la temperatura del agua del mar se eleva 1.5 ªC o más, por arriba de la temeratura promedio del mes más cálido del año (en el verano boreal o austral), las zooxantelas que se alojan en el tejido del coral son expulsadas, debido a que la fotosíntesis se ve afectada (Glynn and D'Croz 1991). Como resultado, los corales palidecen, y posteriormente se turnan completamente blancos, es decir se blanquean. Aunque su apariencia a nuestro ojos puede ser impresionante, dado que los corales dejan de recibir nutrientes de sus socios endosimbiontes, a menos que las temperaturas se reduzcan, los corales mueren tiempo después (Glynn 1996).

Yonge y Nicholls (1931) reportaron, por primera vez, un evento de blanqueamiento coralino masivo en la Gran Barrera de Arrecifes, como consecuencia de las altas temperaturas (Oliver et a. 2009). Glynn (1983, 1984) documentó para el Pacífico Oriental, el primer registro conocido de blanqueamiento masivo, durante el evento de El Niño 1982-1983. Desde entonces, y frecuentemente asociado a El Niño, varios eventos de blanqueamiento masivo han sido registrados a lo largo del Océano Pacífico en 1998, 2010 y 2015 (Heron et al. 2016). En la Gran Barrera de Arrecifes se han reportado tres eventos severos de blanqueamiento masivo en 2016, 2017 y 2020. El daño se fue extendiendo sucesivamente hacia el sur a zonas más templadas (AIMS: https://www.aims.gov.au/). Si la temperatura oceánica superficial (TOS) se eleva en los años venideros, y muy probablemente así sucederá, las ondas de calor marinas se presentarán con mayor frecuencia y, por lo tanto, también los eventos de blanqueamiento masivo (Hughes et al. 2018).

Previamente ya se ha reportado en fenómeno de blanqueamiento masivo en los arrecifes del Atlántico tropical occidental. En el 2005 se reportó blanqueamiento para varias localidades en el Caribe, incluyendo el Sistema Arrecifal Mesoamericano en México (Wilkinson and Souter 2008, Eakin et al. 2010). Afortunadamente en este evento regional de blanqueamiento, los arrecifes del Suroeste del Golfo de México permanecieron si daños. Sin embargo, este año (2023), las TOS global promedio diarias en las latitudes tropicales y templadas (60º N-60º S) han sido las más altas jamás registradas. Desde mediados del mes de marzo, la TOS global promedio diaria se ha situado 0.1-0.3 ºC por arriba del promedio histórico del periodo 1981-2002 (Climate Reanalyzer: https://climatereanalyzer.org/). El evento de El Niño esta en progreso, y es probable que las TOS en el Pacifico central y oriental se mantengan por arriba del promedio al menos hasta inicios del 2024 (NOAA, Climate Prediction Center: https://www.cpc.ncep.noaa.gov/). Además, la TOS se ha mantenido >29 ºC, por lo cual Alerta de Blanqueamiento nivel 2 ha estado en efecto para el Caribe central y occidental, el Golfo de México y el Pacífico oriental, desde el mes de junio (NOAA, Coral Reef Watch: https://coralreefwatch.noaa.gov/index.php). Así, este conjunto de condiciones ha desencadenado el blanqueamiento masivo en ambas costas del continente americano, en el Pacifico oriental desde México hasta Ecuador, y en Atlántico ocidental en Florida, Bahamas, Cuba, Costa Rica, Panama, Colombia, y varias más en el Caribe (AGRAA: https://www.agrra.org/coral-bleaching/). Desafortunadamente, el suroeste del Golfo de México se encuentra entre las áreas que no han podido evitar los efectos del verano más cálido registrado. En el Sistema Arrecifal Veracruzano los buzos deportivos y los pescadores locales reportaron el avistamiento de "corales blancos" a fines del agosto. Por lo anterior, a mediados de septiembre (11-14) llevamos a cabo una campaña de muestreo en tres arrecifes ubicados frente a la ciudad de Veracruz. Se observó blanqueamiento muy extendido, tanto en la zona de planicie, así como en los taludes de sotavento (W) y barlovento (E), de los arrecifes Anegada de Adentro, Blanquilla e Isla Verde.

Para evaluar la extensión del daño a las comunidades de corales hermatípicos, filmamos >100 videotransectos (2 min/transecto) del fondo arrecifal. Los resultados de esta campaña de muestreo serán publicados más adelante, después de haber sido procesados. Basándonos en una estimación visual de los sitios de blanqueamiento, los resultados preliminares in dican que las especies severamente afectadas (>60% de blanqueamiento) fueron: *Acropora palmata, Acropora cervicornis, Colpophyllia natans, Montastraea cavernosa, Porites astreoides, Porites porites* y *Pseudodiploria strigosa*. Las especies moderadamente afectadas (30-60% de blanqueamiento) fueron: *Orbicella annularis, Orbicella faveolata, Millepora alcicornis* y *Siderastrea siderea*. La proporción de corales blanqueados fue mayor en la zona de planicie arrecifal y en el talud de sotavento, que en el talud de barlovento; también fue mayor en las zonas someras (<7 m) que en las zonas profundas. Incluso, otras especies que presentan zooxantelas endosimbióticas, tales como el coral blando *Erythropodium caribaeorum*, el coral córneo *Eunicea flexuosa*, y la anémona colonial *Palythoa caribaeorum*, también se blanquearon. Un posible efecto colateral del blanqueamiento coralino, es un incremento en la prevalencia de la enfermedad de la Banda Negra en *Pseudodiploria strigosa*. Para el 30 de septiembre, a profundidades someras (1-12 m), las TOS se mantenían por arriba del umbral de blanqueamiento de varias especies, por lo cual los arrecifes daban la impresión de un paisaje nevado, con casi todos los corales pálidos o blancos.

Esta es la primera vez que un evento de blanqueamiento masivo se ha registrado simultáneamente en el Atlántico occidental y en el Pacífico oriental. Sentimos que los efectos a largo plazo en los ecosistemas arrecifales de México sean catastróficos, toda vez que la cobertura de coral vivo es, en general, no mayor al 20% (Horta-Puga et al. 2021).

Pies de figura

Figura 1. Sistema Arrecifal Veracruzano, suroeste del Golfo de México..
Figura 2. *Colpophyllia natans*, arrecife Anegada de Adentro, talud de barlovento, 9-12 m.
Figura 3. Arrecife Anegada de Adentro, talud de barlovento, 9-12 m.
Figura 4. Arrecife Anegada de Adentro, talud de sotavento, 9-12 m.
Figura 5. Arrecife Blanquilla, talud de barlovento, 6-9 m.
Figura 6. *Acropora cervicornis*, arrecife Isla Verde, talud de sotavento, 2-5 m.
Figura 7. *Acropora palmata*, arrecife Isla Verde, planicie arrecifal, 1-2 m.
Figura 8. *Acropora palmata*, arrecife Anegada de Adentro, planicie arrecifal, 1-2 m.
Figura 9. *Pseudodiploria strigosa* parcialmente blanqueada y enferma. Coral blando *Erythropodium caribaeorum* blanqueado, a la izquierda. Arrecife Isla Verde, planicie arrecifal, 1 m.
Figura 10. El coral córneo *Pseudoplexaura* blanqueado. Isla Verde, talud de sotavento, 2-5 m. Identificado por Miguel Ángel Lozano, Universidad Veracruzana, México.

El Niño 2023 event in the Southern Mexican Pacific: A preliminary report of an imminent disaster

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The El Niño Southern Oscillation (ENSO) is a periodic oscillation of temperature and atmospheric pressure in the equatorial Pacific that can modify climatic conditions in many parts of the world (Wang et al. 2017). Since the beginning of 2023, the National Oceanic and Atmospheric Administration (NOAA) officially communicated the prospective emergence of an El Niño event expected to gradually increase during the winter in the northern hemisphere (https://www.cpc.ncep.noaa.gov/products/analysis_monitoring/enso_advisory/ensodisc.shtml).

The bays of Huatulco, located in the southern Mexican Pacific, host one of the best-preserved and most extensive coral reef systems in the Eastern Tropical Pacific (ETP) (Glynn and Leyte-Morales 1997). Nevertheless, on June 21, 2023, videos and photographs shared on social networks by tourist service providers (snorkel tours) caused alarm in the scientific community since they portrayed coral bleaching in Huatulco bays. From June 27 to August 20 we surveyed the coral reefs between San Agustín and Chahué bays in Huatulco using Unmanned Aerial Systems (Drone), Remotely Operated Vehicles (ROVs), scuba diving, and snorkeling.

According to our data, during late June and July, bleaching was widespread throughout Huatulco, from San Agustín to Chahué (Fig. 1). In San Agustín, Riscalillo, and La Entrega, due to the size and shape

Figure 1. San Agustín-Chahué reef-tract, southern Mexican Pacific.

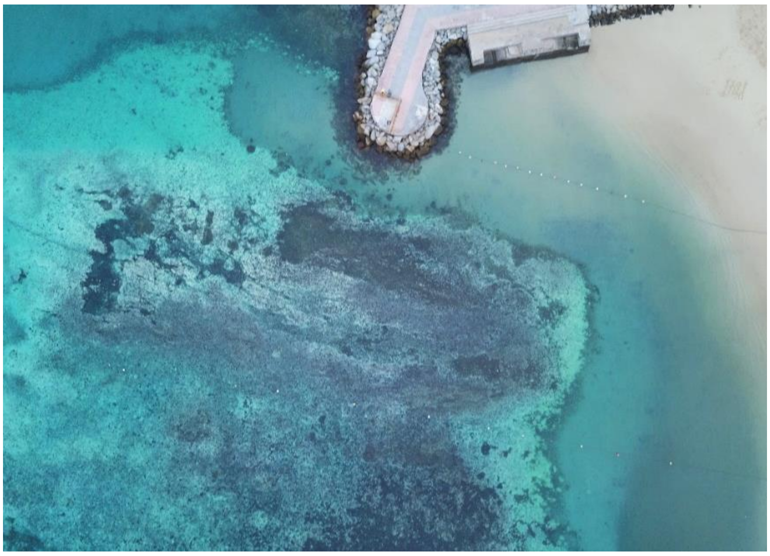

Figure 2. Coral bleaching and recently dead corals from the air. Section of a composite image gathered with an Unmanned Aerial System (Drone). La Entrega reef, July 2023.

of the reef, the bleaching looked more intense and widespread from the air, but diving, snorkeling, and ROVs made it clear that it was equally severe on all the reefs visited in the area (Fig. 2). In shallow waters (0-5 m), severe bleaching ranged from 80-95% in *Pocillopora* spp. Colonies (Fig. 3). At mid-depths (5-7 m), bleaching was slightly reduced (~70%), but all colonies were pale in color, including at the bases of the coral branches. At depths greater than 7 m, the percentage of slightly pigmented corals increased at the bases of the colonies, although all *Pocillopora* branch tips were bleached. Coral species belonging to *Pavona* and *Porites* exhibited complete bleaching in all localities. In some cases, these corals and those belonging to *Pocillopora* presented yellow, pink, or blue fluorescence. This luminescence phenomenon stems from the corals' synthesis of pigments, orchestrated as a photoprotective response mechanism (Fig. 4) (Bollati et al. 2020).

One of the most worrying elements of the present bleaching event in Huatulco results from the analysis of temperature records in the area. According to our data, in May the water temperature in Huatulco (31-33ºC) was barely 0.76 °C above the historical mean, but 1.99 °C above normal during June-July. In August, this situation remained unchanged showing a continued upward trend. The current temperature is approximately 2 °C higher than previous ENSO events recorded in Huatulco (Reyes-Bonilla et al. 2002, López-Pérez et al. 2016). According to reports, during the cold phase of the ENSO (1997-1999), widespread mortality was recorded in the contiguous Puerto Ángel reef area. Meanwhile, only 18% bleaching and mortality were observed during the warm phase of the 2009 event (López-Pérez et al. 2016). Comparatively, higher thermal stress than in 2009 may result in larger coral bleaching and potential mortality, already evident in Huatulco. Compared to previous bleaching in the region, a few weeks after the current El Niño event began, mortality was observed in *Pocillopora* coral colonies, but during the first week of August, mortality began to rise exponentially in several localities of Huatulco, as apparent from the overgrowth of cyanophyte mats on freshly killed coral heads. Mortality is becoming of concern due to its rapid advance.

Within the ETP, the reef-track Puerto Ángel-Bahías de Huatulco, located in the southern Mexican Pacific, is considered a vital coral reef area in terms of percent coral cover and framework development (Glynn and Leyte-Morales 1997), and of pivotal relevance to maintaining coral connectivity across the ETP. Losing the Huatulco coral reefs may represent a catastrophe at both local and regional scales, since Huatulco represents a vital stepping stone and a potential source of larvae to north-western rocky and coral reef systems (Lequeux et al. 2018).

The event currently taking place in the southern Mexican Pacific becomes an excellent opportunity

Figure 3. Fully bleached *Pocillopora* spp. corals. Dos Hermanas reef, July 2023

Figure 4. Colorful bleached corals in Huatulco, July 2023. A) *Pocillopora* spp. corals, Maguey reef. B) *Pavona gigantea* colonies, Dos Hermanas reef. Fluorescence is marked with arrows.

to explore possible management strategies that may reduce and further reverse the effects of ENSO in the region, once the event has passed. Passive management strategies can reduce bleaching, prevent mortality and enhance recovery following disturbance. For the moment, the systems are experiencing (a) Thermal stress (~ 2 °C above the historical average), (b) Light stress derived from extremely clear water, and in addition (c) Stress due to intense tourist use. The first two stressors cannot be avoided due to the regional-global nature of the ENSO event. However, the anthropogenically induced stress could be reduced by restricting activities on beaches with reefs and by reserving tourism access exclusively to areas where beach activities can be carried out.

Finally, we recommend implementing a monitoring protocol with such a periodicity that it allows us to follow the main changes experienced by the reefs during ENSO events. Monitoring should allow for the documentation of the metrics of the ENSO and for the design of effective management strategies to reverse its effects. Synergy between the scientific community, decision-makers, and the wider community will be essential to reduce or prevent the decline of reefs, and to secure future decision-making.

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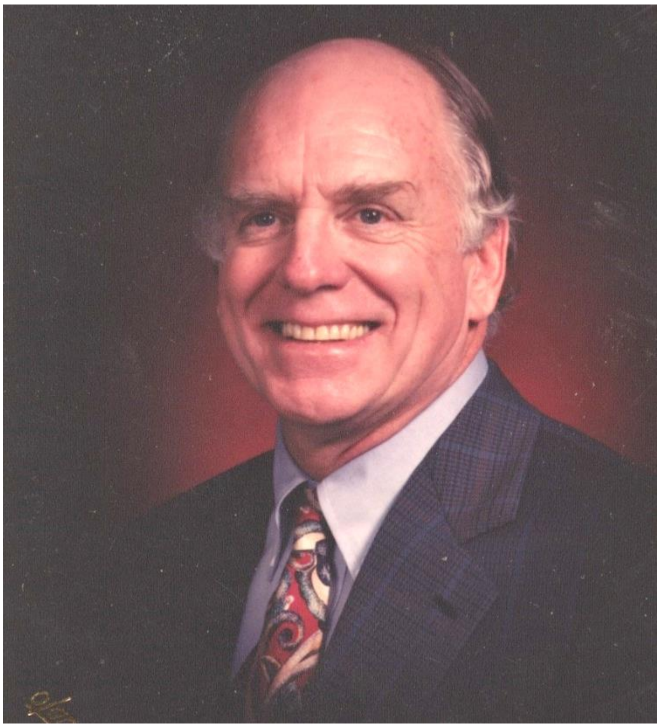
REEF DEPARTURES

Tributes to recently departed members and reef scientists

John Conrad Ogden 1940-2023 (ICRS past-president)

It is difficult to adequately pay a fitting tribute to John Ogden. This compilation of memories and thoughts, from Nancy Ogden, Betsy Gladfelter, Barbara Brown, Terry Done, Alasdair Edwards, Jorge Cortes, Dixon Waruinge and Sue Wells, gives some idea of his worldwide impact and legacy, and the role he played in the Society.



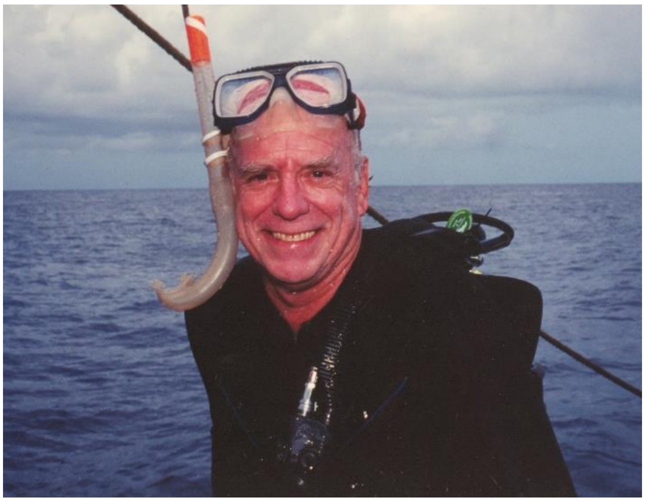
The coral reef community in its broadest sense – academia and research, conservation and management, education and training – has lost one of its most active and influential members, John Ogden. John died on 25th June, 2023, from complications following surgery, whilst still leading a busy and valuable life, and contributing to local, national and global initiatives, including ICRS.

John was a founding member and leading voice in ICRS (formerly the International Society for Reef Studies) since its initiation in 1980, serving for many years as a Council officer, invariably present at the four-yearly Congresses, and one of the most active presidents (1995-1998) that the Society has had.

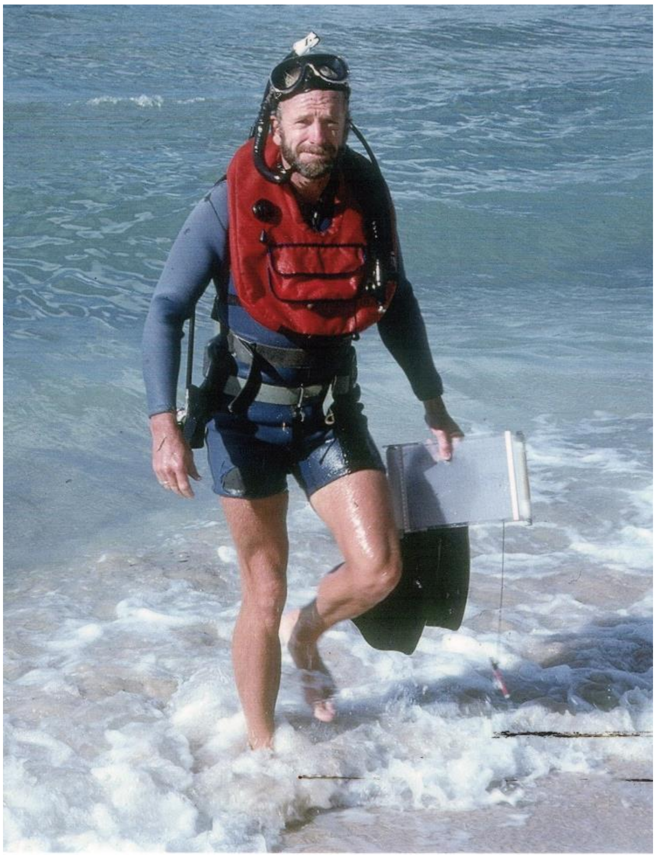
Barbara Brown, a friend and work colleague of John, describes his impact on ICRS:

"*From the moment he became President he highlighted the need to promote more regional meetings and attract young scientists from all over the world to build the Society leadership of tomorrow while encouraging alliances with other scientific societies and NGOs. In particular, he persuaded the philanthropist Professor Phil Sollins to support a Fellowship award in 1997. Then, in 1998 together with Gray Multer, he began a Student Travel Award Program that aided students wishing to attend scientific meetings, focusing initially on students from South/Southeast Asia but with plans to extend the scheme more widely. Later in his life he sustained his support for the Society and its aims by playing a very active role in successfully nominating many scientists for what became a widely expanded program of Society honours. As President, he also presided over a radical re-organisation of the Society with respect to the then outdated Constitution, and led the financial dealings with the publisher Springer of the journal 'Coral Reefs'.*"

Terry Done, who succeeded John as president in 1999, writes: "*he was very much in the hot-seat as our focus transitioned from the joyful science-focused meetings of our early days (viz. 'the coral reef paradox') to the more somber focus of recent meetings of 'coral reef problems'.*"



John was born in Chatham, New Jersey, USA, in 1940 and developed an interest in natural history as a result of spending time as a teenager exploring the nearby Great Swamp (later designated as the USA's first protected wilderness area). This led to a biology degree from Princeton in 1962, and then a PhD from Stanford under the famous Population Bomb author, Paul R. Ehrlich in 1968. After two years, he headed with his wife, Nancy, to Panama for a post doc on parrotfish with the Smithsonian Tropical Research Institute.



John, with homemade underwater recording slate

In 1971, he moved to Fairleigh Dickinson University's new, West Indies Laboratory (WIL) on St. Croix as the resident marine biologist. This was the beginning of nearly two decades of work at WIL, where he became Director, and raised his family. Betsy Gladfelter, also a friend and close colleague, writes about this time at WIL, with John at the helm, as being "*magical*":

"*Life there was work hard, play hard…and idyllic for someone who loved exploration of the natural world…and sharing that with students and researchers from around our country and around the world. John was instrumental in bringing folks from across the natural sciences, and from young, eager undergraduates through seasoned field scientists, to share that special time…whether in the field or lab, over coffee at the dining hall, in the pool after an afternoon run, in spirited competitions including students and faculty, and in parties at the lab and trips into town to listen to bands…sometimes lasting into the wee hours of the morning. John always had a million projects going…writing, photography, birdwatching, diving trips…many of which were lifelong pursuits. …and, he was always up for something new to do.*"

John, during a faculty-student challenge at the Fairleigh Dickenson West Indies Laboratory (USVI) with the staff, at the back (L to R) Bob Carpenter, Bill Gladfelter, John, and Betsy Gladfelter, and students, sitting, (L to R) Scott Boden, Ben Haskell and Andrew Gude.

At WIL, John rapidly began to have a Caribbean-wide influence. Jorge Cortes writes: "*John was one of those early and few scientific leaders with a large spatial and temporal scale view of reality. From the early 1980s he started pushing for a Caribbean-wide monitoring program encompassing the three main coastal ecosystems: mangroves, seagrasses and coral reefs – the first to consider this important holistic perspective. In 1985 he put together a meeting at Discovery Bay Marine Laboratory in Jamaica, bringing scientists and managers from the Greater Caribbean to conceptualize a standardized monitoring of these critical coastal ecosystems across the entire region. That was the beginning of CARICOMP (Caribbean Coastal Marine Productivity) that evolved into a regional program (Cortés et al. 2019), through which many of us met John and subsequently developed life-long friendships built on a common passion and vision for the Caribbean marine environment. John was an enabler to young Caribbean scientists, giving us guidance and hope to make a difference. The CARICOMP participants took several years to agree on a sampling protocol and on how it could be implemented across so* *many countries. John, with great respect for different backgrounds, cultures and academic levels, guided the process in a way in which every participant felt that they were part of a large and meaningful initiative, and not just a data provider, as is so often the case in such multinational "collaborations". The opinion of every participant in CARICOMP had the same weight, which surprised some outsiders who thought that the scientific north should teach and lead the rest. As such, CARICOMP was the creation of many marine scientists across the Caribbean and, over nearly two decades, generated valuable products for science, capacity building and governance of the main coastal ecosystems in the Caribbean. This was John's vision and now his legacy to the region, for which he will never be forgotten. As a passionate scientist and a caring friend to all of us in CARICOMP, John was always there when you needed him and always had words of encouragement not to give up".*

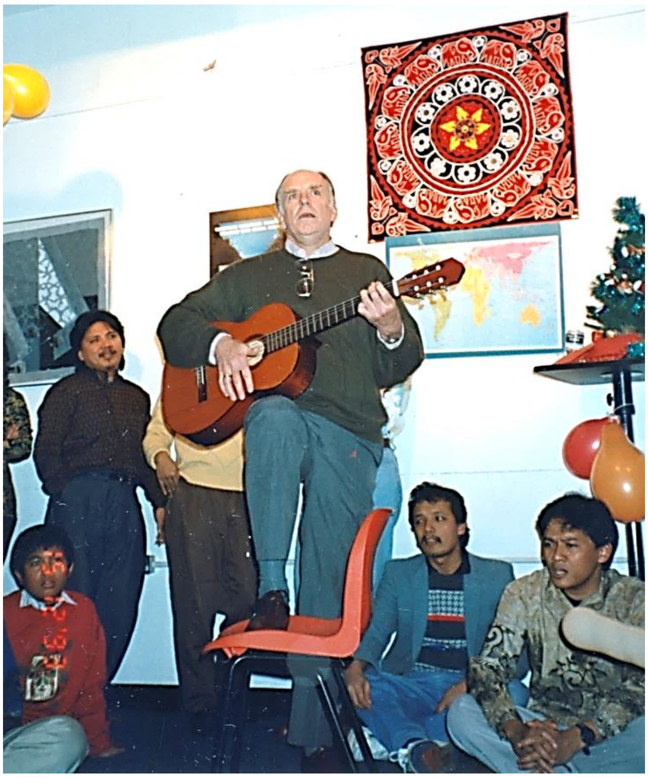
Terry Done also remembers his influence in the 1980s: "*… all too infrequently and all too briefly, John and I were among groups of reef people who visited reefs in those not-so-olden days before the current litany of pressures had so totally decimated so many reefs. We never took for granted how privileged we were to enjoy our brief reef-forays together – be they in Australia, Indonesia, Belize, St Croix or Florida. How fortunate to share some unforgettable 'gee-whiz' times": how about those huge table corals that had covered the Gunung Api lava flow at Banda Neira in only six years? How fragile they were – you could smash their CO2 -weakened skeletons with a flick of your middle finger! Look how damselfish have invaded this patch of Myrmidon Reef: no wonder there are so few corals settling. How good are the fish and corals on this drop-off! Why are there so few corals on this hard-ground? How lucky we were that we could cogitate and wonder about such esoteric natural history, as we hovered with our individual thought bubbles in a reef-front swell or shared a meal at the end of the day".*

A sabbatical from WIL in 1978 generated papers from Palau, Eniwetak and Hawaii. He had a 6-month stint as Program Associate at National Science Foundation (NSF) in 1986 and, also while at WIL, was Program Director of the NOAA Saturation Diving Facility HYDROLAB for 5 years, spending a week underwater with Nancy and two others on a parrotfish project. In the difficult time that WIL faced after hurricane Hugo in 1989, John was central to helping those affected.

In 1988, he took the post of director of the Florida Institute of Oceanography (FIO) where he spent a further two decades, retiring in 2010. During his time there, in partnership with Florida Fish and Wildlife Institute, he added the Keys Marine Lab to

John at the CARICOMP meeting at Coba, Mexico, 1988 (photo by Bjorn Kjerfve)

FIO's facilities and undertook an enormous range of activities, leading to him becoming the global giant of coral reefs that we remember. He was an early leader in the developing field of behavioral ecology, and published over 70 papers, contributed to numerous books and produced several television programs about tropical ecosystems.



John with graduate students at a Christmas party in Newcastle (UK)

Terry Done writes: "*John's breadth of knowledge across the spectrum of science led to a curiosity about big-picture phenomena, such as the ancient and recent histories and environmental drivers and the functional significance of biological diversity within and among coral reefs. It was largely John's efforts that led to the appearance of a comprehensive coral reefs chapter in a mid-1990s compendium 'Functional Roles of Biodiversity: A Global Perspective'. John's big-picture perspective is captured in this quote from a 1994 paper at the creation of the influential SEAKEYS project: "…. natural processes vary on a time scale different from research funding cycles, …. [but] rarely have studies encompassed the time course of: (1) natural phenomena such as population explosions and declines, diseases, storms, and periodic oceanographic atmospheric events such as the ENSO; or (2) natural processes, such as productivity, larval dispersal, recruitment, global warming trends, and sea level rise". These words carry with them a depth and breadth of understanding that came with a life's work trajectory that had progressed to a leadership role from a solid basis of hands-on field ecology and ecosystem science. We had this big picture science foundation with forceful and effective advocacy for each of these institutions, and we have a man who has left his mark*!"

While at FIO, he was invited to be the External Examiner for the international MSc in Tropical Coastal Management at Newcastle University in the UK from 1994-1996. In typical fashion, John wanted to do more, and successfully sought funding for scholarships that allowed students on the course to visit Florida and benefit from the wealth of local scientific and coastal management expertise in the state. Students from Kenya, India and Brazil among others benefitted from the arrangement, often setting up lifelong links to John and Nancy or having career changing experiences. Alasdair Edwards, who ran the MSc course at the time, obtained these memories from two of John's examinees. Dr Satynaryana Masabathula of the Indian Forest Service (retired) vividly remembers: "*the dinner hosted by John and Nancy in their home in mid-June 1994. Since then, not a year has passed without us greeting each other at Christmas each year and I renewing my invitation to him to visit and see Royal Bengal Tigers in the wild. A great mentor, friend, philosopher and above all a great human being.*"

Dixon Waruinge, now Coordinator of the Nairobi Convention for the United Nations Environment Program, wrote on behalf of many such students:

"*Dr John Ogden made a profound contribution to my career choices. In 1992, I was a young Park Warden from Kenya, disillusioned by a very autocratic regime. I harbored a desire to migrate out of Kenya. I was unsure of whether to return back to Kenya to an unhappy job and oppressive politics. In the workplace in Kenya there was no distinction between a marine park warden and a terrestrial park warden. I was often overwhelmed by the conflicts between local communities and park wardens. But one incident changed my view and commitment.*

John not only hosted me in his house but invited me to a hearing on the establishment of the Florida Keys National Marine Sanctuary (FKNMS) at Key West, in 1992. I witnessed first-hand the vociferous opposition by the local community led by the Conch Coalition and others. Conch Coalition *demonstrators were intense, they complained against NOAA and argued against the establishment of the FKNMS and while hearings were going on in one building, the local community was deflating the tires of Dr Ogden's official [FIO] vehicle. All the tires were deflated. I then and at that time understood my calling. I realized I had a good job in Kenya. The Warden's job in Kenya was no longer daunting. I knew what I needed to do, to enjoy my job in Kenya. I was eager to go back home to the job that I had found new love for. No lures, no promise, in the USA or UK could hold me back. I am very happy that I made that choice and, in a strange but wonderful way, Dr Ogden and the Conch Coalition helped me to make that decision. I am truly thankful to John for hosting me and giving me a unique and valuable exposure and experience that no University nor schooling could have done. That experience has paid dividends for me, and my family in so many ways.*"

Sue Wells remembers him as one of those exceptional scientists who understood both the vital role that research and academia must play in conservation and how volunteers and citizen scientists can also contribute. As early as 1989 he pointed out how the Society could help in the development of global strategies and guidance to reduce biodiversity loss (Ogden, 1989). Perhaps more than anyone else, John appreciated how, in his own words (Reef Encounter 18, 1995, p.3), the Society could "*provide an effective bridge between science and management that will have a significant impact on the sustainable use of reef resources and will also advance the cause of reef science*". He supported the establishment of the International Coral Reef Initiative (ICRI) and the International Year of the Reef (IYOR), both of which are central to reef conservation today. While at FIO, he was instrumental in seeing through the 1990 FKNMS Act, and ensuring that it was broadened to address the impact of terrestrial activities on the marine environment and water quality. He was a Board Member of WWF US, and contributed to numerous initiatives for national and international organisations including the NSF, NOAA, U.S. Dept. of State, the World Bank, UNESCO, and private foundations.

A zoom meeting the day after John's memorial service demonstrated his impact on so many people. Betsy Gladfelter writes: "*More than half the folks on the call had been students and/or worked at WIL in the late 1970s, early 1980s (including five PhD students from that period from universities across the country)…and many of the others were friends from school, either high school, college or grad school, all of whom he had kept in touch with through the years and many of whom had visited WIL during that period. …people always wanted to participate in some endeavor or another with John because it was fun to interact with him. His smile and laugh would light up a room. He was interested in many things, had many talents, and loved to share his time with others.* "

John testing out a submersible in Monterey Bay, California (USA).

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Authors are encouraged to include colour pictures or other illustrations (normally 2-4 per article). There are no specifications regarding the format of articles for submission to the editors, but we particularly ask that references should be cited and listed using the style of the ICRS academic journal CORAL REEFS, see: http://www.springer.com/life+sciences/ecology/journal/338. Articles from non-ICRS members are welcome, but those from members are generally given priority. Items should be submitted by email to the senior editor (rupert.ormond.mci@gmail.com) or a relevant member of the editorial panel (see page 2).

Lyndon DeVantier:

Can reef futures be improved by criminalizing ecocide?

(see page 14)

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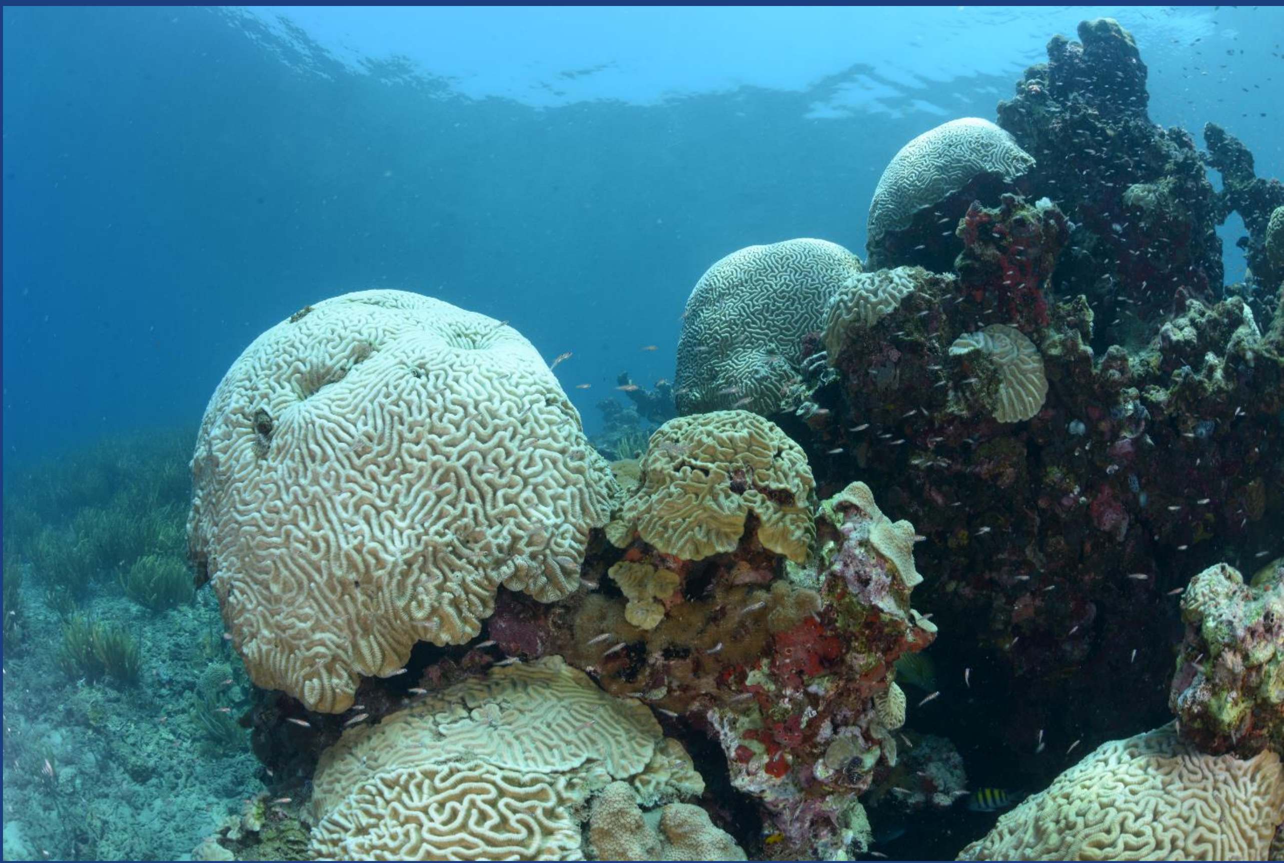

2023 coral bleaching in the south-west Gulf of Mexico, from the report by Guillermo Horta-Puga and colleagues

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