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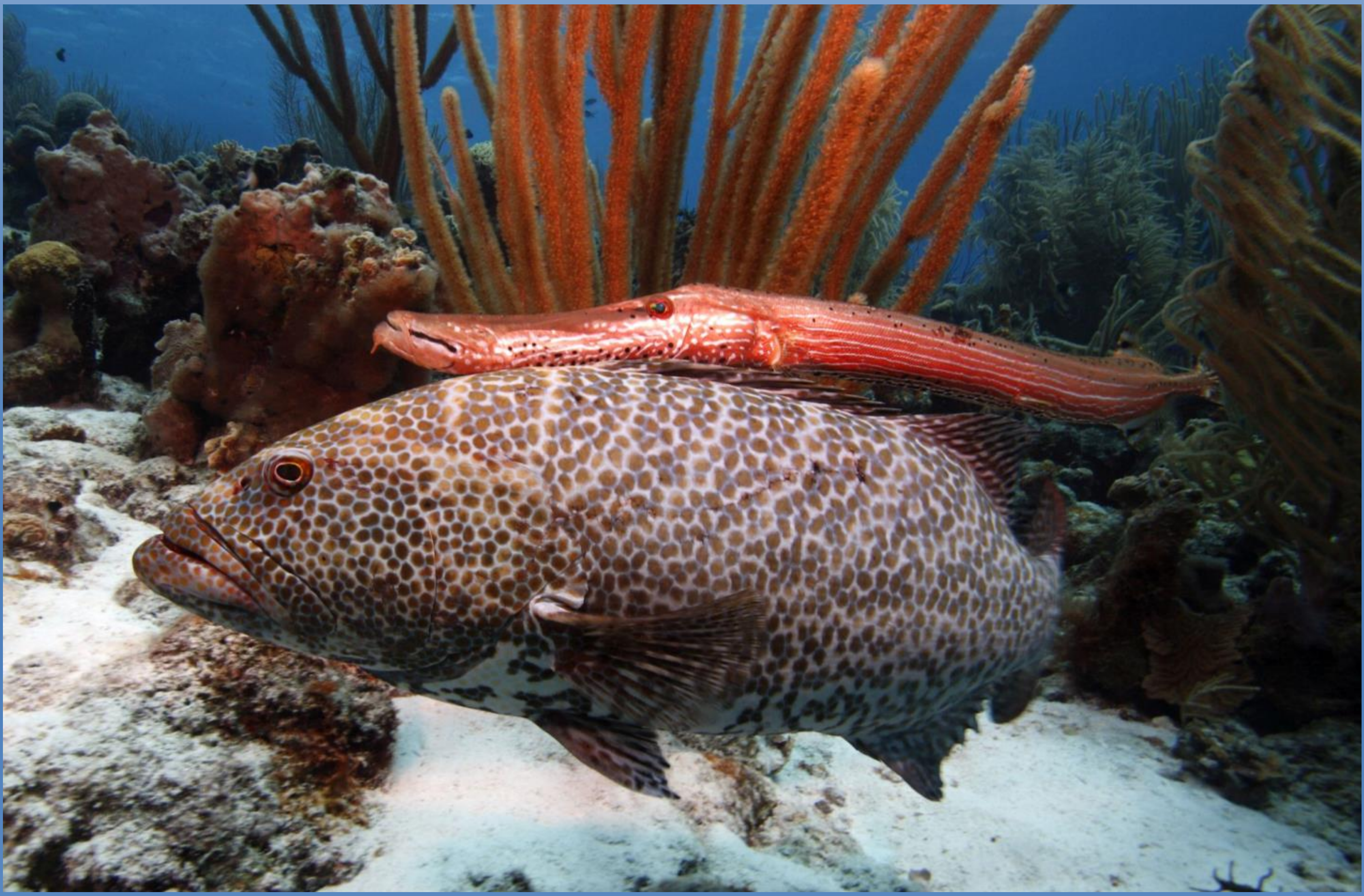
REEF ENCOUNTER



REEF LIVES –Jack Randall, Ian Macintyre, David Bellamy
ARTICLES – Corals and aesthetics, Feed your corals, The deepest photosynthetic coral, Coral wreaths & phoenix corals
GRANTS & AWARDS – ICRS Honors, Graduate Fellowships, Travel Grants
The CBD Post-2020 Framework, The Allen Coral Atlas, 4-D REEF
GRADUATE FELLOWSHIP REPORTS and BOOK REVIEWS
Bleaching in Galapagos, Crown-of-thorns in Mexico, Astropyga in St. Croix

ICRS
International
Coral Reef Society

The News Magazine of the
International Coral Reef Society

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EDITORS, OFFICERS & COUNCIL MEMBERS

REEF ENCOUNTER

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.

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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.

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CORAL REEFS - THE JOURNAL

The International Coral Reef Society also publishes through Springer's 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 (see http://www.springer.com/life+sciences/ecology/journal/338).

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COVER PICTURE: A trumpetfish (*Aulostomus maculatus*) "riding" a tiger grouper (*Mycteroperca tigris*) on a Caribbean reef, in order to approach prey unseen; an illustration from the book "*Coral Reef Curiosities*" by Chuck Weikert (see book review section) – photo by John Anderson / Depositphotos.

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PRESIDENT'S MESSAGE

Dear ICRS Colleagues,

COVID19 has changed the world. We are working remotely, fieldwork and research has been cancelled or postponed, and classes and meetings are being held virtually. In the home, many of our members are trying to work and parent simultaneously. Some have contracted the virus and been sick. In addition, the Black Live Matter movement has shone a stark spotlight on racial inequality and motivated a demanding cry for change. To say "These are uncertain times" is putting it mildly.

But this time of flux provides an opportunity to effect positive change. Global CO2 emissions dropped over the past few months as people adapted to life at home, resulting in fewer cars on the road and fewer planes in the sky. Our innate ability to rapidly adapt is strong and our response to COVID demonstrates that we have the capacity to make large behavioral changes to reduce CO2 emissions and diminish the rate of climate change after the pandemic is over. Could this mark the beginning of society's move toward a meaningful reduction in emissions? A slowing down of climate change would give coral reefs – and all natural ecosystems on the planet - the break they need to thrive and persist over the coming century. ICRS is committed to being part of the solution by making ICRS2024 50% virtual and by supporting regional meetings hosted by our Chapter organizations.

Perhaps it is not so coincidental that, in the midst of the pandemic, the Black Lives Matter movement has raised awareness about racial inequality and inequity across the world. At its core, the movement demands reflection on our present and historical flaws. As an international society, ICRS must do its part. We are committed to continuing to provide graduate student fellowships that are equitably distributed across our membership. We are also actively looking to recruit new members to ICRS Council and Officer positions (taking office January 2021) that will enhance the diversity of our elected members and broaden our collective conversations and actions. The period for candidate nominations for these positions just opened and runs through 31 August 2020. Nomination forms are at http://coralreefs.org/wp-content/uploads/2020/07/ICRS-Council_Nomination.pdf. For additional information, contact Corresponding Secretary Dr. Mike Sweet at m.sweet@derby.ac.uk.

As we move forward, many things continue to change. The ICRS 2020 meeting would have been this month in Bremen, Germany. Because of the heroic efforts of the ICRS 2020 organizing committee chair Dr. Christian Wild and committee members, the meeting has been reschedule for 18-23 July 2021. All accepted abstracts from 2020 will be honored at the 2021 meeting, but need to be resubmitted into the new abstract system. Abstract submissions (including new abstracts) begin 15 July 2020. The program in 2021 will be even better and I am looking forward to seeing all of you in Bremen next summer.

Unfortunately, the financial impact of COVID-19 has also affected ICRS. Delaying the ICRS2020 to 2021 has been quite costly and our projected revenues over the next fiscal year are dramatically lower as a result. We have begun looking into alternative ways to generate revenue for the Society so that we can continue to expand our support for student research and travel, chapter activities, and maintain operations. One recent action was to register ICRS with Smile.Amazon.com in the USA. Purchases made at this website generate 0.05% of the purchase value as a donation to the Society. So far, this option is only available at the US website because ICRS is currently registered as an NGO in the USA. However, we are looking to register ICRS in other countries so that we can be added to the Smile program elsewhere as well. If you are interested in helping us register ICRS in your country, please contact the ICRS Treasurer Dr. Erinn Muller (emuller@mote.org).

Finally, we welcome the Mexican Coral Reef Society as our newest ICRS Chapter member. We look forward to a strong collaboration between our organizations.

As always, I am honored to be President of such an amazing organization. I am grateful to all of you for your continued membership and unwavering commitment to coral reefs.

Sincerely,

Andréa G. Grottoli, ICRS President
(staying safe, social distancing, and wearing a mask)
Professor at Ohio State University

TREASURER'S REPORT

The current financial foundation of the International Coral Reef Society (ICRS) relies upon two primary sources: 1) membership dues and 2) returns gained from the International Coral Reef Symposium in 2016. Membership to ICRS has increased significantly over the last year in association with the membership fee reduction at the upcoming ICRS symposium. Fortunately, many members are choosing to retain membership for multiple years, rather than allowing it to lapse between meetings, providing much needed financial stability to the Society. Membership dues support necessities such as Society Management fees to the Schneider Group, Officers' insurance, state and federal compliance costs as a 501c3 nonprofit, and miscellaneous expenses (webpage upgrades, programming, trophies for awards, etc.). To all of you ICRS members that renew your memberships annually, THANK YOU!

The second source of income for ICRS was net gains from the 2016 ICRS Symposium in Hawaii. These funds allowed us to increase the number of fellowships to students (http://coralreefs.org/student-grants-and-awards/), provide financial awards (Conservation Award, Ruth Gates Award, http://coralreefs.org/awards-and-honors/), as well as sponsorships for Societal Chapters (http://coralreefs.org/committees-and-chapters/) and 'reef-related' meetings. In addition, these funds are supporting the ICRS 2021 meeting in Bremen. Due to Covid 19, the Symposium costs have substantially increased and the Society is providing significant funds to help bridge this funding gap. Without this past success of ICRS 2016, ICRS 2021 could not happen. We very much look forward to seeing all of you in Bremen for a successful symposium, and to the continued success of subsequent symposia.

ICRS is engaged in diversifying our financial portfolio. We have conservatively invested US$ 50,000 in green space mutual funds to securely invest and accrue interest through time. We have also listed ICRS as a charity with Smile.Amazon, as an option for US members to choose (0.5% of purchases are donated to ICRS). Moneys earned from both sources will be used directly to support student scholarships, to help meeting future ICRS Symposia targets of a neutral or negative carbon footprint and to allow for significant remote access and participation. Finally, ICRS Officers and Council members are exploring additional novel ways to increase our financial stability by considering collaborations with corporate partners. We encourage members of our Society to share any insight or recommendations for expanding our revenue options and providing greater financial stability of the International Coral Reef Society. In closing, the ICRS Officers and Councilors want to thank you, the members of ICRS, for supporting the society, not only financially, but also through your continuing support and feedback, essential for ICRS to persist. THANK YOU!

Erinn Muller, ICRS Treasurer

ANNOUNCEMENTS

SOCIETY HONORS AND AWARDS

The Society has announced the following 2020 Award Winners:

Darwin Medal

Nancy Knowlton, Sant Chair of Marine Science Emerita, Smithsonian National Museum of Natural History, USA. She will be awarded the medal and present a plenary lecture at the 14th International Coral Reef Symposium to be held in Bremen, Germany.

Eminence-in-Research Award

Joanie Kleypas, National Center for Atmospheric Research, USA
Valerie Paul, Smithsonian Marine Station at Fort Pierce, USA

Mid-Career Award

Andrew Baird, James Cook University, Australia

Early-Career Award

Carly Kenkel, University of Southern California, USA

Coral Reef Conservation Award

Nyawira Muthiga, Wildlife Conservation Society, Kenya
Susan Wells, conservation consultant, UK

The following members were selected to receive ICRS Fellow status:

Tamar Goulet, University of Mississippi, USA
Janice Lough, Australian Institute of Marine Science, Australia
Hollie Putnam, University of Rhode Island, USA
Mark E. Warner, University of Delaware, USA
Clive Wilkinson, University of Queensland, Australia
Jens Zinke, The University of Leicester, UK

In addition the winners of the awards listed above automatically receive ICRS Fellow status.

Thank you to all nominees, nominators, and writers of letters of support. You all help to make the ICRS a thriving Society. Thank you for all that you do to investigate, protect, and manage coral reef ecosystems.

Nominations for Officers and Councillors for 2021

The International Coral Reef Society (http://coralreefs.org/) (ICRS) is seeking nominations of ICRS members interested in supporting and serving their Society as an Officer or Councillor.

This is a call for nominations (or self-nominations) for 6 council member positions and 2 officer positions (Treasurer and Recording Secretary), to take office from January 2021. All ICRS members are eligible for these positions. The completed nomination form (click here to download), a short CV, and a brief election statement should be submitted to the ICRS Corresponding Secretary Dr. Michael Sweet (m.sweet@derby.ac.uk) by the 31st August 2020. The candidate, proposer and seconder must all be paid-up members of the Society. Members who have served before (other than those who are retiring) are encouraged to offer themselves again, if they wish. Members who are not sure of another person's membership may check with the Corresponding Secretary, or in the on-line directory available on the Members' page of the website at: http://coralreefs.org/membership/membership-services/.

Officers meet monthly via Zoom, and the full council (Officers and Councillors) quarterly also via Zoom. All Officers and Councillors have the opportunity to join committees (i.e., Awards committee, Education committee, Communication committee, Conservation committee, and the Equality, Diversity and Inclusion committee), propose new initiatives, and be involved in decisions about how the Society functions. ICRS Officers and Councillors contribute to the ICRS vision and ensure ICRS remains a global leader in coral reef scientific discovery and education; they also provide a strong voice for science-informed policies that protect our coral reefs for future generations. If you would like more information please contact one or more of the current officers or council, details of whom may be found on the Society's website at: https://coralreefs.org/about-icrs/officers-and-councilors/.

ICRS recognizes the diversity of our members and the strength it provides to our organization and has a proportion of Council positions reserved for members from different global regions. We strongly encourage applicants from all countries, identities, backgrounds, and career stages to consider being nominated (or to self-nominate) for one of the positions.

Michael Sweet, ICRS Corresponding Secretary

Garden Eels, an illustration from the book "*Coral Reef Curiosities*" by Chuck Weikert (see book review section) – photo courtesy Tignogartnahc.

ICRS GRADUATE FELLOWSHIPS

The 2020 graduate fellowships have been awarded to six student members for the research on the topics shown.

Rachel Carlson, School of Earth, Energy & Environment, Stanford University, Stanford, California, USA: Strength in small places: mapping coral larvae in a warming ocean.

Matías Gómez Corrales, Department of Biological Sciences, University of Rhode Island, Kingston, Rhode Island, USA (home country Colombia): Cryptic diversity matters for coral conservation.

Charlotte Page, University of New South Wales, Sydney, New South Wales, Australia: Microbial dynamics during coral reef restoration: the impacts of environment on meta-organism function

Twinkle Sebastian, Marine Biodiversity Division, Central Marine Fisheries Research Institute, Kochi, Kerala, India: Regime shifts in Lakshadweep atoll reef ecosystem.

Rodrigo Rodríguez Vázquez, Programa de Investigación Espacial en Ambientes Costeros y Marinos, Universidad Nacional Autónoma De México, Mexico City, Mexico: Spatiotemporal evaluation of juvenile coral dynamics in a critical condition reef by underwater multispectral orthomosaics.

Kevin H. Wong, College of the Environment and Life Sciences, University of Rhode Island, Kingston, Rhode Island, USA: Determination of the mechanisms driving cross-generational plasticity in reef-building corals to thermal stress

Congratulations to the recipients. 31 applications were received. Many thanks to all applicants and to their sponsors for taking the time to support the Society’s graduate fellowship program.

ICRS Communications Fellowship

As part of the **Action Plan** to be launched in summer 2020, ICRS is intending to create a Science Communication Fellowship (SCF). The idea is to provide funds for an ICRS member to gain science communication skills through a workshop, course, internship, or some other equivalent experience. At the end of their training, the member would provide some service as a science communication person for ICRS. It is anticipated that the Fellowship will not be restricted to students; it will nevertheless be for new training, not for executing existing outreach or communication activities.

The desired outcome is that we will have more coral scientists better versed in science communication. The long-term view is that these individuals will throughout their careers be better able to communicate their findings and those of reef science more generally to the broader public. For further information please contact James Crabbe (Chair, ICRS Education Committee), e-mail: james.crabbe@wolfson.ox.ac.uk.

ICRS Student Travel Awards

The Society has announced the award of 30 Society Student Travel Award Grants, to assist recipients to attend the 14th International Coral Reef Symposium in Bremen, Germany from 18th-23rd July 2021 (ICRS2021). There were 246 applicants.

The following recipients will receive US$1000.00 and have their conference registration fees paid for by ICRS2021 (value of ~500 Euros):

Jonathan Emmett, Manonmaniam Sundaranar University, India
Nuria A. Estrada Saldivar, National Autonomous University of Mexico, Mexico
Roger Guzman Rodriguez, Universidad Ana G. Mendes Recinto de Cupey, Puerto Rico
Kelly Inagaki, Universidade Federal do Rio Grande do Norte, Brazil
Gabrielle Koerich, Federal University of Santa Catarina, Brazil
Laura Martinez, Pontificia Universidad Javeriana, Colombia
Crystal McRae, Simon Fraser University/National Dong Hwa University, Taiwan
Mary Shodipo, Silliman University, Philippines
Holly Trew, University of the West Indies, Barbados
Veronica van der Schyff, North-West University, South Africa

The following recipients will have their conference registration fees paid for by ICRS (value ~500 Euros):

Amanda Alker, San Diego State University & University of California San Diego, USA
Jessica Bleuel, Universidade Federal do Rio Grande do Nort, Brazil
Prishani Boodraj, University of KwaZulu-Natal, South Africa
Sara Cannon, University of British Columbia, Canada
Daphne Cortese, PSL Universite Paris/CRIOBE, French Polynesia
Courtney Dunphy, Northeastern University, USA
Abigail Engleman, Florida State University, USA
Nicolás X. Gómez Andújar, University of Puerto Rico, Puerto Rico
Steven Johnson, Oregon State University, USA
David Juszkiewicz, Curtin University, Australia
Irina Koester, University of California, San Diego, USA
Katrina Luzon, De La Salle University Manila, Philippines
Patrick Nichols, University of Hawaiʻi at Mānoa, USA
Lauren Olinger, University of North Carolina Wilmington, USA
Ashley Nichole Peterson, University of California Irvine, USA
Silas Candido Principe de Souza, University of São Paulo, Brazil
Aida Sotelo, University of California, USA
Rosemary Steinberg, University of New South Wales, Australia
Samiris Suleiman, University of Puerto Rico, Puerto Rico
Layla Poubel Tunala, Federal Fluminense University, Brazil

Congratulations to all recipients and thank you to all applicants and recommenders.

Lisa Rodrigues, Chair Selection Committee

CORAL REEFS BEST PAPER AWARD

Volume 38, 2019

Members of the Coral Reefs editorial team nominated 16 papers for consideration for the journal's 2019 Best Paper Award. The clear winner was a review from Hannah Nelson and Andrew Altieri entitled 'Oxygen: the universal currency on coral reefs'. As ever, some of the editorial team were torn between several good papers; this led one voter to describe effusively Hannah and Andrew's paper as 'a beautifully done review paper that will undoubtedly spur on a whole new flurry of research into low-oxygen tolerance and oxygen flux on reefs in different boundary layers at different depths. This is exciting, scary, and urgently needed research, and while many papers have discussed the role of oxygen on coral reefs, I don't think any prior paper has been quite the rallying cry that this one is'. Here is a paper that truly stands on the shoulders of giants from the pre-Google era until the present. For those for whom a picture is worth a thousand words – take a look at this review's excellent offerings!

Hannah R. Nelson and Andrew H. Altieri. Oxygen: the universal currency on coral reefs

Coral Reefs, 38(2), 177-198.

Abstract: *Coral reefs are suffering unprecedented declines worldwide. Most studies focus on stressors such as rising temperatures, nutrient pollution, overfishing, and ocean acidification as drivers of this degradation. However, recent mass mortality events associated with low oxygen on coral reefs indicate that oxygen is a critical factor that can be limiting in reef environments. Here, we present evidence that integrates across disciplines and perspectives to reveal how natural and anthropogenic factors drive variation in oxygen at multiple scales on coral reefs. This variation, in turn, limits essential processes such as productivity, respiration, and calcification on reefs and often plays a role in the outcome of interactions between corals and their competitors, pathogens, and mutualists. Moreover, the apparent effects of temperature, eutrophication, acidification, and other stressors on corals are commonly mediated by oxygen. As a consequence, the imprint of oxygen variation is evident in many patterns including reef biodiversity, coral bleaching, colony morphology, and fish behavior. We suggest that the structure and dynamics of coral reefs can be fully understood only by considering the ubiquitous role of oxygen, and we identify critical areas of future oxygen research to guide the study and management of coral reefs in a changing world.*

Keywords: Bleaching, Calcification, Climate change, Dead zones, Hyperoxia, Hypoxia

Three other papers received multiple nominations for the year's award and receive honorable mentions. They were:

Rosset S, Koster G, Brandsma J, Hunt AN, Postle AD, & D'Angelo C. Lipidome analysis of Symbiodiniaceae reveals possible mechanisms of heat stress tolerance in reef coral symbionts. Coral Reefs 38, 1241-1253 (2019)

Skirving WJ, Heron SF, Marsh BL, Liu G, De La Cour JL, Geiger EF & Eakin CM The relentless march of mass coral bleaching: a global perspective of changing heat stress. Coral Reefs 38, 547–557 (2019)

Wilson SK, Robinson JPW, Chong-Seng K, Robinson J & Graham NAJ Boom and bust of keystone structure on coral reefs. Coral Reefs 38, 625–635 (2019)

Congratulations to all!

Terry Done (Convener of Coral Reefs Best Paper Award)

Special Issue of *Coral Reefs* on Reefs in Marginal and Extreme Environments

Taking PAM measurements from a coral in the Arabian Gulf

Coral reefs are one of the most biodiverse and economically important ecosystems in the world, but they are rapidly degrading due to the effects of global climate change and local anthropogenic stressors. Scientists are increasingly studying coral reefs that occur in marginal and extreme environments to understand how organisms respond to, and cope with, environmental stress, and to gain insight into how reef organisms may acclimate or adapt to future environmental change. These include systems characterized by unusually high, low, and/or variable temperatures (intertidal, lagoonal, high-latitude areas, and shallow seas), by turbid or urban environments, by acidified habitats, and by mesophotic depth. They include reefs spread geographically throughout most of the tropics. In June 2020 Coral Reefs published a special issue on this topic titled 'Coral Reefs in a Changing World: Insights from Extremes' that includes over 25 articles that build on the growing body of literature on these unique and important ecosystems, providing a deeper understanding of the patterns and processes governing life in marginal reef systems, and the implications that these insights may have for the future of tropical coral reefs in our rapidly changing world. An editorial review on this rapidly growing topic can be found here, and all articles associated with the issue can be found here as a table of contents.

Editorial Review: Burt JA, Camp EF, Enochs IC, Johansen JL, Morgan KM, Riegl B, Hoey AS (2020) Insights from extreme coral reefs in a changing world. Coral Reefs https://doi.org/10.1007/s00338-020-01966-y

Special Issue Table of Contents: Coral Reefs in a Changing World: Insights from Extremes. Issue Editors: Burt JA, Camp EF, Enochs IC, Johansen JL, Morgan KM, Riegl B, Hoey AS (2020) Coral Reefs https://link.springer.com/journal/338/39/3

John Burt, Center for Genomics and Systems Biology,
New York University - Abu Dhabi, UAE

Modified Arrangements for ICRS 2021

As most if not all members will know, because of the Covid-19 crisis, the 14th International Coral Reef Symposium, ICRS 2020, has been postponed for a year, and will now take place, as ICRS 2021, from 18th-23rd July, 2021. The location, the historic city of Bremen in northern Germany, remains the same, the conference venues remain the same, and already most of the intending delegates will have been rebooked in the hotels into which they were previously booked for this year.

Almost all (99%) of the sessions and workshops originally planned for 2020 have been carried over to 2021. These will be as shown on the conference website at: https://www.icrs2021.de/program/session-program/ and https://www.icrs2021.de/program/workshop-program/.

However, naturally, the timetable has shifted. Most importantly, **intending delegates are requested to submit or re-submit their abstracts over the period July 15th to September 15th (2020).** Those delegates who had their oral or poster presentations accepted for 2020 will automatically have this acceptance carried forward to 2021. But in addition, existing abstracts may be revised, or abstracts for posters submitted for consideration as oral presentations, or completely new abstracts submitted.

For members not already registered for 2020, information about Bremen, a most attractive historic city, can be found at: https://www.icrs2021.de/services/bremen/ and information about appropriate accommodation at: https://www.icrs2021.de/services/accommodation/. Much other helpful information is provided on other pages of the conference website: https://www.icrs2021.de/.

Special Pre- and Post- Conference Issues of the Journal *OCEANS*

Arrangements were made with the publishers MDPI for delegates who wished to submit papers based on their oral or poster presentations to a Special Conference Issue of the Journal *OCEANS*. Until ICRS12, following each conference, large volumes of Conference Proceedings were published and distributed to every delegate. But given the general decline in numbers of papers submitted to such Proceedings, ICRS14 decided to arrange for the publication of a special conference issue of a suitable journal. *OCEANS* is an open access journal, but has agreed to publish accepted papers free of charge.

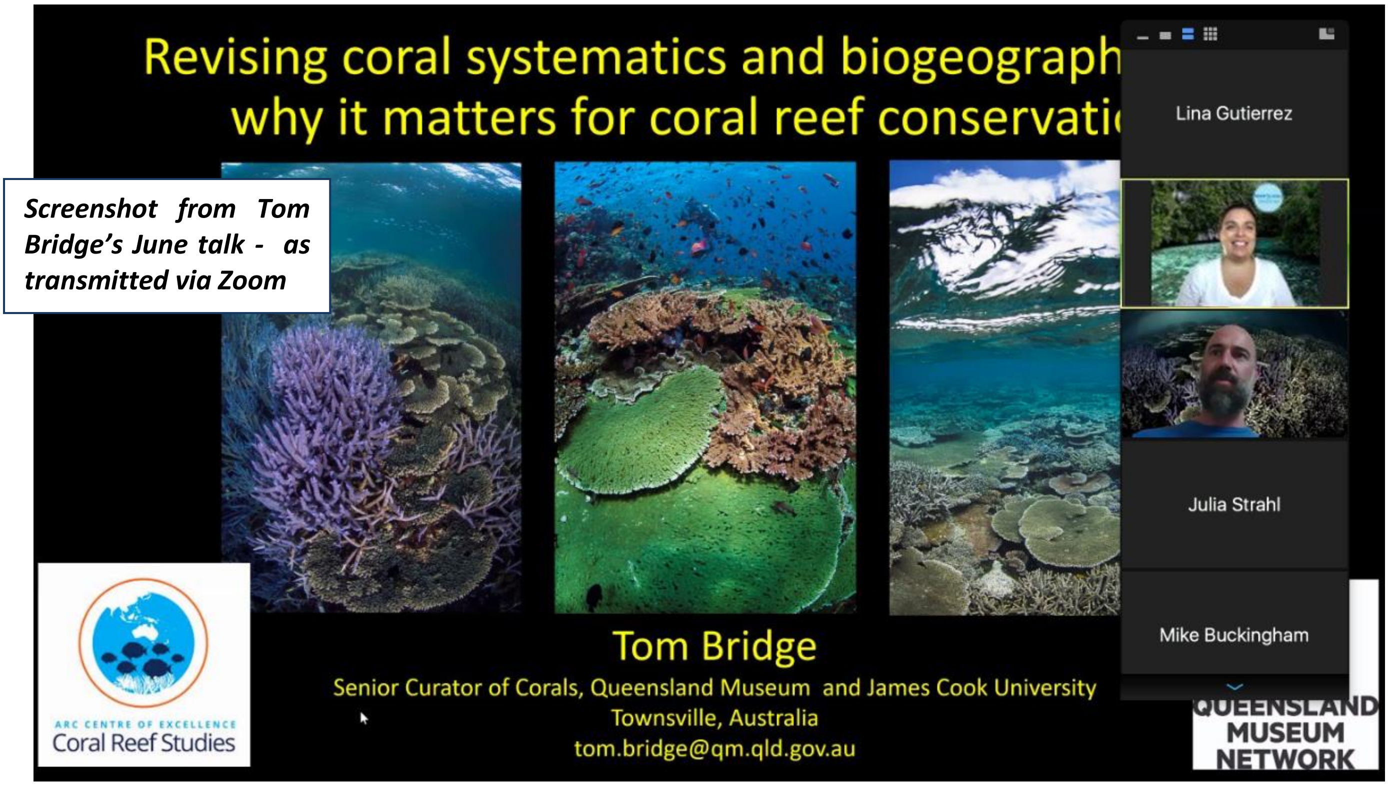
In view of the postponement of the conference, *OCEANS* has now agreed to publish not only an issue following the 2021 conference, but also an earlier issue based on posters or talks that delegates intended to present this July (2020), but consider will be out-of-date (and so will be replaced) by July 2021. Delegates who wish to submit manuscripts based on abstracts submitted to ICRS 2020 are asked to advise the special issue editor, Rupert Ormond (rupert.ormond.mci@gmail.com), of their intention to do so by August 1st 2020. Details are available on the conference website at https://www.icrs2021.de/program/oceans-special-issue/, while further advice can be obtained from the special issue editor. Manuscripts should be submitted by October 30th via the *Ocean*s website at: https://www.mdpi.com/journal/oceans/special_issues/coral_reefs.

REEF e-talks
Online seminar series
by Reef Systems at ZMT

Tune into Reef e-talks today! Enjoy our online seminars series via Zoom and hear the latest coral reef studies no matter where you live. Reef e-talks started as an attempt to communicate science freely and flexibly during times of COVID-19 confinement, but will continue to do so indefinitely. Launched in May 2020, it opened with a brilliant talk by Professor Michail Matz (University of Texas at Austin) on the potential for coral adaptation to global warming in the Indo-West-Pacific. In June, Dr. Thomas Bridge (James Cook University) gave a fantastic overview on why we should consider coral systematics and biogeography when we think about coral reef conservation. In July, Dr. Julia Strahl (Oldenburg University) will present her fascinating findings on coral' reactions to light limitation. The line-up for the rest of the year includes Professor David Booth (University of Technology Sydney) on poleward-shifting coral-reef fishes, and Mr. Tim D'Urban Jackson (Bangor University) on the new era in coral reef spatial ecology facilitated through three-dimensional digital mapping. Registration is a just one-click away; this will give you the Zoom link for joining the different meetings. Our hope is that the talks will attract the interest not only of scientists, but of non-scientists with an interest in the past, present, and future of coral reefs.

Reef e-talks is hosted by Dr. Sonia Bejarano at the Reef Systems Research group at the Leibniz Centre for Tropical Marine Science (ZMT), in Bremen, Germany. More than a hundred registrants per speaker have joined during the last two months, and at least 20 countries have been brought together in the same virtual room. Perhaps the most rewarding outcome of the Reef e-talks so far, has been hearing scientists from small Island countries being genuinely grateful for the opportunity to hear these talks, free and from home, since travelling to international conferences is for some of them prohibitively expensive. All talks are being recorded, and publicly shared (with the consent of the speakers) via a dedicated YouTube channel.

Register here: [Reef e-talks]



Revising coral systematics and biogeograph
why it matters for coral reef conservati

Tom Bridge
Senior Curator of Corals, Queensland Museum and James Cook University
Townsville, Australia
tom.bridge@qm.qld.gov.au

Screenshot from Tom Bridge's June talk - as transmitted via Zoom

ICYMARE 2020 - An online early-career marine researchers networking event

ICYMARE stands for International Conference for Young MArine REsearchers. This annual conference is for early-career researchers from all marine sciences. Organized bottom-up, it is completely run by volunteers, while being hosted by different institutions each year. ICYMARE provides a professional setting but, at the same time, an easy-to-talk-to atmosphere where Bachelor, Master, and PhD candidates in marine sciences can gain their first conference experiences and begin to establish their own personal worldwide network.

After a successful first ICYMARE meeting in Bremen, Germany, with about 350 participants, due to the Corona pandemic, ICYMARE will go online for 2020. Within the ICYMARE family we take care for each other and do not want to put anybody at risk when travelling and meeting in bigger groups. Nevertheless, nowadays it is even more important to connect, discuss our science within the community and create flexible plans for the future. As a means of supporting you, ICYMARE 2020 will enable smaller groups (of about ten people) to connect via a video conference to chat, and to present their research to each other, either topical or interdisciplinary. Volunteer hosts will moderate to make sure everyone gets a chance to discuss their science and related topics. ICYMARE 2020 will be a complimentary online networking event on 26 and 27 August 2020. Participants will also be given a chatroom where they can stay in touch after the video conference so that we can create a long-lasting global and sustainable network with each other. This conference will be accompanied by a study both of the use of online alternatives to on-site conferences and of how marine early-career researchers are dealing emotionally and research-wise, under the circumstances of the Corona pandemic.

ICYMARE is an event of the Bremen Society for Natural Sciences. For more information on how to get involved and support us, check out our homepage www.icymare.com. Feel free to contact us.

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REEF PERSPECTIVES

Personal Views, Experiences and Insights

Corals – the encounter of science with aesthetics

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All these things which come and go in the troubled atmosphere of sleep,
and to which men give the name of dreams,
are, in truth, only realities invisible to those who walk about the daylight world.
The dream-world is the Aquarium of Night.
Victor Hugo, Toilers of the sea, 1911

Human interest in the coral world has evolved considerably over history. While humans were building survival skills for finding food and migrating to new territories, corals were an ominous symbol in maritime navigation. Initially, corals were considered plants. Later, researchers classified them as animals, and most recently, scientists have established their holobiont nature. Their role as ecosystem engineers rose to paramount importance with human penetration into the reef habitat, which Revelle aptly described when remarking that "[o]f all earth's phenomena, coral reefs seem best calculated to excite a sense of wonder" (Revelle 1954, p. III). Charles Darwin's wonder at coral reefs and their builders, from 1845 (p. 439), is also still unreservedly valid: "We feel surprise when travelers tell us of the vast dimensions of the Pyramids and other great ruins, but how utterly insignificant are the greatest of these, when compared to these mountains of stone accumulated by the agency of various minute and tender animals!" Parallel to various biological investigations, geologists performed costly explorations of fossil reefs in search of natural reservoirs of oil and gas. Coral colonies and coral formations were a source of building material for houses and cathedrals that were completed in the 16th and 18th centuries, and that function to this day, in places with abundant coral life such as Panama, Cuba and the Dominican Republic. A piece of fossil coral has been found that served as a pendant in the Upper Paleolithic, c. 10,000 BCE (Shick 2018), while "Hearts of charm" (Fig. 1) were elaborated from coral colonies in the 18th century (Schouppé 1993).

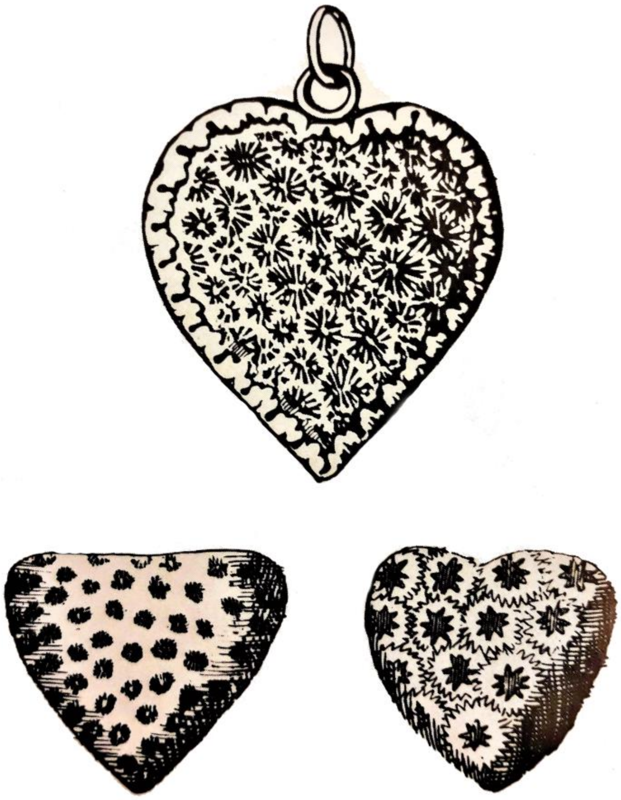

Figure 1. "Hearts of charm", pendants of fossil corals (Schouppé 1993).

Since the 1970s, the accelerating crisis and decimation of coral reef ecosystems has prompted rapidly-growing new disciplines in reef conservation and management. For restoration purposes, corals are now the object of human-assisted evolution, involving interventions to accelerate the rate of natural evolutionary processes while avoiding genetical engineering (van Oppen et al. 2015). Their "combination of attributes – creative power and fragility, resilience and susceptibility, productivity and vulnerability to overexploitation – makes management of coral-reef systems a particular challenge to science" (Birkeland 2015, p. 7). In order to reflect its changing priorities, the name of The International Society for Reef Studies became The International Coral Reef Society. The ancient commodity of corals, for artisanry and apotropaic talismans, received a push from recent tourism to reef destinations all over the world. Coral properties such as their skeletal chemistry and porosity have found applications even in medicine, as excellent human bone grafts (Fessenden 2014).

Figure 2. Painting at first hand, Scientific American, May 1922.

But the coral world has not only been an object of interest for scientific research and environmental protection; for a long time, it has also inspired reflection and the creation of masterpieces by writers and artists of varying cultures and languages. A powerful metamorphosis of the human body into marine organisms is implied as "a sea-change" in "The Tempest" (probably written in 1610-1611), when Ferdinand believes that the bones of his father have become corals (Shakespeare 2006, p. 35-36):

Full fathom five thy father lies,
Of his bones are coral made.
Those are pearls that were his eyes,
Nothing of him that doth fade
But doth suffer a sea-change
Into something rich and strange.

In "The Coral Reef" José-Maria de Heredia, the French poet of Cuban origin, drew in 1893 a reef scenery with "blossomed" animals and a "forest of . . . corals which intermingle" (translation by Shick 2018, p. 117):

The submarine sun, mysterious aurora,
Lights for forest of Abyssinian corals
Which intermingle, in the depths of their worm pools
The blossomed animal and the living flora.

Exploration of the natural reef habitat challenged human perceptions as a result of the physical characteristics of the underwater world. The situation there is real, and at the same time has something "*je ne sais quoi,*" at the least very unusual for the terrestrial inhabitants that we are; it brings up in us strong, strange feelings and impressions. Underwater visual perception is not like that in the air; colors disappear with depth, time pressure and confusion both intensify, there is often no horizon in the background to assist with orientation, and weightlessness empowers with our movements extraterrestrial ability (Cohen 2014, 2015). The coral reefscape bewitches with an unrealistic plasticity and brilliant coloration.

The experienced "fantasy" first attracted the eyes of symbolists and surrealists. Painters, photographers and filmmakers adapted their methods to work underwater (Fig. 2). Coral curiosities galvanized designers of extravagant dress (Fig. 3). Shakespeare's metaphor for corals as "something rich and strange" became a dictum for coral art (Fig. 4) and culture (Endt-Jones 2013, 2014; Schuster 2019). Victorian coral jewellery and glass models are in long-standing vogue, and the hyperbolic crochet of coral reefs is avant-garde (https://artthescience.com/blog/2019/03/01/creators-vanessa-barragao/). Recently, the aesthetics of marine life has led to a lavishly illustrated historical perspective of the natural and cultural history of corals, even including an example of a music score inspired by a coral reef (Shick 2008, 2018, p. 151).

Sadly, over the course of only one generation, the unique euphoric vibrance and plenitude of reef life is declining into pessimism and a disturbed fantasy of an agonizingly poisoned paradise. From an enchanting icon of biodiversity, corals morphed into a barometer of a losing battle ecosystem. It is curious that two domains of human activity related to the coral world - the artistic and scientific - exist so separately. It is conventionally assumed that science brings knowledge and that art offers aesthetic fulfilment and enjoyment. In reality, the extraordinary sensitivity of the masters of literature, visual arts and music, and their poetic tools of expression, surprise us by catching hues and facets of the coral world that remain undetectable using scientific methodologies.

Figure 3. Design for an underwater-themed ball dress, Charles Frederick Worth, 1860. Courtesy V & A, London.

Films like "Chasing coral" (https://www.netflix.com/title/80168188?tctx=0%2C0%2Cbe&trackId=13752289) provide an opportunity to draw closer the scientific and aesthetic approaches to corals, amalgamizing global preoccupations for their future. Another bridge available to bring together artistic and scientific approaches is contemporary digital culture, with its capacity for collecting and sharing information. While scientific literature is managed in many institutions' libraries, it is a timely task to collect existing data about works by writers and artists on corals and reefs. The idea was addressed as an appeal in the forum Coral-List (https://coral.aoml.noaa.gov/pipermail/coral-list/2019-October/021041.html) and is expected to receive for the first time large international attention during the 14th International Coral Reef Symposium in Bremen. In order for us to be able to act more effectively, it is time for us to hear and bring together all the evidence for our preoccupations with, and wonderment at, the coral world.

Figure 4. Life in coral reef, painting, Ginette Callaway https://www.google.com/search?client=firefox-b-1-d&q=ginette+callaway+coral+reef

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Feed Your Corals!

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As a student of the late Ruth Gates, I made a concerted effort when I began my Ph.D. degree back in 2003 to read all of the classic articles in the coral-dinoflagellate symbiosis field; these included seminal works from Dr. Gate's own post-doctoral supervisor Len Muscatine, who, virtually single handedly, pioneered the field. Among the many things we have learned from Dr. Muscatine's collective scientific legacy is that the Symbiodiniaceae dinoflagellates can effectively translocate all of the carbon that they fix into the cytoplasm of the host anthozoan gastrodermal cells in which they reside (Muscatine et al. 1981). In other words, the corals that are responsible for building the beautiful, high-biodiversity reef structures (Fig. 1) we know and love are the ultimate physiological oxymoron: a photosynthetic animal (Fig. 2). Students of marine biology know, however, that, like all cnidarians, coral polyps feature nematocysts that can "harpoon" passing prey (Fig. 3), and that such heterotrophic feeding tends to occur at night (something with which avid night divers like myself are particularly familiar). Although the degree of nitrogen (re)cycling within the coral "holobiont" is still debated, it is clear that corals regularly oscillate between autotrophy and heterotrophy *in situ* (Grottoli et al. 2006); why, then, has it become the norm to starve our corals during experiments? I should mention right away that, prior to 2012, I myself was guilty of this. In fact, I published the results of a short-term heat stress experiment on Indo-Pacific corals in 2011 (Mayfield et al. 2011) in which I unintentionally cultivated malnourished corals by depriving them of exogenous food!

Over the past decade or so, I have had the good fortune to tour, or to collaborate with, approximately 20 marine laboratories and research aquaria; at only two of these (as of July 2020) did students or technicians readily feed corals during experiments. Most researchers simply incubated their colonies, nubbins, larvae, etc. in filtered (or even artificial) seawater. In most of these cases, it was abundantly clear to the trained eye (i.e., mine), and likely even to casual observers, that the "control" study corals were sick; they had essentially stopped growing (or were growing at rates much lower than on the reef), tissues had paled, or they bleached or succumbed to infection under environmental conditions in which they would normally have thrived *in situ*. Why weren't people feeding their corals? I have a few theories that I have posed below as a "devil's advocate" – echoing the claims and questions that I myself would have uttered years ago.

Figure 1. A spectacular, high-biodiversity coral reef in Komodo National Park, Indonesia. You better believe these corals feed on plankton! (photo by author)

"Corals should survive via photosynthesis alone, so I don't need to feed them."

I think this statement has to do, amongst other things, with a misinterpretation of Dr. Muscatine's classic articles; just because the endosymbiotic dinoflagellates *can* translocate virtually all of their fixed carbon to their hosts does not mean this is *always* the case. In other words, simply because, theoretically, most corals *should* be able survive off autotrophy alone, this does not mean that, in practice, they always do. This is no discredit to these works, which form the foundation of the entire field, nor do I intend to say that autotrophy is unimportant to coral biology; in contrast, it is likely the most integral facet of their physiology. It *is* to say to you budding coral reef experimental biologists out there, that you should know *before* you begin your study just to what degree your model coral requires an exogenous food supply (and/or whether it can, as a collective holobiont, synthesize all essential amino acids). You may be astonished by the ravenous appetites of corals, even those with polyps so tiny (e.g., poritids) that you can't help but wonder how they are able to spear anything in the water column!

Figure 2. A dissecting microscope image of the reef-building coral Pocillopora acuta *in which myriad dinoflagellate cells are evident (as yellow-brown pigmentation). Each polyp is about 1 mm in diameter. (photo by author)*

"My experiments are short (hours to days); surely my corals won't become malnourished if I don't feed them over such timescales, right?"

Although I do believe you can get away with performing a multi-hour experiment without feeding your corals, I am no longer so confident about multi-day ones, and if you carry-out long-term (weeks to months) studies of corals, you will quickly notice that your "controls" become increasingly less healthy over time (see signs of distress listed above). Do the requisite experiment yourself: incubate corals at ambient temperatures in replicate tanks, feeding half with brine shrimp (or other aquarium feed) and then starving the rest. I bet you get significantly higher growth rates in the fed treatment.

"I only care about differences WITHIN my experiment (control vs. high-temperature, for instance); who cares if my controls are a little puny compared to what they would be like in the ocean?"

I have heard insidious statements similar to this often, and I actually disagree with this argument; if your control corals gradually die over the course of your study, despite seeing significant differences between treatments that make for a publishable dataset, I honestly don't feel like your study should be published. However, most such studies *do* get published (none aside from my own cited above will be mentioned herein, in order to avoid the perception that I am mounting "attacks" on any particular individuals), and unfortunately this then leads subsequent generations of researchers to think that using unhealthy corals as controls is acceptable! Thankfully, it is becoming increasingly feasible to assess coral growth *in situ* using, amongst other approaches, new imaging technology; why not compare growth rates between corals of your experimental tanks and the host colonies from which biological material was taken in the ocean, so as to be sure that the former corals are not actually *struggling* to acclimate to aquarium life?

“Won’t feeding introduce unwanted bias into an experiment? Couldn’t differential feeding across replicates or between treatments obscure the differences I aim to disentangle?”

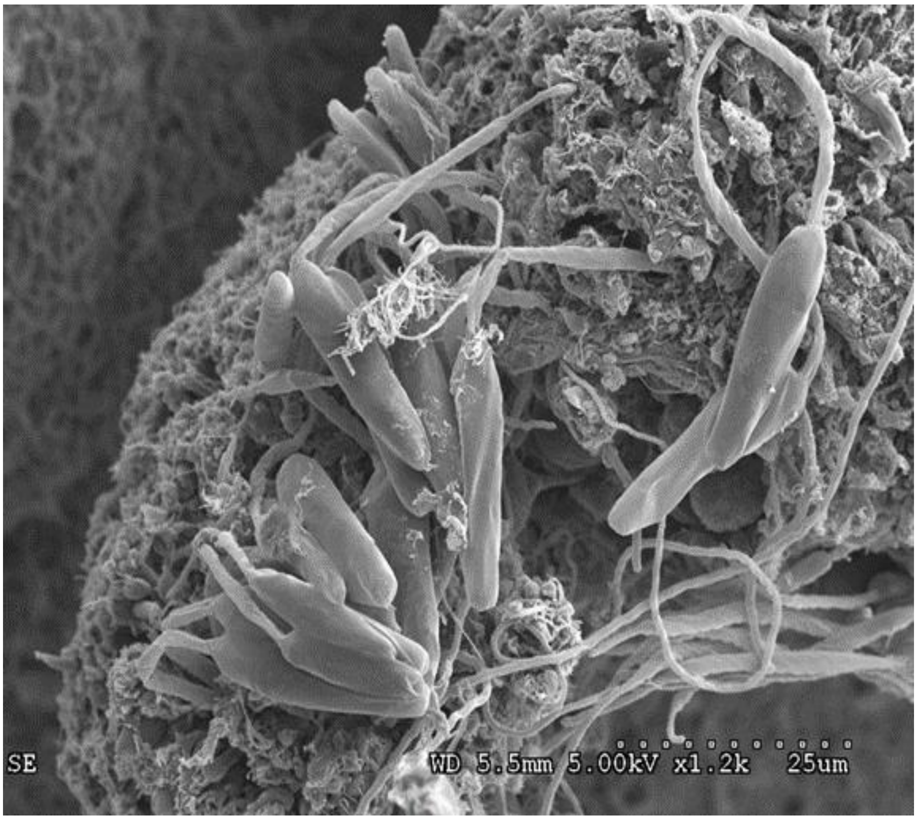

*Figure 3. A scanning electron micrograph of nematocysts discharged from the tentacles of a Taiwanese reef coral (*Pocillopora acuta*). (photo by author)*

This is likely the best argument against feeding, and I would concede that, yes, there is the inherent risk of introducing feeding bias. However, to my mind this represents a tradeoff that must be made: should I slowly kill my “healthy control” corals in order to have a more tightly constrained experiment, or would I rather use fed+nourished corals but risk having introduced the aforementioned bias? To me, if you are attempting to make conjectures as to how corals will fair in the ocean (in response, for instance, to looming climate change scenarios), then feeding them directly, or else culturing them in mesocosms, together with a suite of other reef inhabitants, where they may feed freely, is likely your best bet (Fig. 4). If you are carrying out a multi-hour heat shock, you may be able to get by with counting on autotrophy alone to fuel your corals. But to my mind you should nevertheless, as advocated above, carry out some preliminary experiments (preferably before your big thesis study) in which you attempt to convince yourself of just how well your corals do when deprived of an exogenous food supply. Again, I would venture that the results may astound you.

Now, as I descend from my soapbox, it is time for full disclosure. I worked in the research wing of a public aquarium for a decade, and I had the opportunity to interact extensively with both marine scientists and aquarists. It is from the latter alone that I learned of the importance of feeding corals. Who better to learn from the best ways to grow corals for experiments than people who grow coral for a living? I can’t tell you how many times I visited research facilities (those 20 or so mentioned above), even those adjacent to public aquaria, where the scientists were repeatedly (and inadvertently) killing their corals, while their aquarist neighbors were maintaining corals alive (and presumably healthy) for years. This is also to say that I believe the literature is weak on articles describing just how to go about culturing corals over long timescales, and how such husbandry considerations play into experimental design and data interpretation - an issue we broached recently in a published review article (Mayfield et al. 2019). In concert with this, and in closing, I would recommend that research scientists not discount their local aquarists and coral gardeners; sure, they may not always have advanced degrees or routinely publish peer-reviewed articles on their findings, but they are nevertheless wellsprings of information on coral culture and, at least in my experience, better at keeping corals alive in culture for extended periods than we scientists.

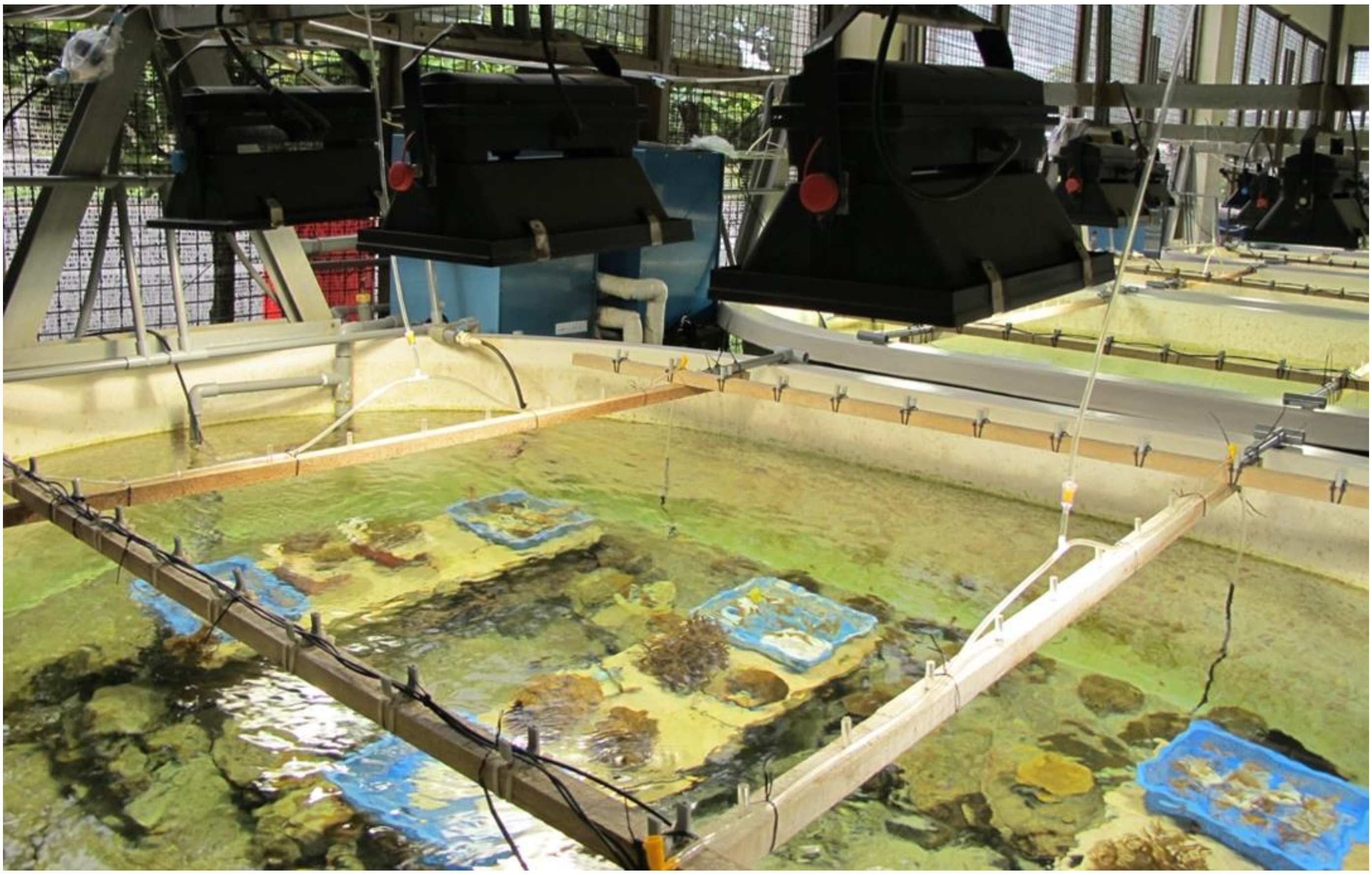

Figure 4. A coral reef mesocosm housed at Taiwan's National Museum of Marine Biology and Aquarium. When corals are allowed to feed freely in these multi-functional group "ecosystems," they can be maintained at temperatures up to 30-31 ℃ for months on end (temperatures that would kill them were they starved; Mayfield et al. 2013). (photo by author)

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REEF CURRENTS

General articles and overviews of reef science and management

Growth rates of the world's deepest photosynthetic corals

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In the warm waters around the world, photosynthetic corals form the foundation of vibrant shallow-water coral reef ecosystems. The success of these corals is tied to their ability to harness the energy of the sun in low nutrient environments and secrete robust calcium carbonate skeletons. These corals are commonly called zooxanthellate due to their symbiotic microalgae (Family Symbiodiniaceae) which live in their transparent tissue and give the corals their primary color. The calcium carbonate skeletons of corals enable them to compete for space, withstand strong hydrodynamic forces, and harvest light much more efficiently than non-calcifying photosynthetic organisms, due to their reflectivity and scattering properties (Enriquez et al. 2017).

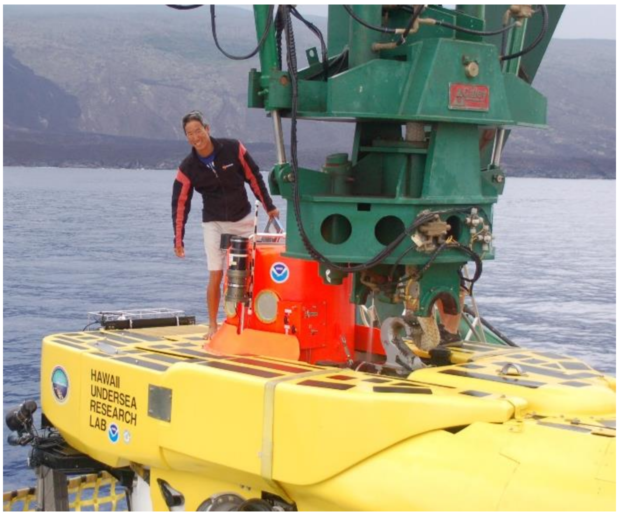

Figure 1. The author with the Undersea Research Laboratory's submersible

Leptoseris: The deepest photosynthetic corals in the world

In the clear oligotrophic waters of the central Pacific, photosynthetic coral communities can extend to extreme depths. Zooxanthellate corals of the genus *Leptoseris* (Family Agaricidae) (Fig. 2) have commonly been observed in the lower photic zone across the Indo-Pacific where such depths have been explored (e.g., Engelbert et al. 2017). In the Caribbean, corals from the same family (genus *Agaricia*) are also common in the lower photic zone (reviewed in Kahng et al. 2017). These species are all close relatives to their shallow-water reef building counterparts and share the same obligate photosynthetic trophic strategy (i.e., they cannot survive without their algal symbionts or without light). The deepest record for an obligate zooxanthellate coral is a small colony of *Leptoseris hawaiiensis* observed at 165 m (541 ft) at Johnston Atoll, in the Central Pacific. In Hawaii, these corals dominate the zooxanthellate coral community at depths >70 m and have been observed to 153 m (Kahng and Maragos 2006). At these depths, these corals form thin, flat, round, horizontal plates aligned perpendicular to the vertically downwelling light (reviewed in Kahng et al. 2019).

Figure 2. A colony of Leptoseris hawaiiensis at 96 m in the Au'au Channel Hawaii.

Light in the lower photic zone

Downwelling light in the ocean decreases exponentially with depth. The rate of this decrease depends on the amounts of dissolved and particulate matter (and of phytoplankton) which absorb and scatter light. For the deepest zooxanthellate corals, the available sunlight is <0.2% of surface irradiance (Kahng et al. 2019). The wavelength spectrum of light (perceived by humans as color) also narrows with increasing depth, with only blue and UVA wavelengths (380-500 nm) reaching the lower photic zone in oligotrophic waters. In addition to reduced intensity and color, the angular distribution of light (directions from which light travels) also changes with depth. In shallow water, there is sufficient light coming from all directions to support photosynthesis due to light scattering and reflections. For example, zooxanthellate corals can grow on the underside of a ledge even though it is permanently shaded and never receives any direct sunlight. With increasing depth in the ocean, the light available to drive photosynthesis (i.e., above a minimum threshold) narrows to a smaller and smaller angular width symmetric around the vertical axis, thereby becoming increasingly unidirectional regardless of the angle of the sun (Kahng et al. 2019). This same concept affects visual acuity and explains why many mesopelagic predators have eyes that only look upwards. For corals in an energy limited environment, orienting their surface perpendicular to the direction of incoming light maximizes their ability to harvest light. This phenomenon also helps explains why zooxanthellate corals adopt a more flattened morphology perpendicular to the vertical axis with increasing depth.

Growth rate patterns with depth

Since the intensity of sunlight in the ocean decreases exponentially with increasing depth, the potential for photosynthesis also declines and can proportionately reduce growth rates (i.e. rates of extension) within a coral species (Grigg 2006). While some coral species grow slowly everywhere (including in shallow water), there is a general trend across species of declining maximum growth rates with increasing depth (Pratchett et al. 2015). Until recently, there were very few data on growth rates of corals at depths >60 m, given the logistical challenges of performing traditional time series growth measurements at these depths. Historically, the available evidence suggested that zooxanthellate corals in the lower photic zone grow extremely slowly (e.g., 0.2-0.8 mm yr^{-1} for *Leptoseris fragilis* in the Red Sea; Fricke et al. 1987).

How fast do *Leptoseris* grow?

Given the dominance of *Leptoseris* spp. at the lower depth ranges of zooxanthellate corals, we most recently investigated their growth rates to gain insight into their ecological dynamics. The *Pisces IV/V* submersibles from the Hawaii Undersea Research Laboratory (HURL) were deployed and collected whole colonies of four species (*L.* sp 1, *L. scabra*, *L.* cf. *foliosa*, *L. hawaiiensis*) at depths 70-111 m in the Au'au Channel, Hawai'i. Instead of tracking *in situ* growth rates across time, reliable radiometric (Uranium-Thorium) dating was used to date the skeleton at multiple points along its radial growth axis. The results were recently published in *Coral Reefs* (Kahng et al. 2020).

Surprising growth rates on the edge of darkness

Considering the low light environment and the universally low extension rates for other zooxanthellate corals measured at depths >40 m (Pratchett et al. 2015), the *a priori* assumption was that large corals at these extreme depths should be very old due to extremely slow growth rates. Surprisingly, the corals were found to be relatively young with growth rates comparable to that of many non-branching shallow water corals. Sustained extension rates were measured to be 24.6 mm yr^{-1} at 70 m; 15.6 mm yr^{-1} at 92 m; and 8.0 mm yr^{-1} at 111 m. Compared to published growth rates of shallow water species in the same family Agaricidae, these growth rates are among the highest reported!

How can these photosynthetic corals thrive on such low light levels?

It seems that these low light, deep water specialists employ an interesting strategy to dominate their preferred habitat. Their thin skeletons allow for an efficient use of calcium carbonate to maximize planar surface area (for light absorption) while using minimal calcification. These thin plate-like corals only grow radially outward but not upward (i.e., they do not thicken across time like many encrusting or massive corals). Thus they can achieve high rates of areal growth with only low rates of calcification. While these thin skeletons would be susceptible to breakage in shallow water, the attenuation of wave stress with depth obviates the need for robust skeletal morphologies.

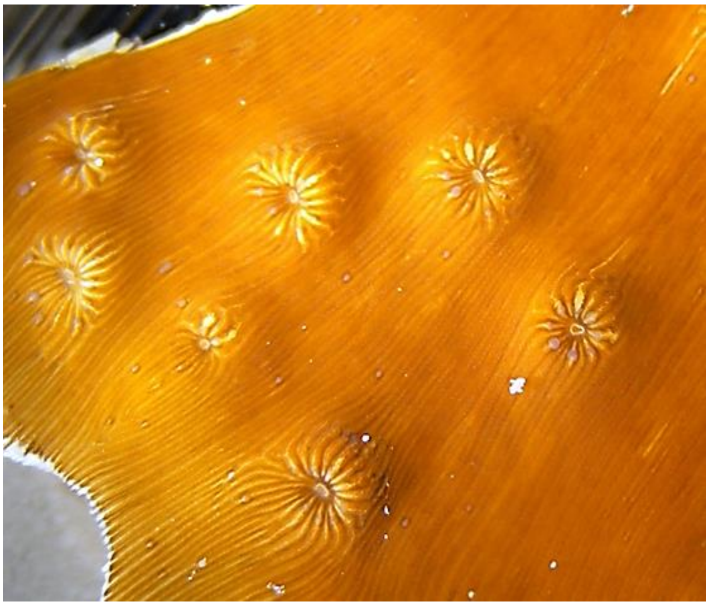

Figure 3 (left). A colony of deep water Leptoseris sp. *Notethe fine rows of septocostae radiating outward from a central origin and the low density of the polyps. Figure 4 (right). A magnified view of the polyps from a deep water* Leptoseris sp. *Note what appear to be vestigial tentacles (which do not extend) surrounding some of the polyps. There are identical bulbs of tissue protruding between some of the septocostae in between the polyps.*

Since corals are also capable of feeding on zooplankton, the prevailing dogma is that these corals must energetically rely heavily on heterotrophy (i.e., eating food) due to the scant light available to drive photosynthesis. Indeed, the deep, warm-water reefs around the world are home to azooxanthellate sea fans and sea whips (i.e., gorgonians) which thrive solely on a diet of zooplankton. In Hawaii where gorgonians are rare, large non-photosynthetic black corals and wire corals are common at these depths. However, the available direct evidence (mainly based on bulk stable isotopic data) supporting the hypothesis that depth specialist zooxanthellate corals sustain their growth via heterotrophy remains tenuous (reviewed in Kahng et al. 2019).

Using long term cultures of additional *Leptoseris* specimens (collected from 70-130 m) grown under a simulated deep-water light regime (low intensity blue light) at the Waikiki Aquarium, other peculiar characteristics of these corals have been observed. These species of *Leptoseris* generally have relatively few polyps (low areal densities) and completely lack functional tentacles for capturing food (Figs. 3, 4). While their low profile morphology maximizes light harvesting area, this morphology is incompatible with effective passive suspension feeding which requires maximizing a large cross-sectional area to intercept ambient water flow above the benthic boundary layer – an attribute that is shared by almost all obligate heterotrophic corals at these depths. In fact, in isolated aquarium cultures, deep water *Leptoseris* colonies were grown for several years strictly photosynthetically (without feeding), since the filtered source water for the Waikiki Aquarium comes from an underground well devoid of particulate and dissolved organic matter (Atkinson et al. 1995).

For zooxanthellate corals in shallow water, light (i.e. energy) is generally not limiting, but inorganic nutrients (such as bioavailable nitrogen and phosphorus) often are. Therefore, heterotrophy in these photosynthetic corals has been considered as a mechanism for acquiring scarce elemental resources (i.e. building blocks for organic matter) which are not readily available from the water itself. However, at depths near the permanent thermocline, concentrations of inorganic nutrients increase, and these elemental resources become less limiting for photosynthetic organisms (reviewed in Kahng et al. 2019). Therefore, heterotrophy as a mechanism for providing elemental resources is less relevant at these extreme depths. Also, the gross colony morphology (tall, arborescent) needed to facilitate heterotrophic feeding directly conflicts with the morphology (horizontal, flat) needed for optimizing light harvesting efficiency at these depths.

Efficiency rules in low energy environments

Growth rates are not only influenced by energy/resource intake but also by energy/resource expenditures. Therefore, higher growth rates can be facilitated either by increasing the former and/or reducing the latter (e.g. many bathypelagic fishes grow faster in terms of mass and caloric content than mesopelagic fishes despite having access to much less food). As reported in Reef Encounter 39 (Kahng 2014), deep water *Leptoseris* species are remarkably efficient at harvesting light despite their relatively low investment in photosynthetic pigments. The secret to this efficiency lies in the optical geometry of their thin, flat, white skeletons which form fine parallel ridges (septocostae) that grow outward from a central origin (Fig. 3). In some cases, these septocostae form convex spaces between them, which effectively trap light in reflective chambers, causing it to pass repeatedly through the coral tissue until it is absorbed by the photosynthetic machinery (Kahng et al. 2012).

In subtropical locations (including Hawaii), the depth distribution of zooxanthellate corals extends well below the surface mixed layer to a depth where they experience cooler waters, especially during the summer/fall when sea surface temperatures are highest (reviewed in Kahng et al. 2019). This cooler thermal regime may also facilitate higher growth efficiency via lower metabolism. Interestingly, some species of *Leptoseris* (e.g., *L. myceteseroides* and *L. incrustans*) are also found in shallow water, but tend to inhabit a special niche of shaded habitat (e.g. Dinesen 1983). In Hawaii's underwater caves and ledges, there is often a zonation of fauna following the gradient of light availability. Of the photosynthetic organisms penetrating into the darkness of the caves, encrusting *Leptoseris* species tend to extend the furthest, until eventually they are replaced by strictly heterotrophic organisms like sponges.

Ecological Implications

The strategic efficiency of *Leptoseris* enabling its robust growth rates in such low light has important implications for its ability to compete for space and overshadow slower growing organisms in the lower photic zone. It also implies that these coral communities may be able to develop and recover from mortality events much faster than previously thought. These surprisingly fast growth rates for a zooxanthellate coral in the lower photic zone provide yet another example of the power of life to evolve adaptations to extreme environments. It is also further illustrates the amazing diversity and flexibility of reef-building corals.

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Coral wreaths and the rise of phoenix corals

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I'm sure we have all seen disaster movies where there is some kind of tipping point, such as a sudden onset of Arctic conditions, which instantly freezes everyone solid except for the hero and a damsel in distress, or something similar. Some of these refer to the phrase tipping point, though by the end of the film conditions usually return to normal (thanks to the same rugged hero). Several tipping points, more often called positive feedbacks in science, have been identified for marine ecosystems and climate conditions now, though these involve warming, not cooling, and we still await a rugged hero or brilliant heroine. These tipping points are where a change triggers a run-away effect which disrupts a previously stable state and flips it into a different stable state.

As we all know, reefs and many other Earth ecosystems work in slow motion compared to the rapid flip in conditions seen in movies. Recently we showed, in the Chagos Archipelago, central Indian Ocean, that there were several signs that the reefs and corals there are gradually tipping over into just such a situation of positive feedback (Sheppard et al. 2020). The situation has developed over two or three years, since the 2015-16 warming events, although it is possible that earlier events such as the 1998 warming moved the reef system to the position where only one more severe ENSO could cause the tip.

Multiple signs suggest this tipping, two being illustrated in Figure 1, which shows that:

- Coral cover is declining, and
- Larval settlement is declining.

But more than that:

- Huge areas of previously high biodiversity in mid depths are now covered in unstable rubble that moves in storms, greatly reducing possible habitat for new coral growth even if the diminishing number of larvae could settle (Fig. 2).
- Many shallow areas have increasing cover by the bioeroding sponge *Cliona*, and by other sponges too. Such areas are no longer available for larval settlement.
- Huge expanses of deep lagoon floors were previously covered in foliaceous corals that are now crumbling, creating an unstable substrate which is now also highly sedimented. Over many sq. km here, coral cover has been next to zero for several years.
- A high proportion of young corals that have managed to settle are seen on dead *Acropora* tables, where they are elevated above the mobile rubble. But these dead tables are crumbling too (Fig. 3) so are a rather unwise place to settle in evolutionary terms, as they too will shortly end up as part of the rubble. They would seem to be candidates for a Darwin award.

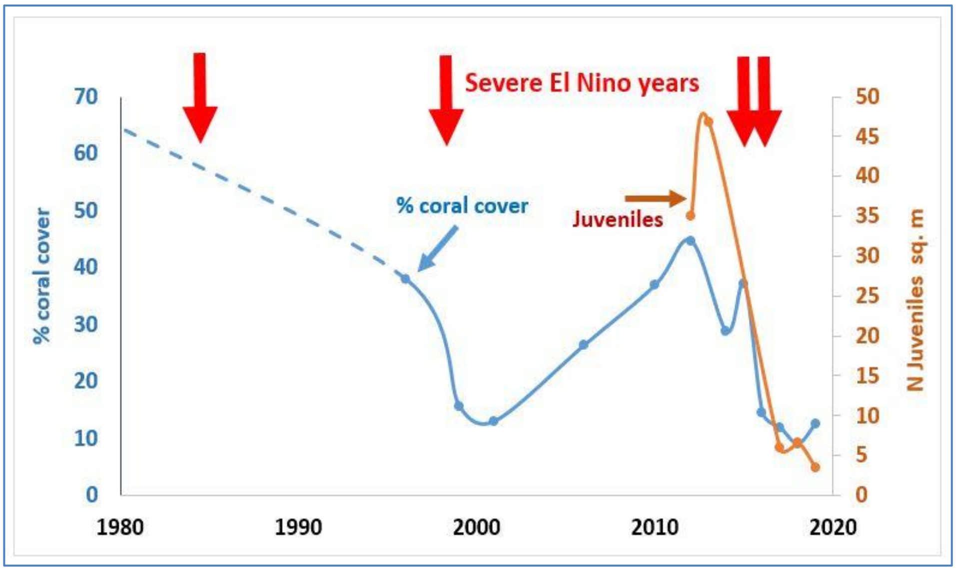

Figure 1. Coral cover (left axis) and numbers of coral juveniles <1 yr old (right axis) on Chagos reefs, with the most severe El Niňo occurrences since 1970. Where the coral cover trace is dashed, no surveys were done and the line is unlikely to be smoothly descending. (Taken from Charles Sheppard, Coral Reefs: A Very Short Introduction, (2021), Figure 18, by permission of Oxford University Press.)

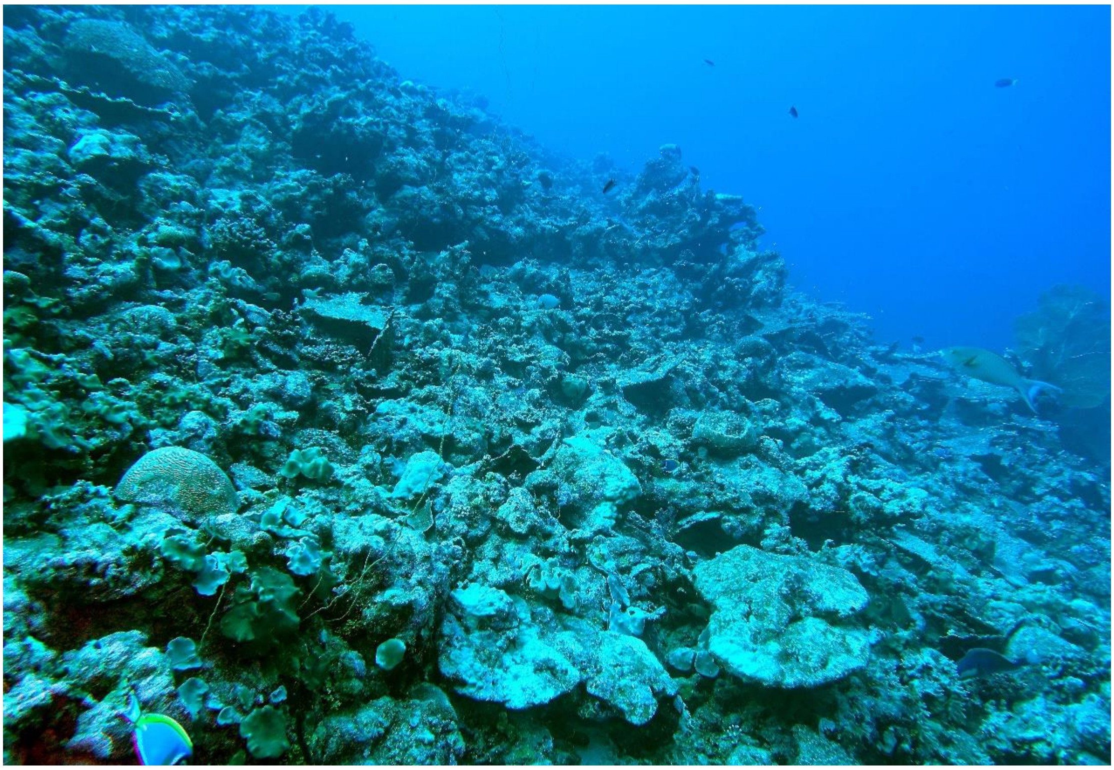

Figure 2. Ocean-facing reef slope, 10-15 m depth in 2019, where loose coral rubble and dead attached corals provided over 70% cover. Live coral cover here was 6.7% and soft coral cover was 2%. Juveniles numbered >5 m^{-2}.

- The shallowest and most exposed areas used to have coral communities of wave resistant coral species that have now essentially disappeared. In all probability (though unmeasured) the reef fabric in such places continues to bioerode while lacking any growth at present.
- Predictions show that the severity of the warming pulses, and their frequency of occurrence, are increasing (Sheppard 2003; van Hooidonk et al. 2016).

Therefore, we have a situation where not only are there fewer adult corals, producing fewer juveniles, there is also much less suitable substrate for larvae to settle on. This is a recipe for disaster. The above pointers indicate that a positive feedback has started.

This tipping point is not instant. It is taking a few years (though perhaps that is ‘instant’ in coral terms, if not in ours). There will be reversals in the form of small up-ticks in coral cover for example, but how long and how persistently such improvements will last remains to be seen. It will depend to a great extent on the frequency and intensity of recurrence of marine heat waves, and that, as we hear repeatedly, does not have a favourable prognosis.

After the heatwave in 1998 recovery was rapid in this archipelago. There were no local human pressures acting on the reefs to impede recovery, and no severe marine heatwaves for another 17 years. A recovery is possible again, though this may require a more benign pattern of marine heatwaves than is predicted, as well as alleviation of the recent local stresses from, for example, sedimentation and mobile rubble beds.

Coral cover is a common measure of reef health and is one of the most easily estimated measures of how corals are doing. However, we know that cover is not a good correlate of coral diversity, or abundance of any particular species. In many places, cover and diversity are not correlated at all (Richards and Hobbs 2014). Cover alone says little about what species are most affected either, or what species are present to help construct reef fabric. For example, in 1979, the coral *Pavona varians* was the commonest coral of all on these reefs in terms of numbers of colonies (Sheppard 1984) but it was inconspicuous and did not have a particularly high cover. It still is very abundant in terms of colony number, and its concrete-hard encrusting skeletons doubtless contribute more to building a reef than do many of the larger, beautiful but fragile species noticed more by divers and which contribute most to 3-D habitat. Still, although coral cover alone does not tell us everything, it is a useful measure all the same.

Reef building by reef-building corals

A rough approximation is that about 10% cover by stony corals is needed to be sure that a coral reef is accreting rather than eroding (Perry and Morgan 2016), though differences in species of coral and amount of calcareous algae are crucial too. In reefs of the Chagos Archipelago, average coral cover is currently about 10%, some places being higher but many much lower at <3%. For amounts of reef building corals to increase, several factors must improve: more reproduction, more stable substrate for larvae to settle, and perhaps more asexual reproduction, which is where 'phoenix' corals come in and which may offer an unexpected boost.

Phoenix corals

We know that bleaching and related mortality results from more than just warming seawater temperatures; intensity of illumination is very important too, which is why on many massive colonies that are partially killed it is usually the top parts that die while shaded parts survived. On atolls of the Chagos Archipelago after the 2015-16 warming events, huge numbers of massive corals appeared to be killed completely, but later it became noticeable that, on many colonies, shaded parts on the base or in deep recesses had some live polyps that had managed to survive. Over the next couple of years these living polyps multiplied, and began to spread back over the original skeleton. After three years sometimes the entire lower portion of the colony was covered by new polyps budded from the original surviving polyps (Figure 4). In this process a garland of new polyps gradually expands, first clothing the base of the massive phoenix colony, slowly working upwards.

On these reefs, the faviids are particularly good at doing this, though other families of corals show this also. Taken to an extreme, this expanding new growth can completely cover the old skeleton in about 3-4 years. The result may then look exactly like a colony that is several decades old: one that, miraculously and quite unlike most neighbours, survived the 2015-16 heatwaves and probably the earlier one of 1998 too. But though it looks like a coral several decades old, it is only a two or three-year-old film of new polyps on its much older skeleton. Only slicing through the whole thing could show the difference – a test that in the circumstances would be rather undesirable!

The reef would seem to gain, in terms of living tissue, a 30 year old coral after only 3-4 years. In contrast, if the same species of massive coral is found growing on the skeleton of a different species of coral, or on a bare limestone patch, it grows as a small expanding hemisphere, just as the species usually would. The phoenix corals seem to behave rather differently. This phenomenon might shorten the route to regaining cover (assuming further marine heat waves permit), but it does not add 30 years of limestone deposition in 3 years.

This begs several interesting research questions. Is this phenomenon more widespread, or was it just a result of the particular temperatures in the Chagos Archipelago falling a tiny bit short of causing total mortality—a unique case? Does the new growth somehow 'recognise' that it is expanding over its old colony, so that polyps save energy by budding without as much vertical growth as usual?

Figure 3. Numerous young Acropora *colonies, all 1-3 yr old, settled on older, dead and disintegrating* Acropora *tables.*

Sometimes in brain corals, we have seen the growing polyp chains following the old valleys. And, just how great is the energy saving, and how much might this help to restore total coral cover?

The near-endemic Chagos brain coral, *Ctenella*, is of particular interest to us, and this exhibits this phenomenon too (Figure 4 bottom right). Even before the recent heatwaves this had been considered the world's most endangered coral species on account of its restricted distribution (Huang 2012) though it used to be very common in this group of atolls (Sheppard et al. 1984). It suffered a decline of two or three orders of magnitude after 2015-16.

Might the phoenix effect provide a meaningful shortcut to raising coral cover at a time when cover is extremely low, or is it just a limited and trivial phenomenon resulting from a very particular set of circumstances? Does it matter anyway? Perhaps we are grasping at straws, but we must cling to almost any hope that these coral atolls will not pass a critical tipping point. If they do, will they sadly become not coral reefs but coral wreaths?

Figure 4. Six examples of a thin veneer of corals expanding from surviving remnants, originating from darker crevices, to cover their old, killed skeleton. Ctenella *is bottom right. Photos taken two years after the mortality.*

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REEF RECRUITS
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Influence of benthic algae on larval behavior and settlement of the coral *Acropora palmata* (Lamarck, 1816)

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Resumen/Summary
El aumento de la cobertura de macroalgas en los arrecifes ha conducido a la inhibición del reclutamiento de las larvas de coral. Existen pocas evidencias experimentales sobre la interacción alga-coral, y es por este motivo que en el presente estudio nos enfocamos en evaluar el efecto de tres géneros de algas: Dictyota *sp.,* Sargassum *sp., y* Laurencia *sp. sobre la conducta y metamorfosis de las larvas del coral* Acropora palmata. *Se llevaron a cabo dos experimentos, en uno se empleó como sustrato de asentamiento fragmentos de algas coralinas costrosas (ACC) y para el otro, tetrápodos. Los resultados evidencian que las larvas de* A. palmata *no presentan una afinidad por el tipo de sustrato, ya que se asentaron y sufrieron metamorfosis sobre ACC, tetrápodos e incluso sobre los contenedores de plástico. Se muestra que,* Dictyota, Sargassum *y* Laurencia *causan una tasa baja de supervivencia en las larvas y en los reclutas de* A. palmata, *provocando mortalidad total desde los cuatro a ocho días de exposición a las macroalgas. Finalmente, se comprobó que la presencia de las tres especies de algas en conjunto causa una mayor mortalidad a los corales durante las primeras etapas de desarrollo, que cuando cada especie se encuentra por separado.*

Introduction

Globally, coral reef degradation is increasingly resulting in algal-dominated environments. Due to their opportunistic characteristics, algae are able to rapidly occupy newly available substratum (Bakker et al. 2017). In their reviews, McCook et al.(2001) and Titlyanov and Titlyanova (2008) set out the competitive interrelation of algae and corals, including the negative effects of algal communities on coral vital functions and the positive effects of epilithic algal communities on coral growth and production. Inhibition of coral recruitment by benthic algae is a critical bottleneck in the recovery and resilience of coral reefs (Diaz-Pulido et al. 2010). There is relatively little direct experimental evidence that algae do compete, either directly or indirectly, with corals; it is therefore necessary to have more information about the relative roles of direct competition and other interactions (McCook et al. 2001; Jompa and McCook 2003). Different types of algae may have very different effects on corals, and much of this variation may be related to properties of the algae, including their physical, biological and chemical characteristics (Rasher and Hay 2010). The survival of corals can be enhanced by particular species of crustose coralline algae (CCA) and associated bacteria that can act as primary inducers of settlement and metamorphosis in coral larvae (Ritson-Williams et al. 2009).

This study aimed to increase our understanding of documented coral–algal interactions, by comparing the effects of different types of macroalgae on coral larval behavior and settlement. First, I tested the effects of three morphologically distinct algae, *Dictyota* sp., *Sargassum fluitans*, and *Laurencia* sp. on larval pre-settlement behavior and larval metamorphosis in the presence of CCA. Second, I tested the effects of these algae on larval settlement on artificial substrates. I used *Acropora palmata* (Lamarck 1816) larvae, because this species has historically been a dominant reef-building coral in the Caribbean and has suffered recent and drastic population declines throughout the region (Aronson and Precht 2001; Porto-Hannes et al. 2015).

Material and Methods

Mature gametes from colonies of *A. palmata* were collected from La Virgen reef located in Akumal, Quintana Roo, Mexico. The gametes of different coral colonies were immediately mixed until fertilization occurred and the embryos were cultured for a period of five days until the larval stage was reached.

Experimental design (1). Fragments of CCA were collected from the reef and identified to species level in the laboratory. These fragments were used as substrates for coral-larval settlement. We established six treatments, each with five replicates of 200 larvae each. The negative control treatment only contained larvae, whereas the other five treatments contained both larvae and (i) CCAs, or (ii) *Dictyota* sp., or (iii) *S. fluitans*, or (iv) 5) *Laurencia* sp, or (v) a combination of all three species of fleshy macroalgae. Larval settlement and mortality were assessed with the assistance of a dissecting microscope and blue light.

Experimental design (2). For this experiment we established five treatments, each with five replicates using the same macroalgal species. In contrast to experiment (1), we used tetrapods, designed by SECORE International, and previously conditioned by a period on the reef, as substrates (Fig. 1). Macroalgae were placed in the containers after larval metamorphosis had occurred, and we measured the survival of coral recruits in the presence of macroalgae on the second and fifth day after the initiation of the experiment.

Data and analysis

For experiment (1) the STATISTICA 7.0 program was used and multiple comparisons of mean ranks were carried out for all groups to test for differences between treatments. For experiment (2) the SigmaPlot 12.5 program was used for plotting graphs. Statistical analysis was performed with PRIMER software version 6.0 for WINDOWS. A factorial design was carried out applying PERMANOVA, to include treatments and time.

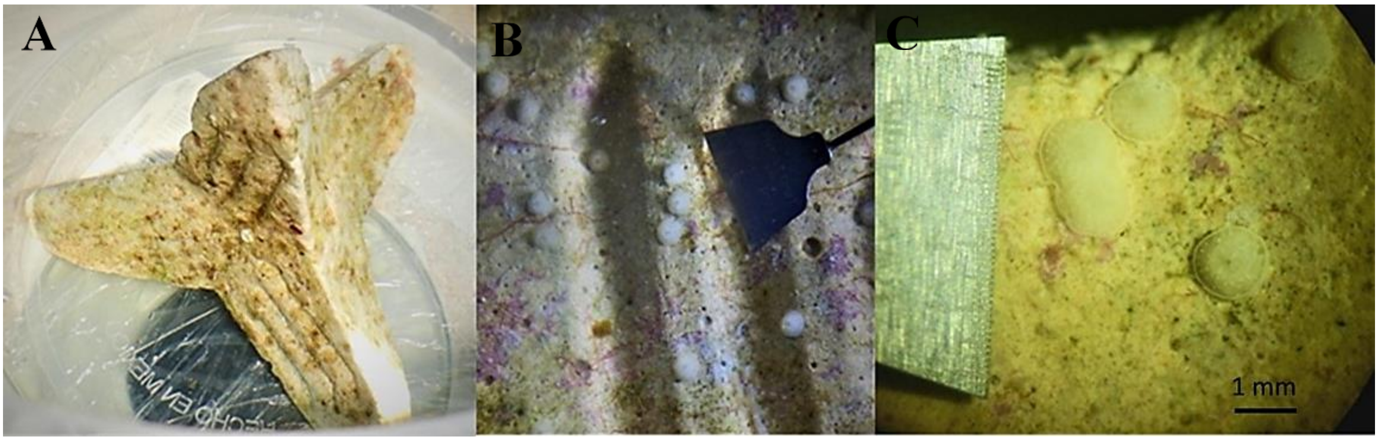

Fig 1 A. Tetrapods used as larval settlement substrates in experiment (2); B. and C. Acropora palmata *recruits.*

Results

Experiment (1). Histological processing of the CCA fragments used as a substrate revealed that they belonged to the genus *Neogoniolithon* sp. In general, I observed low survivorship for all treatments (Fig. 2). After adding a mean of about 200 larvae to each replicate, the control (with no added algae) showed the highest survivorship (mean 120.6). There were lower rates of survival when only one of the species *Laurencia*, *Dictyota* or *Sargassum* was added, but there was no significant difference between these treatments. The lowest mean larval survival rate (29.8) occurred following treatment with the multi-species mixture. Though the results are not presented here, within each treatment we observed individuals of *A. palmata* that were at different stages of development, with for example a mixture of larvae, juvenile polyps and coral recruits present in the same container.

Experiment (2). Before placing macroalgae in the containers, we observed a high larval settlement rate on tetrapods and a high survivorship of the coral recruits (≥ 60 %) (Fig. 3). The exposure of coral recruits to macroalgae (either of one species or of all three) started after 16 days. After two more days, survivorship was down to about 70 %, while after four days larvae survival had fallen to below 40 %. Notably in the treatment with *Laurencia*, the mortality was 100 %. The survival of coral recruits varied significantly with time of exposure ($p < 0.001$) but there were no significant differences between the separate treatments with different macroalgal species ($p = 0.11$).

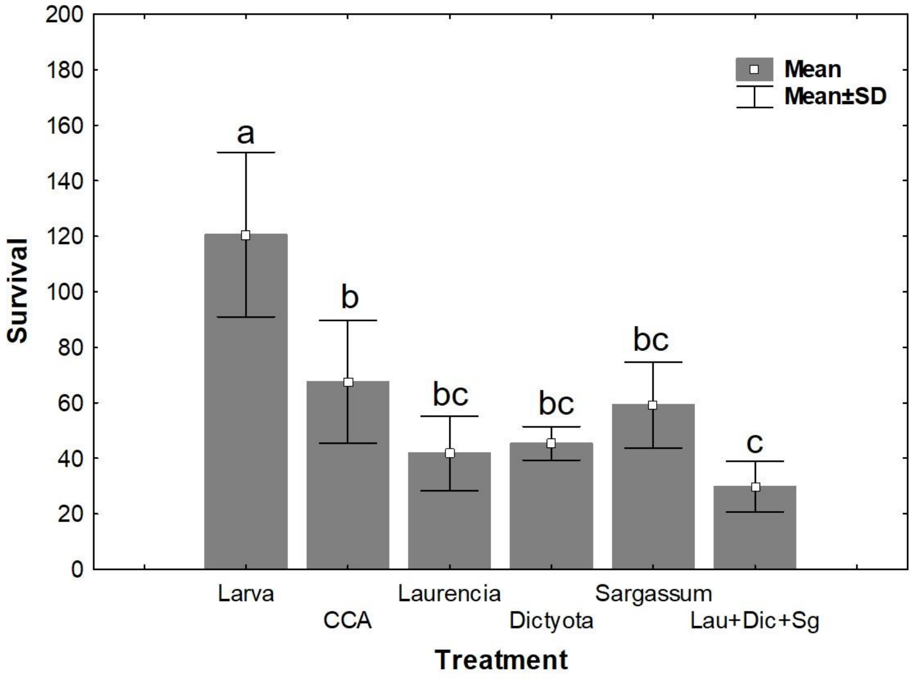

Figure 2. Average survival of Acropora palmata *individuals following 48 h of exposure to treatments.*

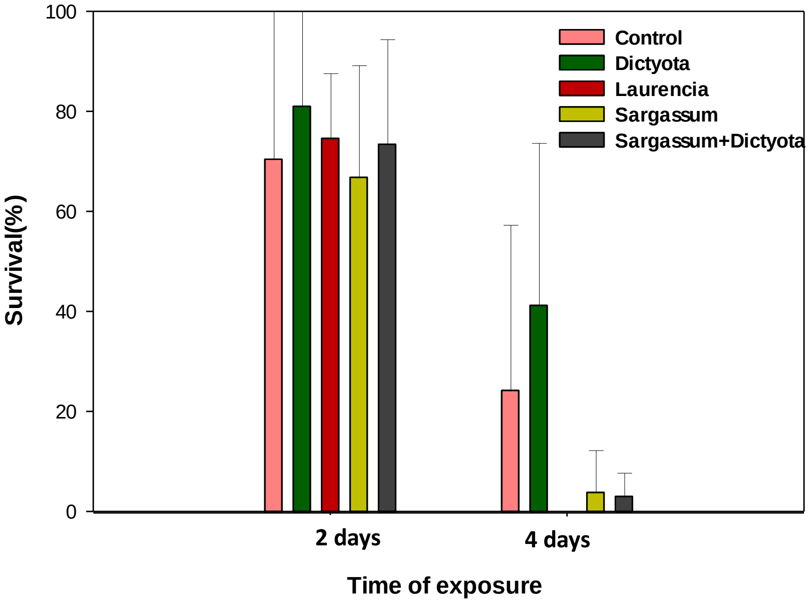

Figure 3. Percent survival of Acropora palmata *coral recruits following 48 h and 96 h of exposure to treatments.*

Discussion and Conclusions

Our findings suggest that short-term (up to 72 hours) exposure to various species of macroalgae has negative effects on both the settlement and survival of *A. palmata*. The results illustrate the separate and combined impacts that the algae have on the coral larvae and, in agreement with Swierts and Vermeij (2016) and Beatty et al. (2018), highlight the potential consequences for the early stages of coral recruitment. Macroalgae may also compete directly with corals through physical interactions such as basal encroachment, shading or abrasion. They also indirectly influence the coral's micro-habitat by bringing about water flow reduction and increased localized sedimentation, chemical induced mortality, and enhanced microbial activity caused by algal exudates, and by acting as a reservoir for coral pathogens (Barott and Rohwer 2012). However, surveys have also indicated that pathogens or microbes associated with the macroalgae may decrease the mortality rates of the coral planulae (Vermeij et al. 2009). Macroalgae may also compete at a population level by reducing the space available for the successful settlement of coral larvae (Box and

Mumby 2007). These biotic interactions have the capacity to lead to and perpetuate macroalgal-dominated reef states (Mumby and Steneck 2008).

The macroalgal genera used in these experiments are typical of Caribbean coral reefs (Littler and Littler 2000), except for *S. fluitans*. Large *Sargassum* blooms are becoming more common every summer in the Caribbean, including in Mexico. These blooms have affected marine ecosystems such as seagrass beds, as well as coral reefs, causing mortality and disease (Oviatt et al. 2019). Otherwise, on Caribbean reefs brown macroalgae such as *Dictyota* spp. are also becoming increasingly abundant (Duran et al. 2016), and consequently coral-macroalgal interactions are more frequent (Morrow et al. 2013). The results obtained in the present study, in terms of the percentage survival of *A. palmata*, are similar to those obtained by Olsen et al. (2015). Those authors carried out experiments with *Dictyota* and *Portites astreoides*, and found that the algae reduced coral settlement by an average of 14%. The negative effects of algae on larvae were attributed to significantly increased levels of oxidative damage in *P. astreoides* larvae. Another alga tested was *Laurencia*, which is often abundant on Caribbean the reefs. According to Voss (2016) some species such as *Laurencia* may induce settlement and metamorphosis of invertebrates. However, our results were different, with *Laurencia* causing a high mortality.

In contrast CCA, which we used in our first experiment as settlement substratum, is believed, due to its chemical properties and the associated diatoms and bacteria (Tebben et al. 2015), to provide biological and physical signals that improve settlement and metamorphosis of both coral and octocoral planulae (Ritson-Williams et al. 2010). They increase the roughness of the surface, so that in comparison with bare rock provide a more suitable substratum (Bulleri et al. 2009). The species identified in this study was *Neogoniolithon* sp. which has been reported as improving the survival of corals during the early stages of recruitment (Nelson 2009). However, our experiment showed a lower rate of settlement of larvae on CCA, even though we observed successful metamorphosis of some larvae.

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The importance of mangroves as habitat for corals

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Introduction

While coral conservation research and restoration efforts have focused almost exclusively on reefs, many "reef" corals also inhabit non-reef habitats such as seagrass beds and mangroves (Lohr et al. 2017, Rogers 2017, Lesser et al. 2018, Camp et al. 2019). In light of the widespread and worsening deterioration of coral reefs, these reef-associated habitats are receiving increased attention as potential climate refugia, or reservoirs of resilient coral individuals (Rogers and Herlan 2012, Yates et al. 2014, Lesser et al. 2018, Camp et al. 2019). These largely overlooked coral habitats may prove critical to the survival of many coral species and/or the recovery of coral reefs.

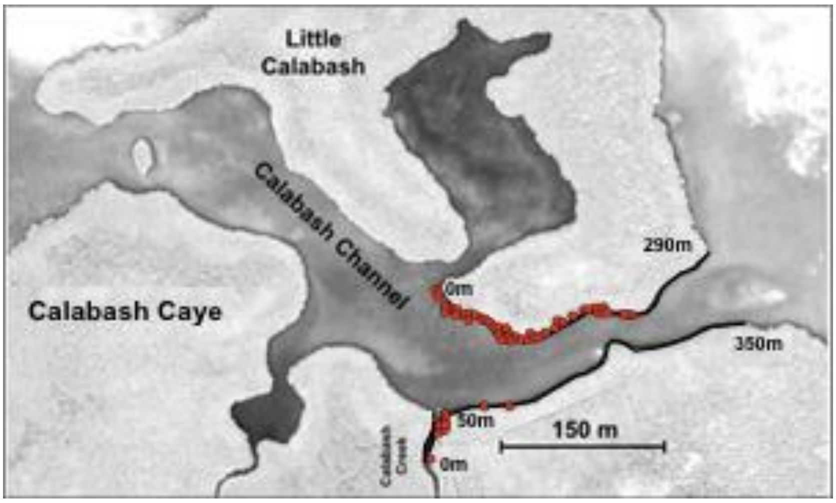

Figure 1. Map of study site in Calabash Channel. Red circles indicate individual colonies of P. divaricata *growing along 3 transects: 0-290m, 0-50m, and 50-350m.*

Mangroves, which are often in close proximity to coral reefs, tend to be overlooked as habitat for corals because they are assumed to be too dark, too turbid, and too high in nutrients and sediments for corals to thrive. However, as a handful of recent studies show, over half of the Caribbean coral species that are found on reefs also inhabit, and can thrive in mangroves (Rogers and Herlan 2012; Yates et al. 2014; Hernandez-Fernandez 2015; Rogers 2017; Bengtsson et al. 2019; Camp et al. 2019). Indeed, mangroves may be potentially critical to the survival of some coral species during temperature extremes resulting from global climate change (Rogers and Herlan 2012; Yates et al. 2014; Camp et al. 2019). For example, two common Caribbean corals in the mangroves apparently suffered less mortality during a bleaching event that caused mortality of conspecifics on nearby reefs (Rogers and Herlan 2012; Yates et al. 2014). Their survival could have been attributed to shade provided by the mangrove canopy, or alternatively because corals in the mangroves may be pre-adapted to heat stress because mangroves exhibit higher and greater fluctuation of temperatures (Rogers and Herlan 2012).

If mangroves are to contribute significantly to reef survival and recovery in the face of climate change, mangrove coral populations must be viable and self-sustaining, with the potential to serve as a source to the reefs. Despite the growing number of mangrove-coral communities that have been documented in recent work, the viability, demographic structure, and reproductive potential has not been studied in any mangrove coral population. Given this, our two primary objectives were to determine if mangroves can support a 1) viable and 2) self-sustaining coral population.

Study System and Species

In a survey of an offshore mangrove channel on Calabash Caye, Turneffe Atoll, Belize, in 2014, we identified over 150 individual colonies of the thin finger coral, *Porites divaricata*, growing vertically on the submerged prop roots of red mangroves (*Rhizophora mangle*) along three transects (Figs 1-2) (Bengtsson et al. 2019). *P. divaricata* is commonly found inhabiting shallow reefs and seagrass meadows, and also appears to be one of the most prevalent mangrove coral species in the Caribbean, recorded in nearly all published Caribbean mangrove coral surveys to date (Yates et al. 2014; Hernandez-Fernandez 2015; Rogers 2017; Bengtsson et al. 2019;). Given this, *Porites divaricata* is an ideal model coral to explore the relationship of reef and mangrove coral populations.

Figure 2. A Porites divaricata *colony grows on a submerged red mangrove prop root. Photo by Dr. John R. Finnerty.*

Methods

Longitudinal Monitoring: to determine if this population is viable and stable over time, we conducted an exhaustive, longitudinal census of all *P. divaricata* colonies living along the three transects in our study site (Fig. 1). Beginning in

2015, we tagged each colony along our three transects (Fig. 3). Over four years (2015-2018), we re-visited each colony annually to monitor its survival and growth. We also tagged, recorded, and monitored all new colonies that recruited to the nearby prop roots in the population each year.

Demographic Analyses: With these data, we conducted in-depth analyses of the demographic fundamentals, documenting the growth and death of individual corals, as well as changes in the population's size, size distribution, and spatial location of new recruits along the 3 transects. We also developed integral projection models to project long-term population growth going forward (Easterling et al. 2000). In brief, this modeling approach uses the data to infer how an individual's size relates to its vital rates (survival, growth, recruitment), and based on these relationships, it is possible to develop a projection of long-term growth for the population as a whole (Easterling et al. 2000; Edmunds et al. 2014; Merow et al. 2014). In our study, the relationships between colony size and individual growth and survival were based on empirical data, but, as in prior studies, we did not directly measure the reproductive output of individual corals, so we assumed a positive relationship between a colony's size and its fecundity (Madin et al. 2012; Edmunds et al. 2014). This work is described in a paper submitted to the journal, *Frontiers in Marine Science* (Scavo Lord et al. *In Revision*).


Figure 3. In situ monitoring of a Porites divaricata *colony growing on a red mangrove prop root. Photo by Dr. John R. Finnerty.*

Genetic Analysis of Recruitment and Population Structure: To determine if the *P. divaricata* population is self-sustaining, we used a genetic fingerprinting technique called 2bRAD (Wang et al. 2012) to identify individuals through their possession of a unique combination of single nucleotide polymorphisms, or SNPs. This allowed us to identify relationships among colonies based on estimates of genetic distance and to estimate the percentage of self-recruitment. In 2018, we collected tissue samples from 140 colonies in our study site, each with a known demographic history (ie. approximate age), extracted genomic DNA, and prepared 2bRAD "libraries" for sequencing. Following sequencing, the DNA sequences from each individual were quality filtered, and mapped to the sequenced genome of a closely related species (*Porites lutea*). We then determined the genotype of each individual at each polymorphic site.

Results and Discussion

Population Viability: Demographic monitoring revealed that the population along the 3 transects increased each year from 2016-2018, with increases ranging from 1.5% to 9%. The size distribution remained relatively stable over the four years, aside from an unusually high loss of complete larger colonies in 2017, likely due to a storm or other disturbance that disproportionately impacted larger colonies. For example, some large colonies were found buried in the mud/silt bottom, suggesting that they were either knocked off the roots entirely or that the roots were weak/weakened and broke off with these heavier larger colonies. Importantly, the overall stability in the proportion of small, medium and large individuals is indicative of a viable population. However, this overall stability masked substantial interannual turnover (something we could not have known about if we did not conduct an exhaustive longitudinal study). For example, between 2016 and 2017 the recruitment of 89 new recruits offset the complete mortality of over 70 colonies, resulting in a net population increase of 9%. The integral projection model suggests that the population is self-sustaining as long as 68% or more of the recruitment is local (Scavo Lord et al. *In Revision*).

Population Genetic Analysis: Using the 2bRAD approach described above, we were able to genetically fingerprint ~140 individuals. These data are giving us important insights into patterns of reproduction and dispersal in the population. Specifically, in many instances, we have been able to associate particular recruits in a given year with potential parents. In a manuscript currently nearing completion, we describe clear evidence that (1) the level of local recruitment exceeds the threshold necessary for the population to be self-sustaining, and (2) that much of this local reproduction is asexual. Furthermore, by combining the genetic data with the unique spatially-explicit demographic data we compiled over four years, we have been able to calculate potential dispersal distances of individual coral larvae.

The work described above represents the first study on the longitudinal demographics and reproduction of a mangrove coral population. This work will help to determine the importance of mangroves to the survival of individual coral species and to reef recovery. Going forward it will also be important to understand the limitations of mangrove habitats to contribute to coral reef survival and recovery (i.e. two sequential hurricanes caused extensive damage to a diverse mangrove coral community in the U.S. Virgin Islands (Rogers 2019)). In future work, we will use the newly developed 2bRAD markers to directly test the genetic connectivity between mangrove populations and nearby reef populations. Specifically, we will ask whether these habitats regularly exchange recruits. Additionally, we are expanding our studies to other mangrove- dwelling coral species that represent different life history strategies (e.g., comparing brooders like *P. divaricata* with broadcasters like *Orbicella* spp. and comparing habitat generalists like *Orbicella* spp. with stress-tolerant species like *Siderastrea siderea*). The broader implications of this work are two-fold. First, these results can inform the design of marine protected areas (MPAs), whereby both mangroves as well as the connection between mangroves and reefs is preserved to facilitate coral survival and recovery. Second, this work will raise awareness of other non-reef habitats that host reef corals.

Acknowledgements

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Sibling zoantharians: phylogeography and associated symbiodiniaceans

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Background

Zoantharians (Cnidaria: Hexacorallia: Zoantharia) are distributed in reef ecosystems worldwide. Studies with benthic cnidarians have shown restricted population connectivity at the ocean basin scale (e.g., Nunes et al., 2011). Nonetheless, some zoantharian species have a generalist strategy (Santos 2019) coupled with long-living larvae (up to 150 days for *Palythoa tuberculosa*; Polak et al. 2011) and high rafting potential (Santos and Reimer 2018) that could promote dispersal across barriers. In contrast to shallow-water scleractinians and hydrocorals that have deep genetic divergences among species in the Atlantic and the Indian/Pacific oceans (Fukami et al. 2004; Arrigoni et al. 2018), there are sibling zoantharians species between these two regions (Reimer et al. 2012; Santos et al. 2016; Santos 2019). For example, *Palythoa caribaeorum* has an amphi-Atlantic distribution (Santos et al. 2019) and is the sibling species of *P. tuberculosa*, which has a wide distribution in the Indo-Pacific Ocean (Hibino et al. 2013). Although population genetic analyses are crucial to identify filters to gene flow and have applications in management strategies, there are still no data on the phylogeographical patterns of zoantharian populations at large scales. Research in this field has been limited to localized studies of *Zoanthus* species in Australia (Burnett 1995) and southern Japan (Albinsky et al. 2018).

Ongoing work

My study will reveal global patterns of connectivity and symbioses in coral reefs with a cutting-edge approach. First, I will evaluate the phylogeography of *P. tuberculosa* across the Indo-Pacific Ocean and of *P. caribaeorum* across the Atlantic Ocean using next-generation sequencing (NGS) methods. I will also identify the Symbiodiniaceae communities associated with *Palythoa* populations using NGS-based analyses. Results of this research will show genetic connectivity data across some of the most extensive geographical distances ever investigated for shallow waters corals, and we will identify key environmental barriers to gene flow at both small and larger scales. By combining such data with diversity of symbiont lineages, our study will allow prediction and monitoring potential outcomes of environmental changes, including species outbreaks and bleaching (symbionts loss/switch). Such analyses are vital to conservation of coral reefs worldwide.

The ICRS 2018 Fellowship Award was used to cover a visit to the ToBo lab at the Hawai'i Institute of Marine Biology in January 2019. In this visit, I generated pooled libraries for populations of *P. caribaeorum* and *P. tuberculosa*, as well as libraries for additional zoantharian species. A manuscript with these results will be published in a peer-reviewed journal, with the ICRS fellowship cited in the acknowledgements (Santos MEA, Toonen RJ, Dudoit A, Kitahara MV, Iguchi A, Reimer JD; in prep).

Methods

Sampling:
Specimens were collected by myself and collaborators using snorkeling and SCUBA diving (Fig. 1).

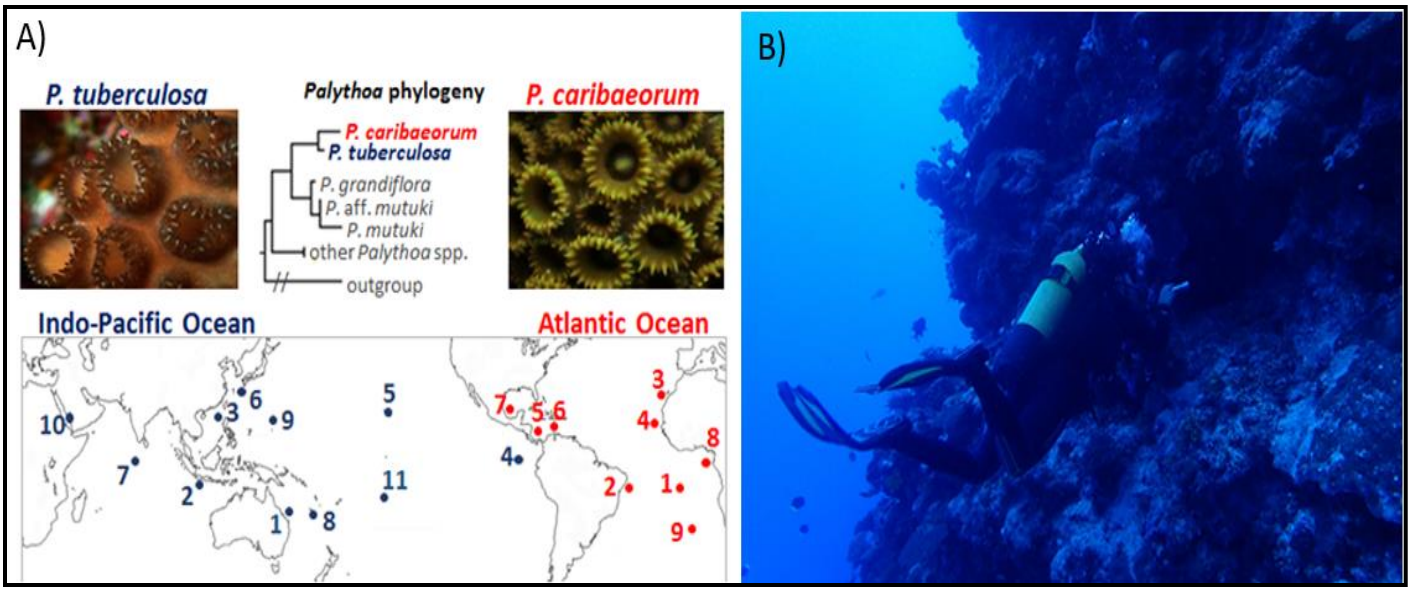


***Figure 1**: Sibling species* Palythoa tuberculosa *and* P. caribaeorum *are distributed across the Indo-Pacific and Atlantic oceans, respectively. 1A) Samples of these species were collected in the Indo-Pacific Ocean in Australia (1), Christmas Isl. (2), Dongsha Atoll (3), Galapagos Isl. (4), Hawaii Isl. (5), Japan (6), Maldives Isl. (7), New Caledonia (8), Palau (9), Red Sea (10) and French Polynesia (11), and in the Atlantic Ocean in Ascension Isl. (1), Brazil (2), Canaries Isl. (3), Cape Verde Isl. (4), Costa Rica (5), Curacao Isl. (6), Mexico (7), Principe Isl. (8) and Saint Helena Isl. (9). 1B) Myself collecting* Palythoa *samples in Chesterfield Islands, New Caledonia (image credits: G Lasne).*

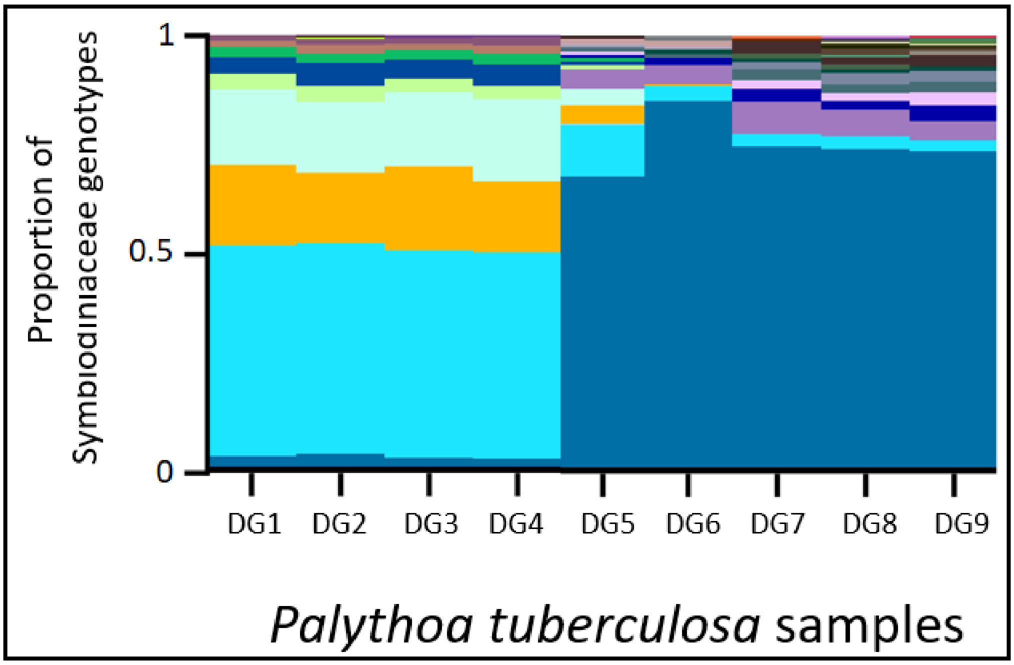
Palythoa phylogeography:
Genomic DNA was extracted using a Qiagen DNeasy Tissue and Blood kit and following manufacturer's instructions, with an adaptation using four elutions to yield higher DNA quality. Electrophoresis gel was used to check the DNA quality. The DNA quantitation was performed using the AccuClear Ultra high sensitivity dsDNA kit with eight standards. An ezRAD protocol (Toonen et al. 2013; Nielsen et al. 2018) was used to prepare libraries for samples of *P. caribaeorum* and *P. tuberculosa*. Pooled libraries for populations were generated using the Kapa Hyper Prep kit, which needs 1ng input DNA. MiSeq sequencing was performed externally using an Illumina sequencing. Bioinformatics are currently in progress and these data will be combined with analyses of the associated symbiodiniacean community of *Palythoa* species.

Symbiodiniaceae genotype:
Palythoa tuberculosa is known to associate to symbionts of the genera *Cladocopicum* and *Durusdinium,* while *P. caribaeorum* can host symbionts of *Cladocopicum, Durusdinium* and *Symbiodinium* (reviewed in Santos, 2019). An NGS protocol examining the internal transcribed spacer 2 of the rRNA gene and the SymPortal analytical framework (Hume et al., 2019) was used to identify the genotypes of the Symbiodiniaceae community associated to *Palythoa* samples.

Results

These analyses are in progress. We will use multinomial regression models to determine the degree that factors such as the host genetic flow and the sampling locations affect symbiont genotypes. Some preliminary results are shown in Figure 2.

Figure 2: Symbiodiniaceae community associated with Palythoa tuberculosa *from Dongsha Atoll. Bars represent the proportion of Symbiodiniaceae lineages associated with each sample, with each color representing a symbiont lineage.* Palythoa tuberculosa *colonies were associated with different* Cladocopicum *lineages in a high proportion (>97%), while some colonies also host* Durusdinium *symbionts in small proportions.*



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Coral population connectivity of Lakshadweep atolls under climate change

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Introduction and Background

Over the last few decades, global stressors related to climate change have been recognized as a significant threat to coral reef ecosystems. Initially the scientific community was concerned about the broad impact of coral bleaching and mortality due to warming ocean surface waters and ocean acidification (Hoegh-Guldberg et al. 2007). Recently, it has been realized that it is also important to identify those corals which are resilient to such stressors, since climatic change is happening rapidly and disproportionally in some regions (IPCC Report 2017). Coral reefs that are more resilient to the impacts of global and local stressors are better able to resist and potentially to replenish coral metapopulations (Cowen et al. 2000).

Larval connectivity forms an important indicator for studies of coral resilience of a region. It plays a dominant role in community dynamics and structure, in local and metapopulation dynamics, in the resilience of populations to human exploitation, in ecosystem responses to environmental changes, and in the maintenance of genetic diversity (Cowen et al. 2007). The study of larval connectivity among corals is however dynamic and complex. Connectivity through larval transport is inherently driven by various physical and biological factors. Temperature, physical transport and dispersion, and the dependent biological responses, such as pelagic larval duration (PLD), phenology, larval behavior and mortality, are among the factors controlling larval connectivity between marine populations. The spatial scale of a population over which it is connected is determined by the pooled effect of these processes (Gawarkiewicz et al. 2007). Connectivity is a major driver of spatial variation in coral and fish recruitment, factors which will affect coral diversity and herbivore biomass and, in turn, macroalgae cover. In consequence connectivity can vary greatly across spatial and temporal scales (Cowen et. al. 2006; Le Corre et. al. 2015).

Figure 1. Map of the study region showing the location of the Lakshadweep Archipelago, south-west of India.

The Lakshadweep Archipelago, situated 225 to 450 km south-west of the west coast of India, is the only Indian territory containing atoll type reefs; it consists of islands, atolls, and submerged coralline banks and seamounts (Mallik 2017). The Indian Ocean (IO) is amongst the warmest of tropical oceans and is also affected by a decadal climate variability associated with the IO Dipole (IOD), increasing the vulnerability of Indian corals reefs to climate change. The warming trend of sea surface temperature (SST) around Lakshadweep has already caused bleaching in years when there has been a delayed onset of monsoon periods. Yet, the impact of climate change and the resilience of Lakshadweep coral reefs cannot be assessed without a baseline knowledge of larval connectivity across the region. In order to understand larval connectivity between the Lakshadweep atolls and evaluate the effects of IOD climatic variability and IPCC projected temperature on potential connectivity, I conducted a numerical modelling study using available information on ocean circulation and data from acroporid coral mapping of the region. This study was undertaken at the University of Miami's Rosenstiel School of Marine and Atmospheric Science, under the guidance of Prof. Claire B. Paris.

Methods and Data

Reef data from throughout the Lakshadweep Archipelago were taken from the Millenium Coral Reef Mapping Project (Andrefouet et al. 2006). The data were divided into 4 km x 4 km raster using Qgis 3.3.3 to create the reef habitat module of the model. The reef areas were then divided based on bathymetry from the General Bathymetric Chart of the Oceans (GEBCO; http://www.gebco.net) in order to investigate the connectivity of shallow acroporid corals. The current data were collected from the Hybrid Coordinate Ocean Model (HYCOM-Global, 1/12 degree horizontal resolution). Larval connectivity among the reefs / islands was then examined using the Connectivity Modeling System (CMS; Paris et al. 2013), coupled to the Global HyCOM model in the Laccadive Sea, so as to predict the probability of dispersal and connectivity of acroporids across the region during 2015-2018. Competency period for the larvae was set from 4-100 days, with an exponential mortality of 50 days half-life. For the climate change scenario, data on expected changes to the maximum PLD of 60 days were collated from the literature concerning the larval competency of different coral species after an increase in temperature (O'Connor et al. 2007; Munday et al. 2009; Conolly and Baird 2010). Data on larval mortality rate at different temperatures was also noted. Given these data, model particles were released from each spawning site on or around full moon in April and March using a three-dimensional velocity field. The simulations were run under different scenarios in order to study the anticipated spatial variation in the sources and sinks of larvae among the reefs.

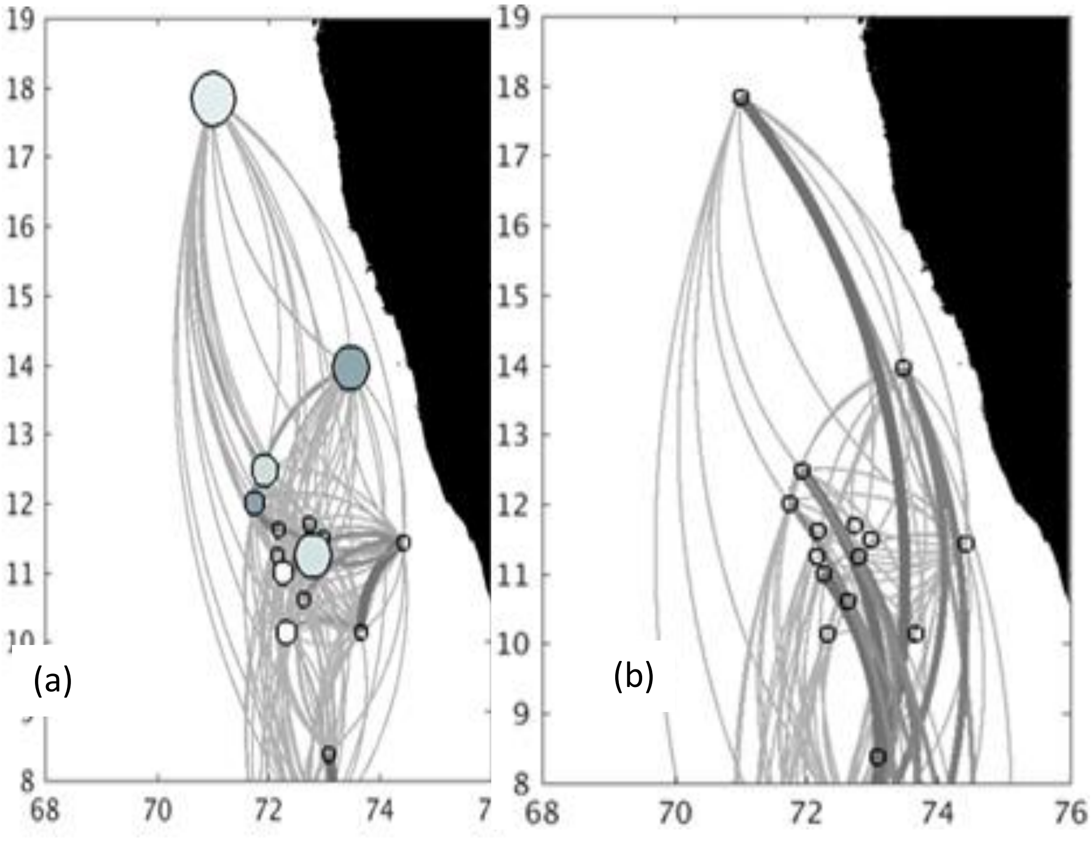

Figure 2. Larval acroporid connectivity among Lackshadweep atolls, islands, and seamounts (a) at the present time, and (b) assuming 2°C climate change. Vertices represent islands; edges represent larval exchanges (clockwise along an arc); the size of a vertex indicates the proportion of regional self-recruitment; shading indicates the betweenness centrality (darker shades indicating higher values); and the thickness of the edge represents the probability of migration. There model indicates high connectivity among Lakshadweep reefs.

Results and Discussion

The connectivity in the scenario with a larval competency starting at 4 days and a maximum PLD of 100 days and a half-life mortality function, indicates that the regional self-recruitment is high in most of the reefs (Fig. 2a). There is strong connectivity between all reefs and they all show a high potential for acting as both sources and sinks. The rate of self-recruitment is also high in various regions.

A high migratory pattern was also evident when we simulated larval connectivity with the same larval initial competency at 4 days, a maximum PLD of 60 days and a half-life of 30 days (Fig. 2b), corresponding to the IPCC climate change scenario with a projected global increase in temperature of 2°C (IPCC Report 2017). However, the model predicted a marked shift in the connectivity network, with acroporid larvae from most reef locations showing a southward movement trend compared to the present-day scenario. The model also predicts a decrease in self-recruitment with climate change. The connectivity matrix for the current scenario indicates two seamounts in the northern part of Lakshadweep (Seamounts 1 & 2) as especially active sources and sinks for acroporids (Fig. 3a), but their importance is expected to decrease with global warming (Fig. 3b). In the warming scenario, the larvae have a low probability of settling so far from their reef of origin, since they are found mostly on the diagonal of the connectivity matrix (Fig. 2b). Therefore, some conservation decision may be required for this region.

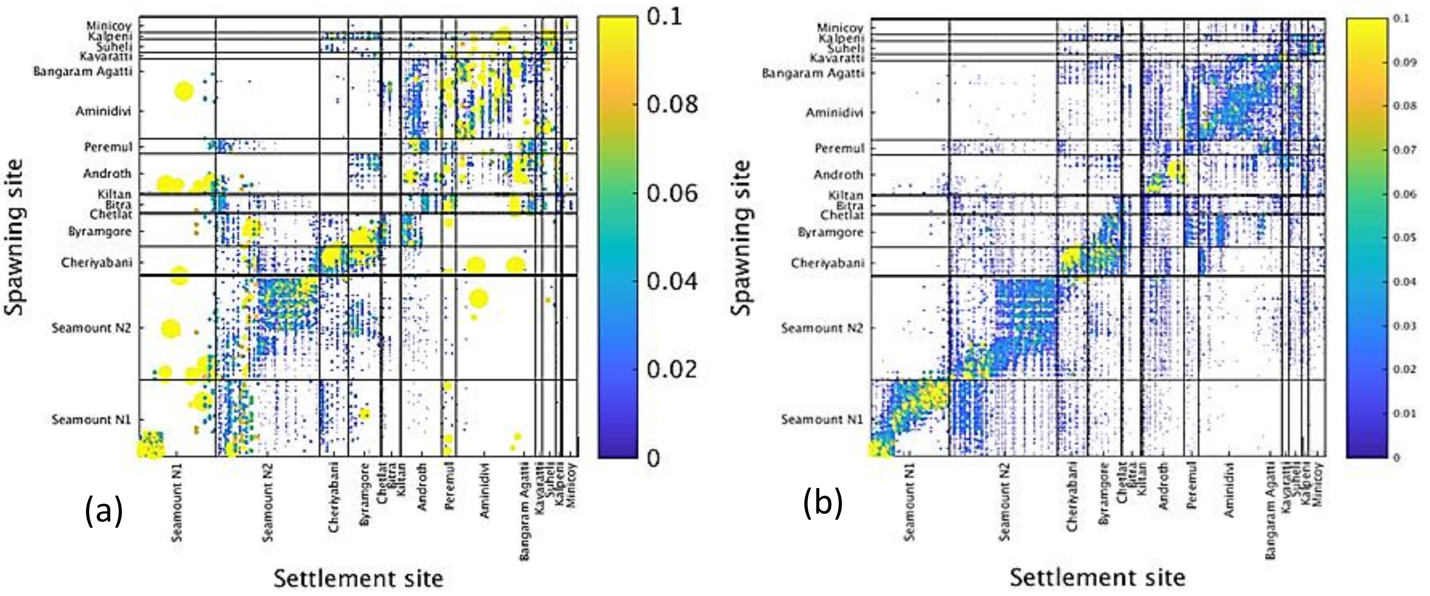

Figure 3. Lakshadweep Archipelago Acroporid Connectivity Matrix. (a) expected probability of larval connectivity at the present time, allowing for IOD climatic variability, (b) expected probability of larval connectivity under the climate change scenario. Color and size of circles represent low (small blue) to high (large yellow) probabilities.

These changes occur because when temperature increases, the metabolic rate of larvae also increases, which hastens larval development, so decreasing PLD and likely increasing larval mortality. These changes affect the time the larvae can spend in the pelagic environment, and hence their potential dispersal distances, and the connectivity between reefs (Munday et al. 2009). In such cases, if there is an intermediate reef, a new connectivity pattern will be formed. Otherwise it is assumed that the absence of reefs that can act as a sink will result in the death of these larvae.

During the past few years, there has been an increase in the frequency of cyclones within the study region resulting in corals also facing considerable physical damage. The combined effect of ocean warming and increased exposures to cyclonic events may further change dispersal patterns and decrease recruitment in affected regions. Lakshadweep is also becoming increasingly popular as a tourist destination, for activities like scuba diving and snorkeling. Such anthropogenic impacts may well amplify the effects of climate change. A further factor is that the Western Indian Ocean is oceanographically unique with the presence of a reversing circulation driven by alternating southwest and northeast monsoons. In consequence the dispersal pattern of larvae will be significantly affected by IOD variability, which during the present time is producing both a Lakshadweep low and high (Shetye 1998). In particular March to April is both the transition period of the monsoon circulation, and the time when the spawning of most *Acropora* corals occurs in this region. Therefore, shifts in the timing of monsoon onset and offset could have a major effect on the connectivity and dispersal patterns of their larvae.

Conclusions

This first coral reef connectivity investigation of the Lakshadweep Archipelago found that climate change may be expected to affect connectivity patterns at both local and regional scales. The model represents a valuable baseline tool for the implementation of resilience-based management (RBM) and designation of Marine Protected Areas (MPA) in Lakshadweep. Ongoing work is examining the effect of IOD climatic variability on connectivity both across Lakshadweep as well as on larger regional connectivity in the Laccadive Sea, including the Maldives and Chagos islands. Resilience based management (RBM) of coral reefs can include assessing spatial variation in resilience potential; this can assist with targeting and tailoring of appropriate management actions. Understanding the strength and geographic patterns of larval connectivity can play a role in ecosystem-based fisheries management plans, MPA network design and identification of reefs that may be resistant to disturbance. Climate change will influence connectivity and hence the effectiveness of MPA networks, and should receive more attention in both future conservation planning and studies of large-scale population dynamics.

Acknowledgments

I would like to thank the International Coral Reef Society (ICRS) for financial assistance in the form of the ICRS graduate fellowship award. I must express my profound gratitude to Dr. Claire Paris for her keen interest in my work, and her assistance in producing the results. I also thank Dr. Ana Vaz and the members of Paris Lab of the University of Miami's Rosenstiel School of Marine and Atmospheric Sciences, and my mentor Dr. Sreenath K.R. (Central Marine Fisheries Research Institute) for his patience, motivation, and meticulous guidance throughout the period of my MSc project work.

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Coral resilience to global change: roles of the microbiome

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Increasing atmospheric concentrations of CO_2 are leading to rising seawater temperatures and ocean acidification, both of which threaten the persistence of coral reef ecosystems as we know them today (e.g. Brown 1997; Hoegh-Guldberg et al. 2007). The ability of corals to acclimatize to these rapid environmental changes is likely a key factor in the survival and overall resilience of corals throughout the rest of this century. Numerous physiological traits are known to enhance the resilience of corals to stressful environmental conditions, such as the ability to supplement metabolic demands with zooplankton (e.g. Grottoli et al. 2006) or to maintain high levels of energy reserves (e.g. Grottoli et al. 2014). However, the potential flexibility and diversity of the coral microbiome may also have an important role in coral resilience in a changing climate (reviewed by Bourne et al. 2016).

The coral microbiome includes a diverse community of bacteria, archaea, fungi, protists, and viruses. These microorganisms can have a wide variety of relationships with a coral, including antagonistic interactions, such as those caused by pathogenic bacteria driving coral disease, or beneficial associations, such as the provisioning of nitrogen to the micro-algal endosymbionts within a coral (e.g. Bourne et al. 2016). Indeed, under experimentally-elevated temperature conditions there are often shifts in the composition of the microbial community, which could potentially affect the mortality or survival of the coral host (e.g. Ziegler et al. 2017; Grottoli et al. 2018). Different members of the microbial community have different roles and tolerances to environmental conditions, suggesting that the potential flexibility of the microbiome could increase the resilience of a coral in a rapidly changing climate. Yet, our knowledge of the coral microbiome is still growing, accelerating more recently with the advent of new sequencing technologies that allow for comprehensive taxonomic and functional characterizations. Much of the coral microbiome has yet to successfully be cultured under laboratory conditions, which necessitates DNA sequencing to gain insight into the activities and community composition of coral-associated microbes.

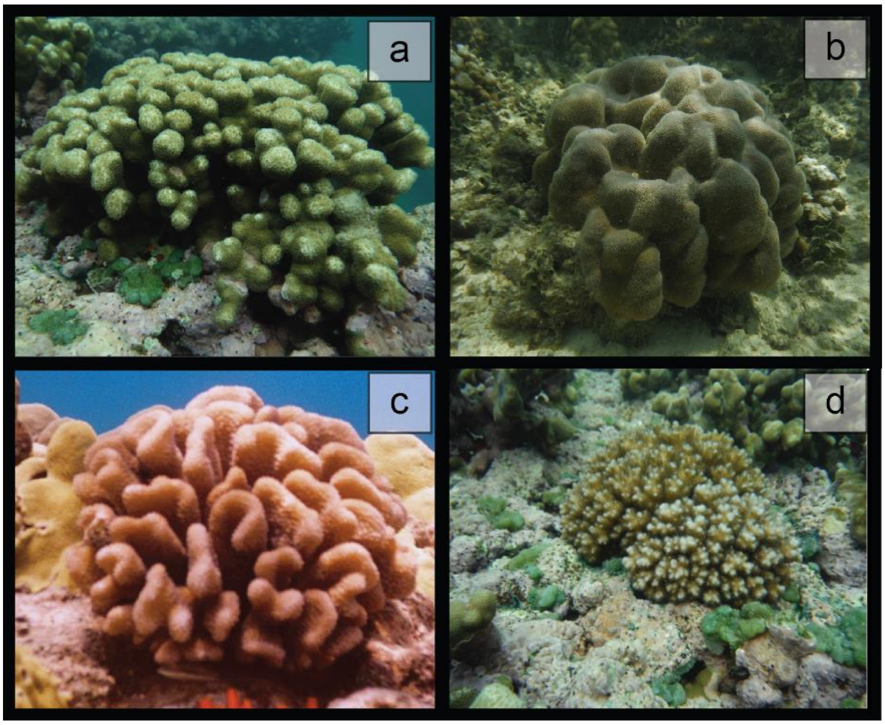
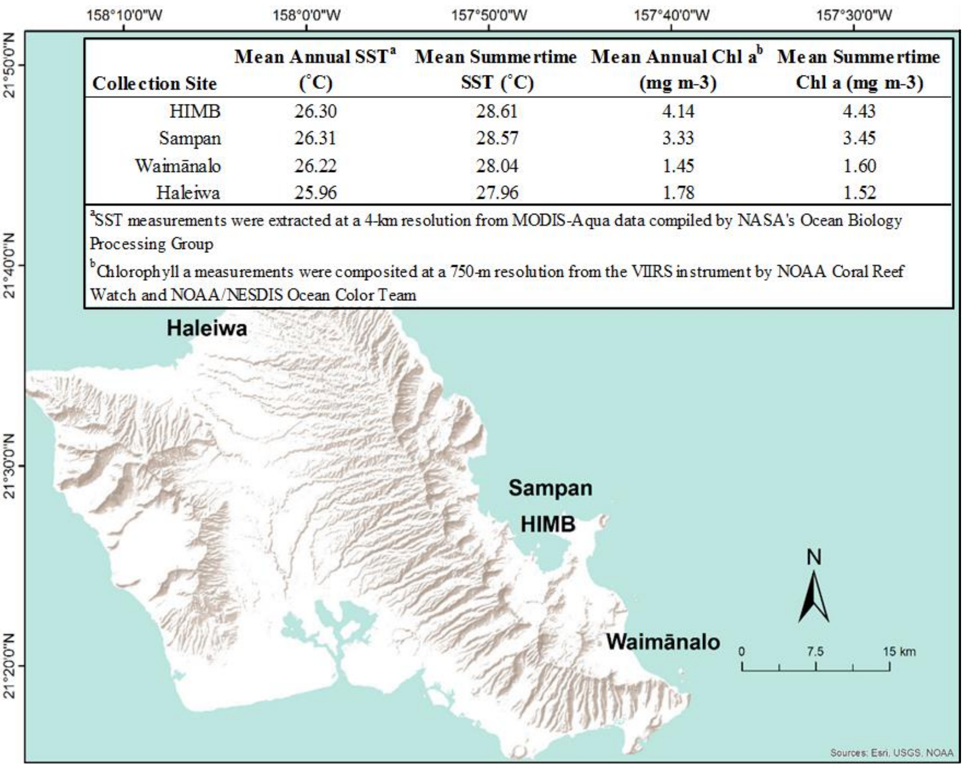


Figure 1. Colonies of the four Hawaiian coral species chosen for characterization of the microbial communities: (a) Porites compressa, *(b)* Porites lobata*, (c)* Pocillopora meandrina, *(d)* Pocillopora acuta. *Photo credit: Andréa Grottoli*

Throughout my PhD, I have aimed to advance our understanding of how the coral microbiome relates to coral resilience under changing ocean conditions. To accomplish this, I have primarily focused on four coral species: *Porites compressa*, *Porites lobata*, *Pocillopora meandrina*, and *Pocillopora acuta* (Fig. 1). Specimens of these corals were collected from multiple sites around Oahu with varying environmental conditions, including two reefs in Kāne’ohe Bay (the Hawaii Institute of Marine Biology [HIMB] and the Sampan Channel), which generally have higher mean summer seawater temperatures and elevated chlorophyll a concentrations, a proxy for potential primary productivity in the water column (Fig. 2). Specifically, these elevated temperature conditions in Kāne’ohe Bay are not expected to persist in most tropical waters until mid-century (IPCC 2013). Thus, the varied environmental conditions across the island of Oahu provide a natural laboratory to test for potential differences in the composition of the coral microbiome. If the corals that persist in elevated temperature conditions host a unique microbiome, this study could provide a novel perspective on whether microbes potentially confer some level of coral resilience as seawater temperatures continue to rise.



Collection Site	Mean Annual SST^a (°C)	Mean Summertime SST (°C)	Mean Annual Chl a^b (mg m-3)	Mean Summertime Chl a (mg m-3)
HIMB	26.30	28.61	4.14	4.43
Sampan	26.31	28.57	3.33	3.45
Waimānalo	26.22	28.04	1.45	1.60
Haleiwa	25.96	27.96	1.78	1.52

^{a}SST measurements were extracted at a 4-km resolution from MODIS-Aqua data compiled by NASA's Ocean Biology Processing Group

^{b}Chlorophyll a measurements were composited at a 750-m resolution from the VIIRS instrument by NOAA Coral Reef Watch and NOAA/NESDIS Ocean Color Team

Figure 2. Collection sites around Oahu, Hawaii and the sea surface temperature (SST) and Chlorophyll a (Chl a) conditions at each site. Monthly satellite SST and Chl a data were used to obtain mean annual and mean summertime values.

The preliminary results of this research suggest each coral species collected for this study hosts a distinct microbial community, primarily driven by differences in the relative abundance of bacteria in the genus *Endozoicomonas*. Further, the prevalence of these bacteria was also related to variation in microbial community composition among collection sites for all species except *Pocillopora meandrina*. *Endozoicomonas* sp. are suspected to be important coral symbionts, as their relative abundance can often be upward of 90% of the total sequenced bacterial community in a given coral (e.g. Bayer et al. 2013). Suggested roles for *Endozoicomonas* bacteria include dissolved sulfur recycling, carbohydrate metabolism, and antimicrobial activity, among others (e.g. Neave et al. 2016). Although its exact functional properties have yet to be completely explored, it is clear that *Endozoicomonas* is intertwined with shallow-water coral health, since this study and many others have found high relative abundance and consistent presence of the bacterial genus, irrespective of habitat.

Next Steps

With the support of the ICRS graduate fellowship, I was able to travel to Hawaii and complete the characterization of coral-associated microbial communities around the island of Oahu. As the processing of this information continues, I will begin to assess whether any relationships exist between the coral microbiome and specific environmental parameters, such as temperature and chlorophyll a levels at each collection site. I will also assess potential relationships between the structure of the coral microbiome and several physiological parameters of the coral host. Together, these analyses will help elucidate potential connections between traits of coral resilience, local environmental conditions, and roles of the coral microbiome in a changing climate.

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Functioning of a coral reef transformed by climate change

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The world's coral reefs have been fundamentally altered as the frequency and severity of stressors that impact these iconic ecosystems intensify (Hughes et al. 2017; Williams et al. 2019). Indeed, there is broad consensus that future coral reefs will not reflect those of the recent past (Graham et al. 2014; Hughes et al. 2017; Bellwood et al. 2019a; Williams et al. 2019). Increasingly, we will be confronted with highly-altered coral reef ecosystems which exist in a range of configurations and states (Graham et al. 2014; Hughes et al. 2017). As such, it is important to understand how these reef assemblages will function, and if they can continue to sustain the key services that we depend upon, in the aftermath of environmental stressors (Hughes et al. 2017; Bellwood et al. 2019b).

Amongst the suite of stressors that impact the world's coral reefs, anthropogenic heating has emerged as the most pervasive (Hughes et al. 2017; Bruno et al. 2019). Heating has now resulted in repeated, global-scale, coral bleaching events, which have profoundly altered the future for coral reefs (Hughes et al. 2018; Eakin et al. 2019; Sully et al. 2019). Indeed, as of this year, there have been five mass coral bleaching events (1998, 2003, 2016, 2017, 2020) on the world's largest coral reef system, Australia's Great Barrier Reef (Hughes et al. 2019). As such, the effects of recent bleaching events on reefs, and associated coral cover, have received substantial attention (e.g. Hoogenboom et al. 2017; Richardson et al. 2018; Stuart-Smith et al. 2018; Bruno et al. 2019). As coral species differ in their susceptibility to bleaching (Marshall and Baird 2000; Loya et al. 2001), this has led to a range of predictions about the dominance of different coral taxa on future reefs (Wilson et al. 2019; Pratchett et al. 2020), as well as investigations pertaining to the potential functions (e.g. rates of productivity and calcification) different coral assemblages can sustain (Hughes et al. 2018; McWilliam et al. 2020). Nevertheless, average coral cover in many of the world's key reef realms is now a fraction of what it once was (Bellwood et al. 2019a; Bruno et al. 2019). Therefore, regardless of the coral taxa that dominate, it appears that future reef configurations will generally have lower coral cover, notwithstanding the potential for intermediate periods of high coral cover in boom and bust dynamics (Wilson et al. 2019; Pratchett et al. 2020). Unfortunately, we have a limited understanding of this low coral cover operating space, and the potential for such reefs to maintain key functions after repetitive coral bleaching events.

To address this knowledge gap, this research focused on the coral reefs around Lizard Island, on the Great Barrier Reef. Lizard Island was at the epicentre of the 2016 coral bleaching event on the Great Barrier Reef (Hughes et al. 2019), which received world-wide media attention. Since January 2016, immediately prior to the widespread onset of coral bleaching at Lizard Island (Fig. 1a), I and other members of the Function Hub at James Cook University, led by Prof. David Bellwood, have documented the nature of the coral reef benthos on these reefs. To do this we used a technique that relied on over 350 temporally and spatially matched photoquadrats. Already this database of photos has yielded new insights into coral-fish interactions across bleaching events (Wismer et al. 2019a, 2019b) and documented an unprecedented expansion of the ascidian *Didemnum molle* (Tebbett et al. 2019). However, the database was limited by its short temporal scale.

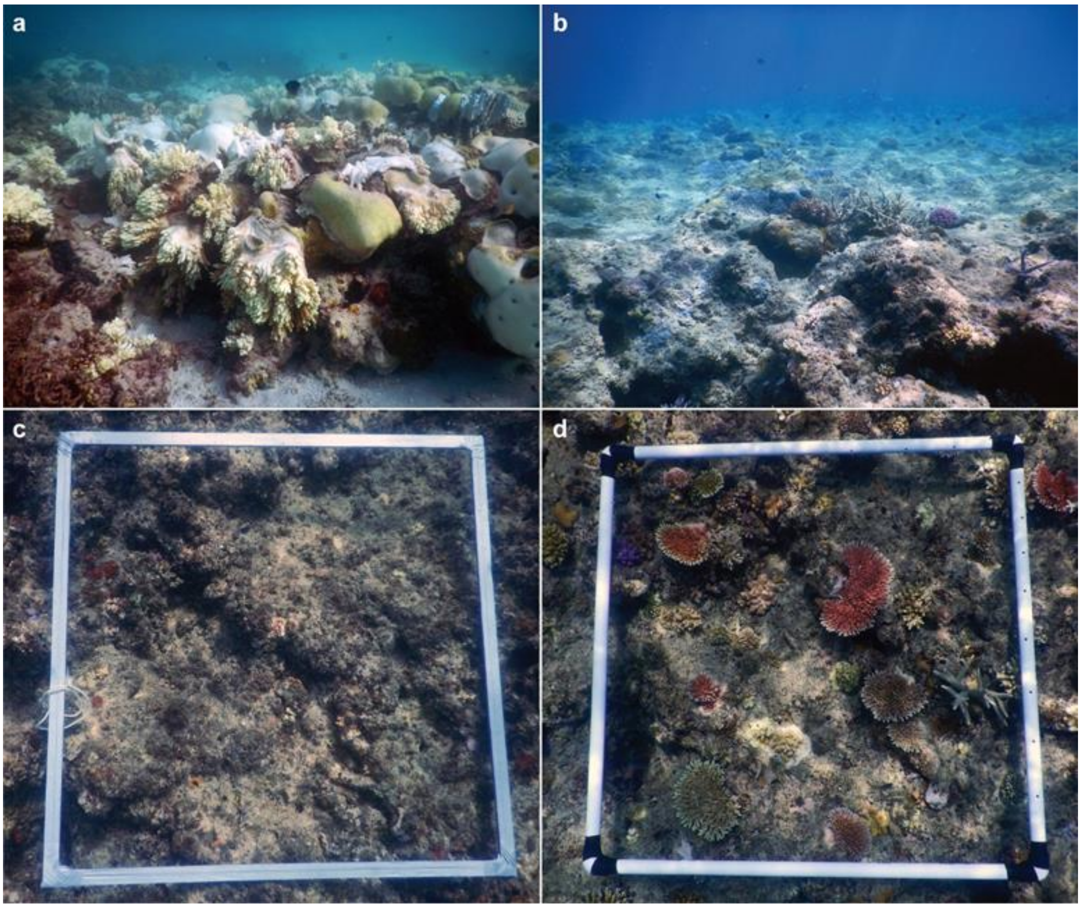

Figure 1
a) Coral bleaching at Lizard Island in April 2016 (Photograph R.P. Streit). b) Many of the reefs around Lizard Island are now typified by a low-complexity, algal turf-covered state (photo January 2020). c) and d) Photographs of the same quadrat taken in January 2018 and in January 2020, highlight the early stages of coral recovery in some locations.

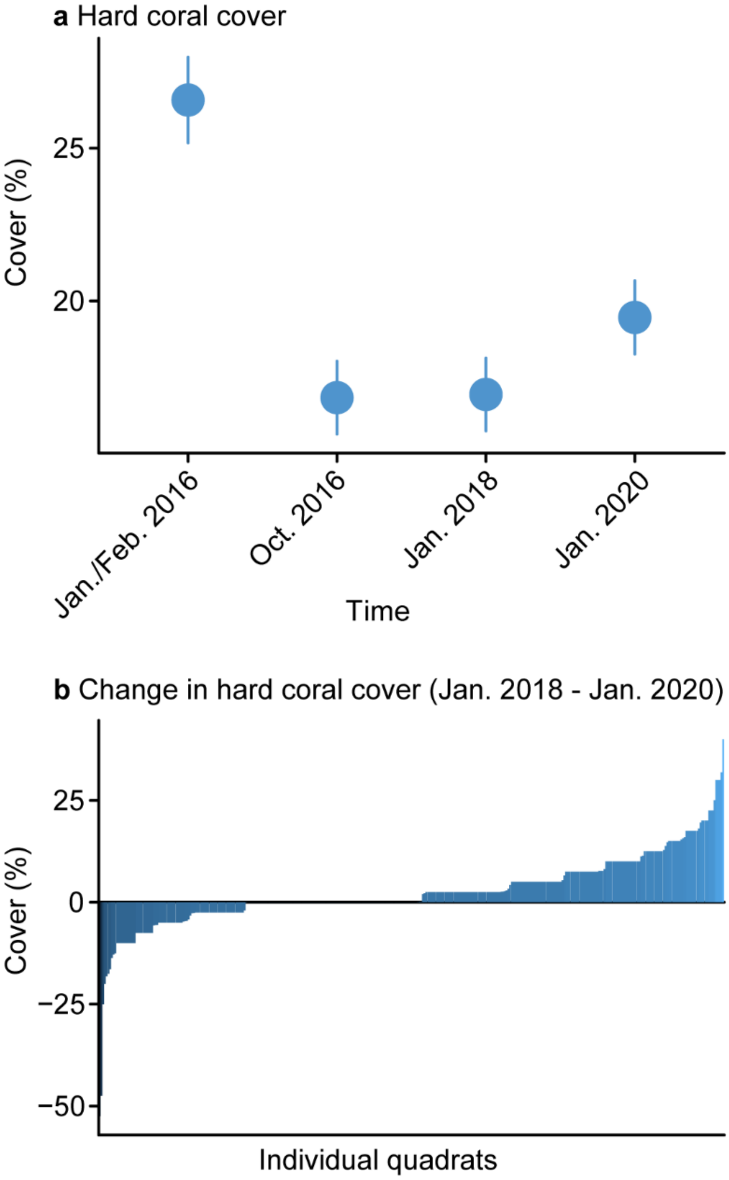

Figure 2 a Scleractinian hard coral cover (mean ± SE) at Lizard Island immediately before (January/February 2016) the 2016 coral bleaching event and at three subsequent time periods after this event. b The absolute change in scleractinian hard coral cover in each sampled quadrat between January 2018 and January 2020. Note the continued decline in coral cover in some quadrats during this period despite no major coral bleaching events or tropical cyclones.

In January 2020, approximately four years post 2016 bleaching, I therefore undertook a field trip to Lizard Island, funded by an International Coral Reef Society Graduate Fellowship, to re-take the photographs. This process was revealing, and presented a glimmer of hope, as despite many of the reefs still being in low-complexity, low-coral cover states (Fig. 1b), there were clear signs of early successional coral recovery in a number of quadrats, with marked increases of coral cover (Figs 1c, d). However, this field trip was fortuitously timed, as I was able to document the condition of these reefs before the Great Barrier Reef was subjected to a fifth mass coral bleaching event (the third in five years), which began to manifest itself at Lizard Island in mid-February.

Since returning from the field and transitioning to working from home in this brave new world we are all adjusting to, I have analysed all of the photographs taken in January 2020, as well as those taken in January/February 2016, October 2016, and January 2018 and undertaken some exploratory analysis. From January 2016 to October 2016 it appears that average scleractinian hard coral cover fell by more than 36% as a result of the 2016 bleaching event (Fig. 2a). Coral cover then remained relatively stable (despite another coral bleaching event in the early months of 2017) before increasing by nearly 15% from January 2018 – 2020 (Fig. 2a). However, increases in coral cover were only documented in approximately 50% of quadrats (Fig. 2b), with a large number of quadrats experiencing no change in coral cover, or even further decreases (Fig. 2b).

Despite early signs of recovery, hard coral cover on these reefs still accounts for less than 20% of total cover (Fig. 2b). The functioning of future coral reefs will be intimately linked to not just corals, but the entire benthic assemblage. As such, the consideration of benthic community composition is more revealing. Since the bleaching event in 2016, and the decrease in coral cover, there have been notable increases in the relative coverage of algal turfs, as well as the other main functional groups of algae (Fig. 3). Indeed, in January 2020 there was a distinct shift in benthic community composition towards a higher relative cover of crustose coralline algae and macroalgae, rather than returning to a higher coral cover state (Fig. 3).

Considering the timing of the latest sampling trip, in relation to the fifth mass-coral bleaching event on the Great Barrier Reef beginning in February 2020, these photographs and data will prove pivotal in understanding how

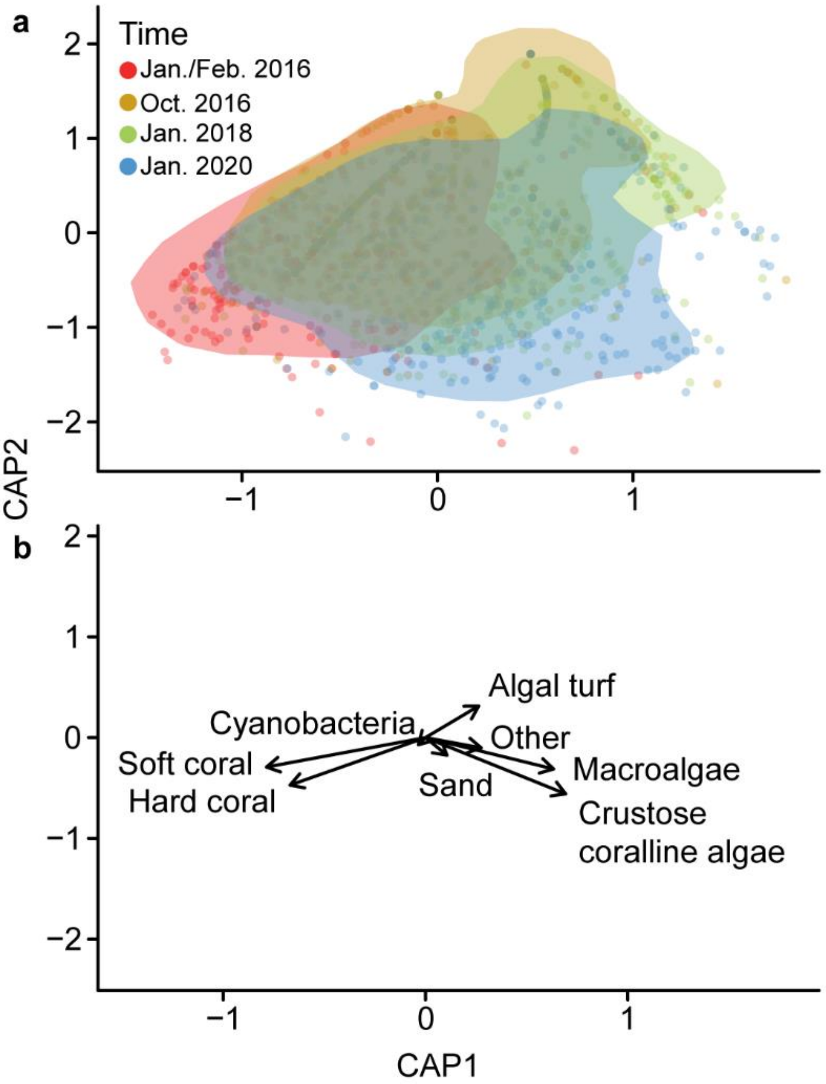

Figure 3 The coral reef benthic community composition during the four sampling periods. a Constrained ordination plot based on a Bray Curtis dissimilarity matrix. The coloured polygons are based on 75% kernel utilisation distributions and therefore denote where the majority of points fall in multivariate space for each sampling period. b Vectors show the relationship between the benthic components and how they influence the position of the data points (individual quadrats) in a.

repeated bleaching events, and associated stressors such as coral disease outbreaks, impact recovery trajectories on coral reefs. In addition, these data will reveal what the implications of such bleaching events are in terms of the functioning of these highly-altered assemblages. To do this, the next step in this research involves using this dataset as the foundation for a functional analysis, where I will explore potential changes within this ecosystem that have functional ramifications. In doing so, this will shed new light on the ability of this climate-reconfigured coral reef ecosystem to sustain key functions (e.g. productivity and calcification) into the future.

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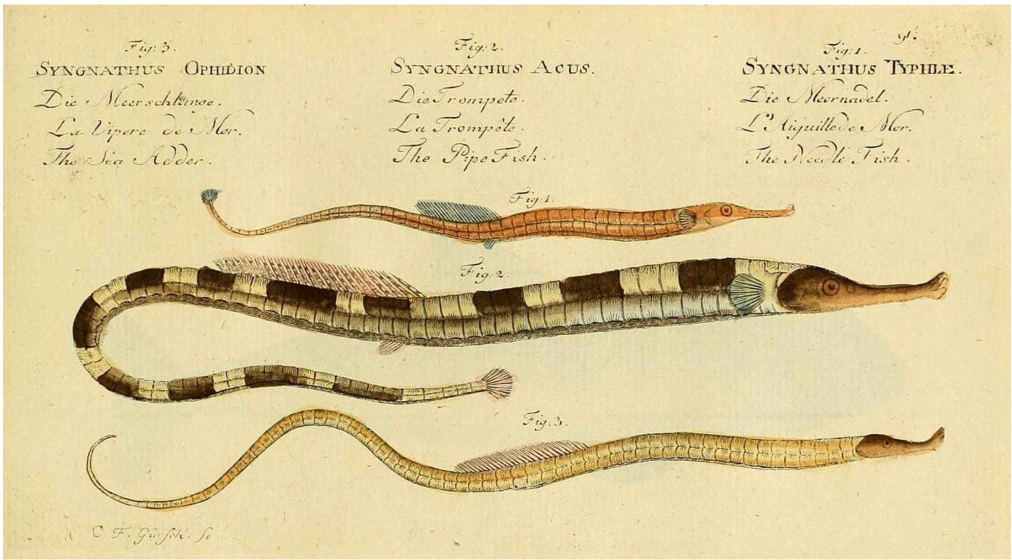

Trumpetfishes as illustrated in Georges Cuvier's 22 volume Histoire Naturalle des Poissons; an illustration from the book "*Coral Reef Curiosities*" by Chuck Weikert (see book review section).

PROGRAMS & PROJECTS

Coral Reefs and the Convention of Biological Diversity Post-2020 Global Biodiversity Framework

Emily Corcoran (Consultant to ICRI) and Francis Staub (ICRI Secretariat), with Firdaus Agung (Ministry of Marine Affairs and Fisheries, Indonesia), Emily Darling (WCS), Alfred DeGemmis (WCS), Simon Harding (ICRS), Susan Lieberman (WCS), Pauli Merriman (WWF International), David Obura (CORDIO East Africa), Claire Rumsey (ICRI Secretariat), Sue Wells (ICRS)
Contact: Francis Staub fstaub@icriforum.org

The International Coral Reef Initiative (ICRI) was established to promote conservation and sustainable management of coral reefs and related ecosystems. With close to 90 members, ICRI has a unique opportunity to bring member countries and organisations together and help to streamline policy instruments relating to coral reefs. The ICRI Secretariat is hosted for a set term (usually two years) by State members, on a voluntary basis, and is currently co-chaired by the governments of Australia, Indonesia and Monaco. https://www.icriforum.org/

The CBD came into force in 1993[1] and currently has 196 Parties; it is based around three objectives: conservation of biodiversity, sustainable use of its components, and fair and equitable sharing of the benefits arising from the use of genetic resources. At the end of the 1990s, global attention was drawn to the impact of the coral reef bleaching episodes of 1998. This triggered a series of international activities in partnership with the United Nations Framework Convention on Climate Change and other relevant conventions and organizations including ICRI which led to the adoption, by the CBD parties, of a Specific Work Plan on Coral Bleaching in 2004. The Work Plan recognized the urgent need to implement action to manage coral reefs for resistance and resilience to, and recovery from, episodes of raised sea temperature and/or coral bleaching.

In 2010, at the 10th meeting of the CBD CoP in Japan, the Parties to the convention agreed to what became known as the 'Aichi Targets'; these became a key part of the CBD 2011-2020 Strategic Biodiversity Plan. In the Aichi Targets coral reefs were addressed directly in Target 10 (AT10), which required that *"By 2015, the multiple anthropogenic pressures on* coral *reefs, and other vulnerable ecosystems impacted by climate change or ocean acidification are minimized,* so *as to maintain their integrity and functioning."*

With the expiry this year of the Strategic Biodiversity Plan and of the Aichi Targets, a consultative process to develop the new Global Biodiversity Framework is underway, led by the Parties to the CBD and drawing on voices from indigenous peoples and local communities, young people, science and non-governmental stakeholders. The Global Biodiversity Framework (GBF) has been developed from a theory of change (Fig. 1) which "*recognizes that urgent policy action globally, regionally and nationally is required to transform economic, social and financial models so that the trends that have exacerbated biodiversity loss will stabilize in the next 10 years (by 2030) and allow for the recovery*

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[1] cbd.int/history

of natural ecosystems in the following 20 years, with net improvements by 2050 to achieve the Convention's vision of living in harmony with nature by 2050" (CBD 2020). Development of an effective GBF requires engagement across government and society in order identify priorities and allocate resources to make the transformative changes that are needed over the coming decade – connecting people, climate and nature.

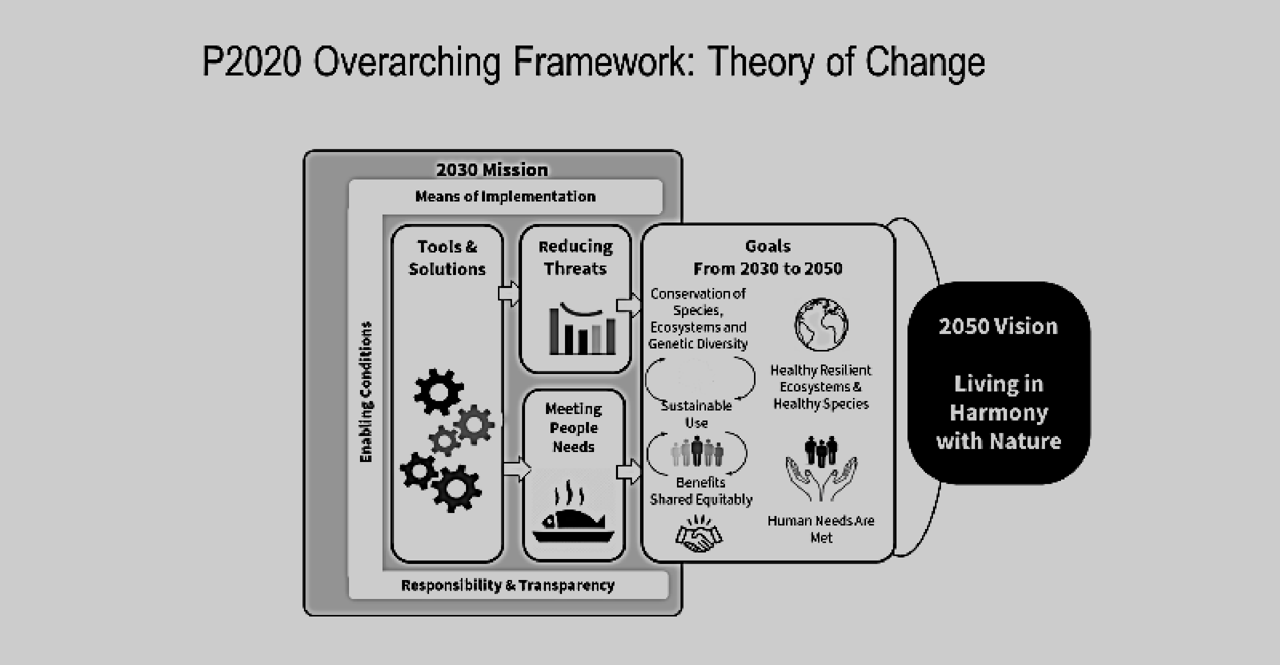


Figure 1: Theory of change for the Post-2020 Global Biodiversity Framework (Source: CBD, 2020)

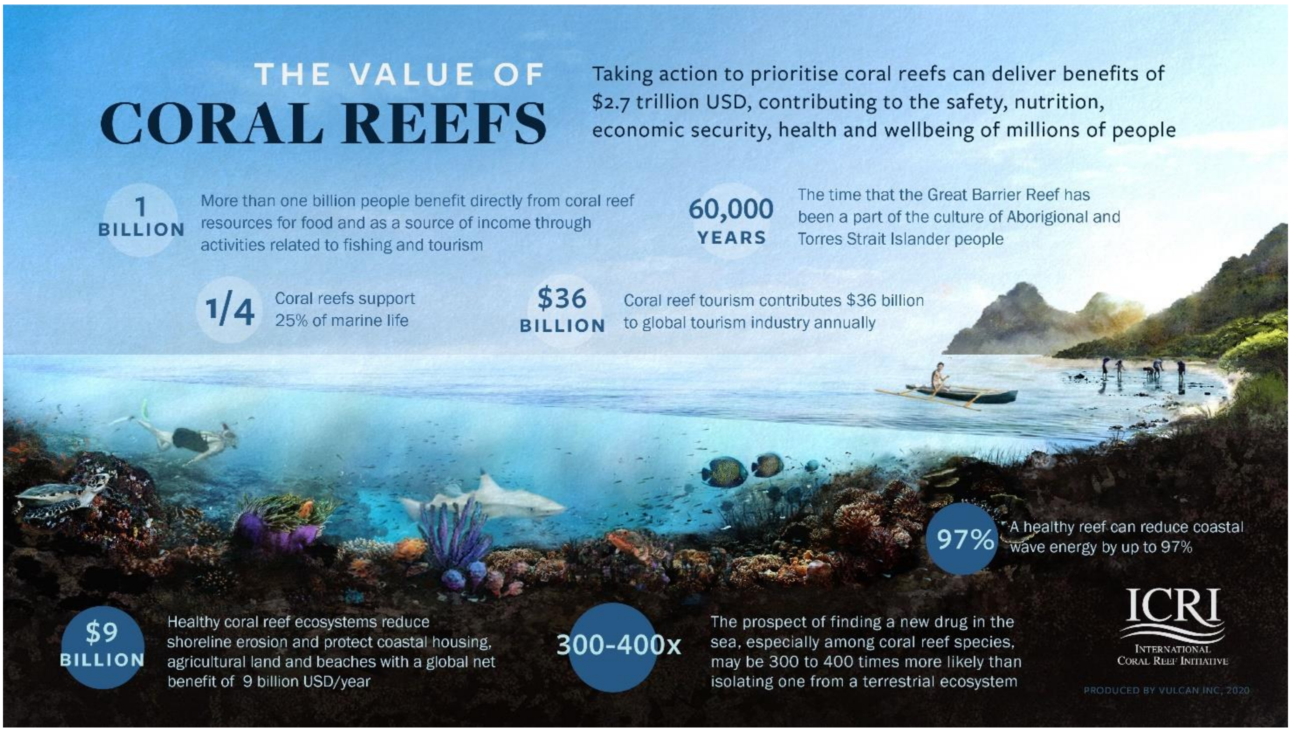
Now more than ever, the critical and vulnerable nature of coral reef ecosystems is recognised, having been repeatedly highlighted in numerous recent landmark assessments such as the Global Biodiversity Assessment (IPBES 2019) and the Special Reports of the International Panel on Climate Change (IPCC 2018, 2019). Although coral reefs cover a relatively small area of the planet, they are among the most diverse ecosystems, delivering disproportionate benefits to the global economy, food security and human well-being (Fig. 2). Ecosystem services of coral reefs and associated ecosystems are linked not only to the Agenda 2030 Sustainable Development Goal (SDG) 14: Life Below Water, but to all the goals (Obura 2019).

However, AT10 was one of the least successful Aichi Targets, and so ICRI undertook a review of the experiences of selected countries in its implementation (ICRI, 2018). On the positive side, the study found that AT10 had drawn attention to coral reefs as a special ecosystem in crisis and provided an opportunity to focus effort and coordinate policy action. Some of the countries interviewed reported that AT10 was useful to stimulate increased activity on marine conservation as it provided leverage for regional and global engagement, helped to demonstrate the wider contribution made by national and regional initiatives, and instigated funding streams to support coral reef conservation work.

Less positively, ICRI's analysis highlighted several problems with implementation: the target language was vague, ambiguous, complex, and difficult to understand; the initial deadline of 2015 was intended to convey the need for urgency but was unrealistic in terms of the type and scale of change required at institutional level; and the indicators for measuring progress were adopted late in the process, were not clearly identified and were unrealistic for both national and international tracking.

In December 2018 ICRI members established an Ad Hoc Committee to contribute to the work needed to address coral reefs adequately in the post-2020 GBF. The Committee is chaired by Monaco, Vulcan Inc. and the ICRI

Secretariat and has the following members: Australia, France, Indonesia, Jamaica, Japan, Maldives, New Caledonia, Seychelles, UK, USA, CORDIO East Africa, GCRMN, the International Coral Reef Society (represented by Sue Wells and Simon Harding), the Reef World Foundation, SPREP, UN Environment, UNEP-WCMC, the Wildlife Conservation Society, the World Resources Institute, and WWF International.



THE VALUE OF CORAL REEFS

Taking action to prioritise coral reefs can deliver benefits of $2.7 trillion USD, contributing to the safety, nutrition, economic security, health and wellbeing of millions of people

1 BILLION More than one billion people benefit directly from coral reef resources for food and as a source of income through activities related to fishing and tourism

60,000 YEARS The time that the Great Barrier Reef has been a part of the culture of Aborigional and Torres Strait Islander people

1/4 Coral reefs support 25% of marine life

$36 BILLION Coral reef tourism contributes $36 billion to global tourism industry annually

97% A healthy reef can reduce coastal wave energy by up to 97%

$9 BILLION Healthy coral reef ecosystems reduce shoreline erosion and protect coastal housing, agricultural land and beaches with a global net benefit of 9 billion USD/year

300-400x The prospect of finding a new drug in the sea, especially among coral reef species, may be 300 to 400 times more likely than isolating one from a terrestrial ecosystem

Figure 2: The value of coral reef ecosystems (Source: ICRI, 2020/ Produced by Vulcan Inc.)

ICRI Recommendation to the Parties of the CBD

After more than 18 months of work by the committee and many consultations, ICRI adopted a Recommendation on how coral reefs and related ecosystems could best be included within the GBF. Given that the overall goals and targets for the GBF are being developed at the broad ecosystem level, the ICRI recommendation calls for the prominent recognition of coral reef ecosystems within the text. It is also recommended that the GBF should be designed to trigger actions that will enhance the **integrity** and **resilience** of coral reef ecosystems, so they can remain functional with their full complement of biodiversity, and continue to provide services to local communities into the future. The Recommendation advises that the timescale for the new goals and targets are appropriate: 2050 will be ambitious for coral reefs, but potentially achievable for a number of outcomes, such as the stabilisation and recovery of these ecosystems, provided they are prioritised and conservation actions are undertaken promptly.

The Recommendation proposes that the Parties should include clear, specific and actionable indicators in the GBF that will inform interventions aimed at improving reef integrity, quality and function. Countries can determine their progress towards meeting targets by using these indicators, learn what is working or not working, and so adapt their conservation and management efforts accordingly. These metrics will also contribute to a global understanding of coral reef status.

Six indicators have been recommended (Fig. 3, Table 1). In selecting these, ICRI took into account available and emerging tools and methods as well as various local and regional data collection resources. The Recommendation also includes five additional indicators that need further development, and that are designed to improve feedback on ecosystem integrity and resilience (Table 2). It is acknowledged that this is not an exhaustive list of potential indicators and should be kept under review.

Table 1: **Recommended Indicators** (Source ICRI, 2020)

1	Live coral cover	*An indicator of coral dominance and the most widely used indicator in coral reef science and national to international policy*
2	Coral reef extent	*A metric for detecting changes in the area of coral reef ecosystems*
3	Fleshy algae cover and cover of key benthic groups	*Increases in fleshy algae indicate decline in coral reef health and can give information on ecosystem function and resilience*
4	Fish abundance and biomass	*Important for any ecosystem scale target, and necessary to understand the health, functioning and productivity of the reef*
5	[Percentage / area] of coral reefs included in [effectively managed] Marine Protected Areas and Other Effective Area-based Conservation Measures	*Relevant to any target on area-based protection, this indicator gives information on the area of coral reef habitat included within area-based management schemes of different kinds*
6	Index of coastal eutrophication	*Nutrient pollution from land-based sources is of high concern for many inshore reefs. This indicator would also be relevant to the pollution targets that are being developed*

Table 2: Recommended indicators for further development (source ICRI, 2020)

7	Red list of ecosystems (coral reef ecosystems)	*This new tool will help to measure how close an ecosystem is to collapse, which is important for providing information on changes in function and integrity*
8	Hard coral genera richness	*Helps understand coral community change and structure, and so relevant to ecosystem integrity*
9	Structural complexity of coral reefs	*Provides information on expected function and resilience of the system over time and changes in coral community structure, and/or complexity, in response to changing climate*
10	CATAMI Classification Scheme (Collaborative and Annotation Tools for Analysis of Marine Imagery and Video)	*A standardised, new approach to understanding the benthic habitats and improving information on community composition and intactness*
11	Carbonate budgets	*A proxy for understanding function and impacts of climate change relevant to understanding changes in integrity and resilience of the ecosystem*

Next steps

The work to progress the GBF continues and can be followed at: https://www.cbd.int/conferences/post2020. The text of the GBF is likely to be revised significantly, and will be considered for adoption by the 15th meeting of the COP, which is expected to take place in 2021 in Kunming, China. ICRI, working with and through its members, will continue to take part in the process to ensure that coral reefs are adequately addressed. This will include a technical webinar in August 2020 and a side event at the upcoming CBD scientific and technical meetings, scheduled for November 2020. To help promote the ICRI Recommendation two posters have been produced (see Figs 2 and 3), and ICRI partners are being encouraged to use these in their communications work. The GBF provides a key opportunity to galvanise the urgency and coherence needed to safeguard coral reefs from further decline and potential collapse. Details of future ICRI events and of the ICRI Recommendation can be found at www.icriforum.org/post2020, together with associated communication materials.

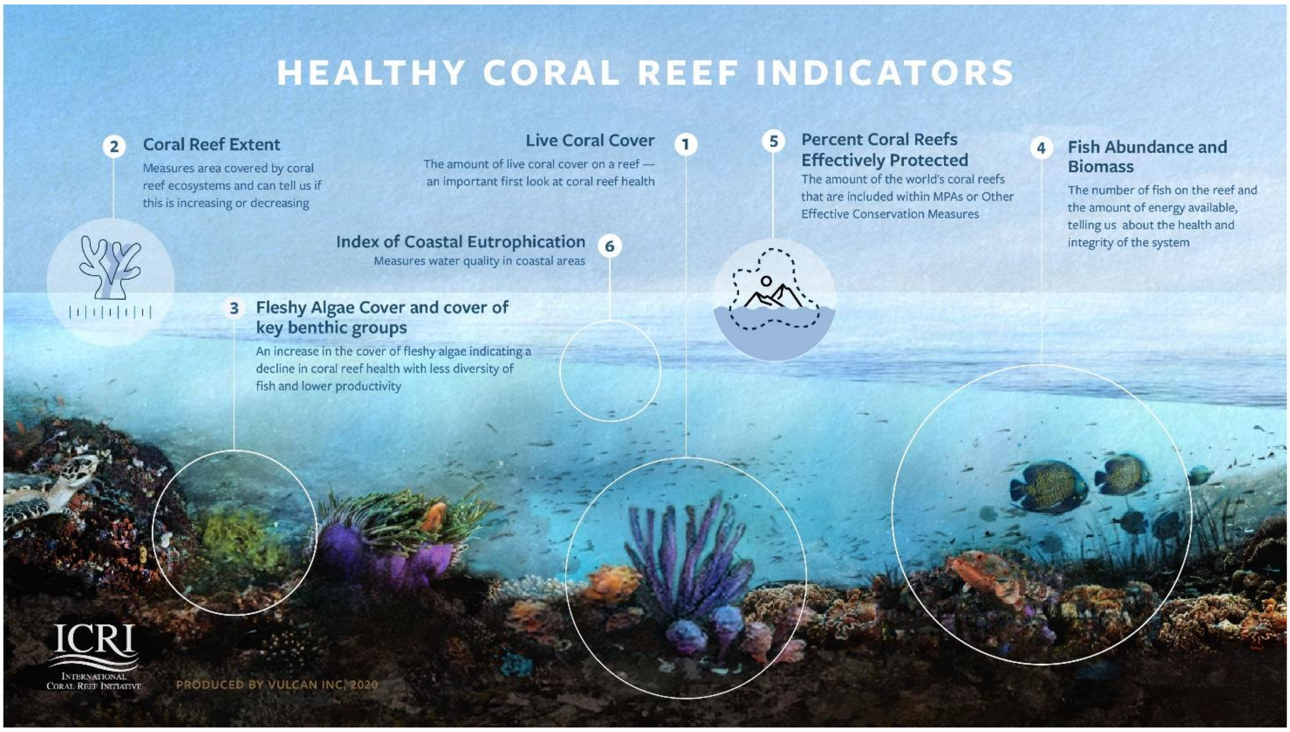


Figure 3: (Source: ICRI, 2020/Produced by Vulcan Inc)

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Allen Coral Atlas: a new map for coral conservation

Brianna Bambic[1], Zoë Lieb[1], Emma Kennedy[2], Chris Roelfsema[2], Helen Fox[1] (on behalf of the Allen Coral Atlas partnership)

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An entrepreneur philanthropist's love of the ocean combined with technological developments in satellite technology has sparked an exciting opportunity to rapidly map coral reef habitats across the planet. Global coral reef mapping efforts - from Darwin's 1842 map of global reef type distribution to the Millennium Coral Reef Mapping Project at the turn of the century - captured reef extent but did not have access to the resources or computing power of the 2020s to be able to map coral reef habitats to a high level of detail in a consistent way, relying on huge amounts of expert manual input. By leveraging advances in satellite imaging, cloud computing, and benthic data sourced throughout the coral reef community, the Allen Coral Atlas (https://allencoralatlas.org/) is part-way through mapping the world's coral reefs in an automated way that uses machine learning to scale mapping to regional areas**.** Ecological data is critical to support the computation of benthic habitat maps, but due to covid19 restrictions, field teams have been unable to collect as much field data as hoped to support our mapping effort. As requested recently via the coral-list, if you or your organization have a) coral reef geomorphic or benthic habitat maps, or b) spatially geo-referenced benthic data (photo quadrats, transect data) that you can share to help us produce better maps for our coral reef community, please contact us at submissions@allencoralatlas.com. All data are attributed on the website, and we do not publish the actual dataset you provide.

Why are we mapping Coral Reefs?

Coral reef ecosystems' limited spatial extent (reefs are just 0.09% of the ocean's surface area), widespread and often remote distribution, and submerged nature have traditionally made coral reef mapping at large scales challenging. Maps of coral reef habitat extent and distribution can underpin scientific discoveries (e.g. biogeography and coral reef distribution in Veron's Coral Geographic), support conservation planning (e.g. 2020 Aichi biodiversity targets), help track reef health (e.g. Global Coral Reef Monitoring Network), and be important in a geopolitical context (e.g. regional valuation of reef ecosystem services). But mapping has in the past been expensive in terms of resources, people and time; at the scale needed, comprehensive in-water surveys can take years for a country the size of the Solomon Islands.

The Allen Coral Atlas builds on the knowledge and principles from hundreds of years of reef mapping efforts, including recent regional to global mapping projects such as the Millennium Coral Reef Mapping Project, UNEP-WCMC Global Atlas of World Reefs, Living Ocean Foundations' World Reef Map, NOAA efforts to map US reef territories, and the Nature Conservancy's Caribbean Science Atlas, which have pushed the boundaries of our spatial knowledge of coral reefs. The Atlas attempts to significantly broaden the potential scale and scope by consistently mapping the world's shallow tropical coral reefs to a new level of detail and creating the first ever global benthic habitat map. The consistent approach results in comparable map classes that will make the Atlas an ideal tool for reporting conservation indicators and targets within and across regions, such as the forthcoming post-2020 targets from the Convention on Biological Diversity (CBD) and UNEP's Sustainable Development Goals. Because it is open-access and shared along with tools and user guides on an easy-to-use platform, the Atlas levels the playing field for coral reef practitioners around the world. Even without GIS training, expensive programs, or advanced spatial data analysis skills, users will be able to quickly and easily access satellite imagery, download map data, and experiment with on-platform statistical analysis for their reefs of interest. To provide further support, an online course on the Atlas is in development with the Reef Resilience Network.

The beginning of the Atlas

In 2017, renowned much-loved scientist, the late Dr Ruth Gates (Director of the Hawaii Institute of Marine Biology and ICRS president) met with Andrew Zolli of Planet Inc., a satellite imagery and mapping start-up. Their conversation sparked a vision to leverage new satellite technology combined with a community of coral reef scientists motivated to work collaboratively to share data to produce a global coral reef habitat map - the first of its kind. Zolli presented the idea to colleagues at Vulcan Inc., the organization led by Microsoft's co-founder, the late Paul G. Allen. Allen, lifelong ocean enthusiast and passionate diver, was distressed after experiencing degradation of his favorite reef, and a strong supporter of coral reef conservation. To address the knowledge gap and to support, inform, and inspire critical actions to manage and protect coral reefs, the collaborative Allen Coral Atlas partnership was born.

The Allen Coral Atlas Partnership includes the following members. (Please note, the "Science and Methods" section of the website provides greater detail on each partner's contributions.)

Planet Labs Inc.'s constellation of over 100 Dove nanosatellites provide images of the world's reefs on a daily basis, providing a ~3.7 m resolution seamless mosaic as the Atlas' foundation. This satellite imagery is corrected for cloud cover, sun glint, and atmospheric interference so that the shallow reef habitat bottom becomes far more visible and can be used to derive water depth, following approaches developed by Arizona State University's Center for Global Discovery and Conservation Science.

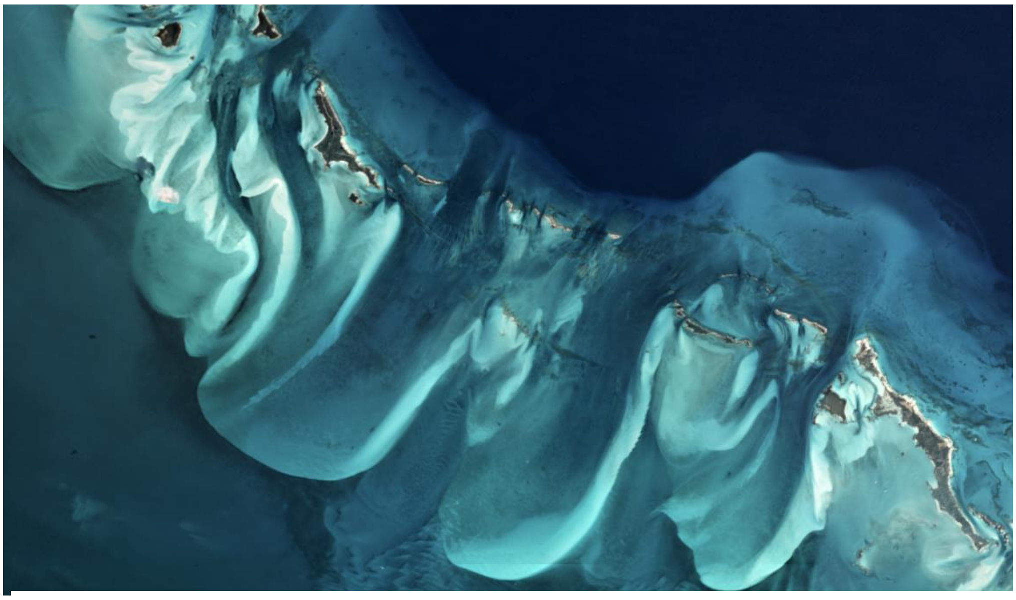


Figure 1. Bahamas, Planet Labs, Inc.

Next, a team of experts at the University of Queensland's Remote Sensing Research Center (UQ-RSRC) generates benthic and geomorphic habitat map layers based on a powerful approach initially developed for mapping the Great Barrier Reef (Roelfsema et al. 2020), which was then adjusted specifically for the Atlas (Lyons et al 2020). The corrected satellite imagery, field reference samples, water depth and waves are uploaded into Google Earth Engine for processing. Automated machine learning mapping creates a first pass raw map, followed by an object-based clean-up procedure and validation process (Lyons et al. 2020). Maps created by the UQ-RSRC team are then delivered to Vulcan Inc., who host them on an open-access website: AllenCoralAtlas.org. The Vulcan team is continually developing tools and functions to improve the access and usability of the site - one reason why user feedback and input about the platform is so valuable. Finally, the Field Engagement team, based at the National Geographic Society, raises awareness and uptake of the Atlas, so as to improve conservation efforts, and inform management strategies and policies regarding coral reefs; they also work with the Reef Resilience Network to provide training on the application of the Atlas for coral reef conservation practitioners, coastal communities, and coral reef scientists worldwide.

Features of the Atlas

In addition to global imagery and NOAA's Coral Reef Watch products, the Atlas currently contains two mapped layers; a geomorphic layer, with twelve distinct classes, and a benthic layer, with six classes (see the User guides on the website for more information).

Geomorphic Global Classes: Coral reefs display immense variability in shape and size, but most have comparable "zones" dictated by underlying geological structural features (the reef "geomorphology") characterized by differences in depth, slope and exposure (Fig. 1). Satellite-derived bathymetry and slope data are examined in combination with the color, brightness levels and texture of pixels to map reef geomorphic classes.

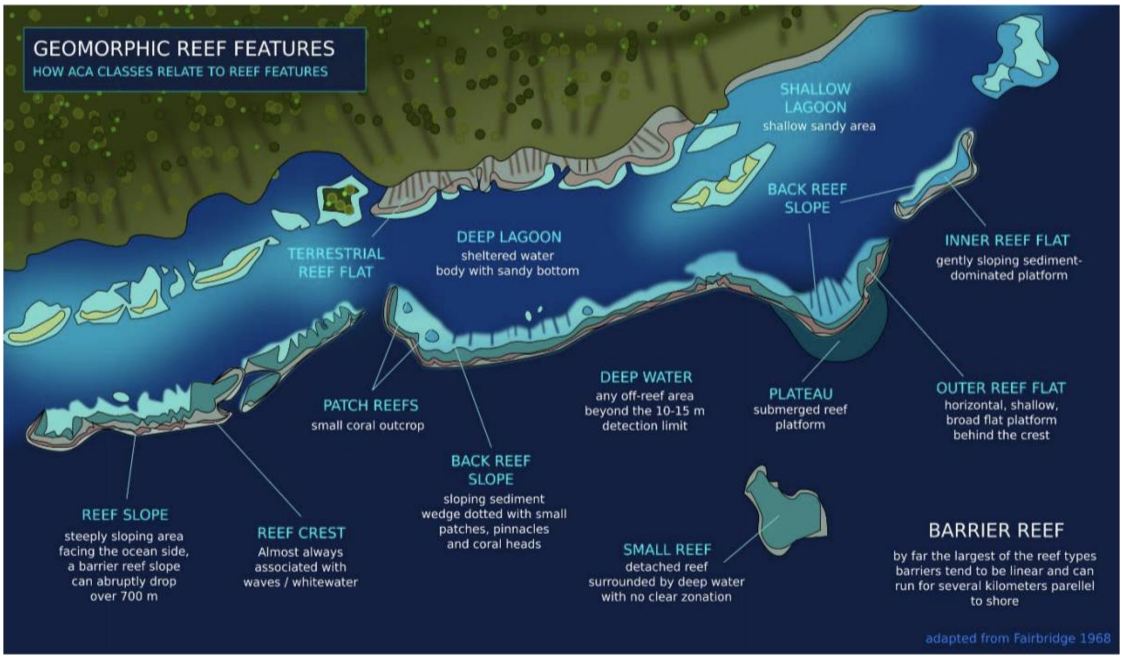
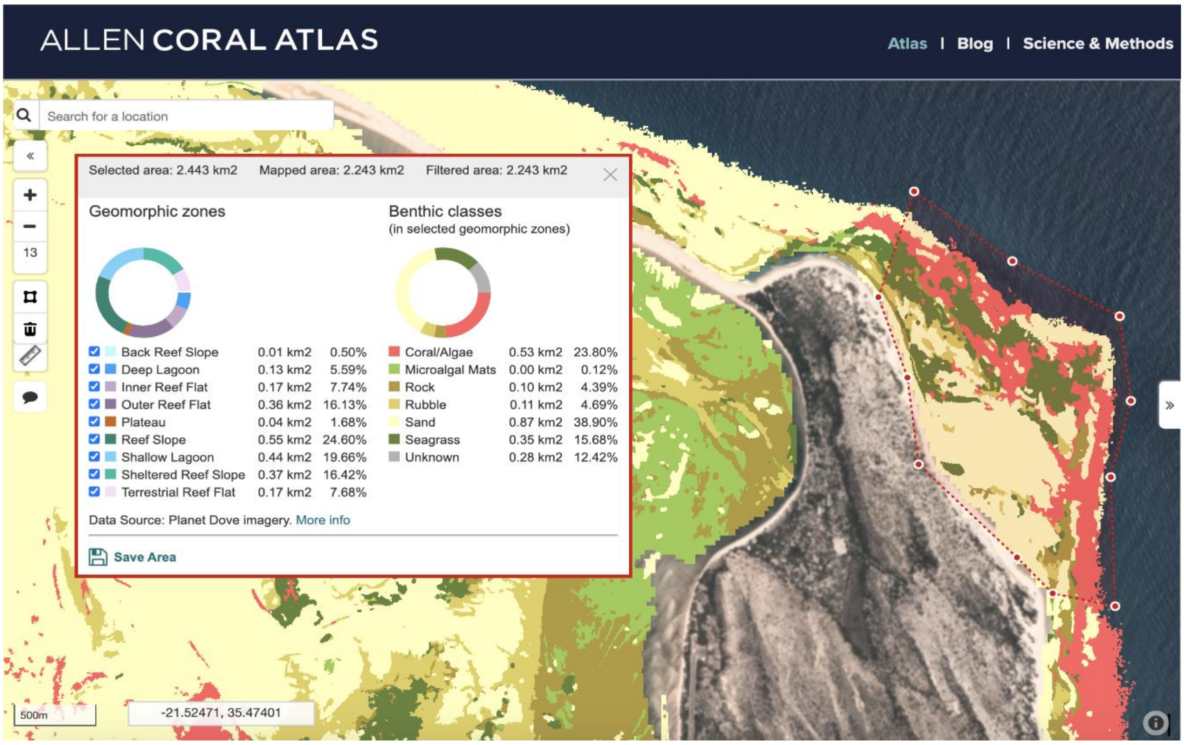


Figure 2. The geomorphic zones included in the Allen Coral Atlas with brief definitions (Kennedy et al. in prep)

Benthic Classes: Benthic classes characterize the different bottom types - especially communities of living organisms attached to the reef (benthos), as well as sediments and underlying substrate. The benthic layer of the Atlas is made up of coral/algae, microalgal mats, rock, rubble, sand, and seagrass. Coral habitat is reflected by a class called "coral/algae" because coral and algae are both photosynthetic organisms and have similar pigmentation, meaning multi-spectral satellite sensors are still unable to distinguish some of the key measures that ecologists prefer to use to assess reef health, such as cover of living coral, cover of dead coral, cover of bleached corals and functional forms of algae; nevertheless this class essentially shows where corals may be growing. The polygon and analysis tool can be used to create summary statistics about an area of interest based on geomorphic and benthic data layers (Fig. 3).



Selected area: 2.443 km2 Mapped area: 2.243 km2 Filtered area: 2.243 km2

Geomorphic zones

☑	Back Reef Slope	0.01 km2	0.50%
☑	Deep Lagoon	0.13 km2	5.59%
☑	Inner Reef Flat	0.17 km2	7.74%
☑	Outer Reef Flat	0.36 km2	16.13%
☑	Plateau	0.04 km2	1.68%
☑	Reef Slope	0.55 km2	24.60%
☑	Shallow Lagoon	0.44 km2	19.66%
☑	Sheltered Reef Slope	0.37 km2	16.42%
☑	Terrestrial Reef Flat	0.17 km2	7.68%

Benthic classes
(in selected geomorphic zones)

Coral/Algae	0.53 km2	23.80%
Microalgal Mats	0.00 km2	0.12%
Rock	0.10 km2	4.39%
Rubble	0.11 km2	4.69%
Sand	0.87 km2	38.90%
Seagrass	0.35 km2	15.68%
Unknown	0.28 km2	12.42%

Data Source: Planet Dove imagery. More info

Save Area

Figure 3. Vamizi Island, Mozambique with a benthic layer displayed on AllenCoralAtlas.org, showing the statistical summary of a polygon

The Atlas is designed for a greatly accelerated and standardized mapping of all shallow tropical coral reefs globally. There is a trade-off with accuracy over a small local map that has been meticulously created strictly with field data of the entire mapped area. The Atlas best supports national to regional and ocean-basin reef maps produced in support of large-scale assessment and regional-global conservation planning; but in places where existing maps are lacking or out-dated, they may still be the first cut for areas where maps would have otherwise taken years and significant funding to complete. Each global coral reef mapping project throughout history has been able to refine the estimate of coral reef extent, and these latest products are more conservative in what is defined as reef, and thus may give a more accurate description of true coral extent (Fig. 4).

How is the Allen Coral Atlas being used?

The Atlas team has reached out to hundreds of reef practitioners, decision-makers, and NGO staff working on dozens of topics to understand how the Atlas might be applied to a wide range of coral reef conservation contexts including community engagement, marine spatial planning, exploration and research, monitoring and evaluation, and planning for restoration or coastal adaptation. We present a few representative case studies here; as the Atlas team develops and refines the products, we hope they help other researchers and conservation practitioners to save resources, money, and time.

Marine Protected Areas and Marine Spatial Planning - Micronesia case study

Peter Houk at the University of Guam is working with both government agencies and non-governmental organization partners in Micronesia as part of an effort to create new marine management plans. They monitor reefs, identify trends, and present findings to local communities to help them to decide where Locally Managed Marine Areas (LMMAs) or partial no take zones should be implemented. He noticed that the benthic classification of Atlas's maps is similar to NOAA's habitat maps for Micronesia, and stated, "The first thing everyone does is stick a big map on the wall." Currently he's using static ecological data to make the analysis, which needs to be redone for different dimensions of a potential LMMA. Instead he suggests that the Atlas is an "interactive tool to change things & create immediate feedback." Because analysis can be done on the Atlas website itself, it can be used during a community meeting to draw out proposed no take zones and compare different benthic cover analyses.

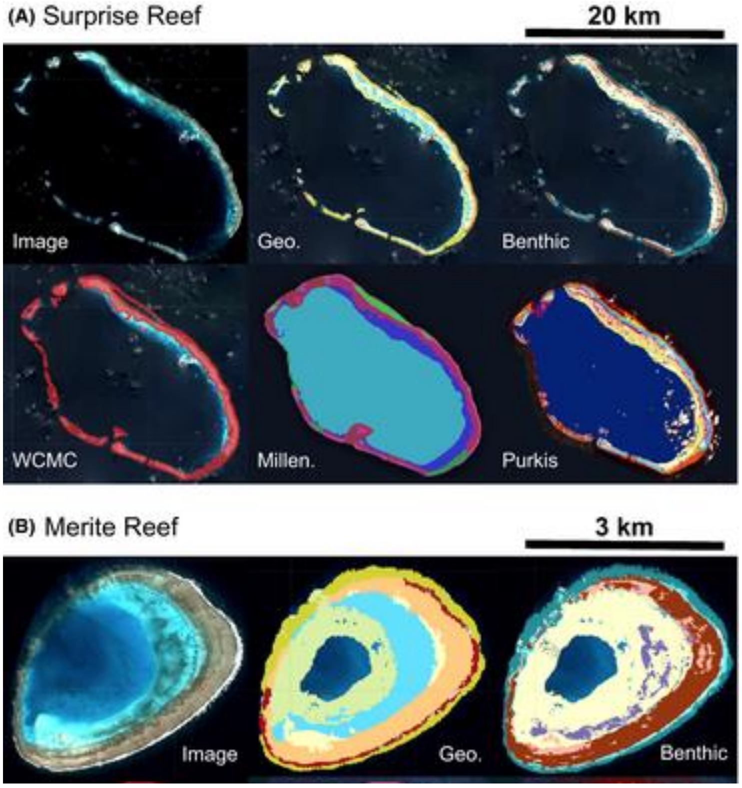


Figure 4 (from Lyons et al. 2020, Fig. 5). A comparison of the geomorphic and benthic maps produced by the Atlas (Geo. & Benthic) with the reef maps generated by UNEP -WCMC (Spalding et al. 2001), the Millennium Project (Andrefouet et al. 2006) and by Purkis et al. (2019). Surprise Reef and Merite reef are situated at the north-west tip of New Caledonia. This figure provides a broad comparison of class resolution and distribution rather than a direct comparison of habitat classification; no class colour definitions are provided as there are around 40 different classes used by the different mapping projects.

Exploration and Research - Myanmar Case Study

Me'ira Mizrahi from the Wildlife Conservation Society in Myanmar used the imagery to plan their expeditions to the Rakhine coast, since to the best of their knowledge, no coral reef habitat maps of the area exist. The clear seamless mosaic allowed staff to explore sand and fringing reefs to determine if sites were dive-able (Fig. 5).

Monitoring and Evaluation - Vanuatu case study

For a Global Environmental Facility (GEF) funded National International Waters Ridge-to-Reef project in Vanuatu, Jade Delevaux and her team from the Secretariat of Pacific Community (SPC) are asking "Which coral reef areas are potentially vulnerable to run-off?" The Atlas allows Jade and her team to more accurately model where coral reefs are experiencing high turbidity and degradation due to run-off based on their locations and proximity to watersheds (Fig. 6). As the Atlas team develops and refines the maps, they may be helpful for other researchers and conservation practitioners to support planning and save resources, money, and time.

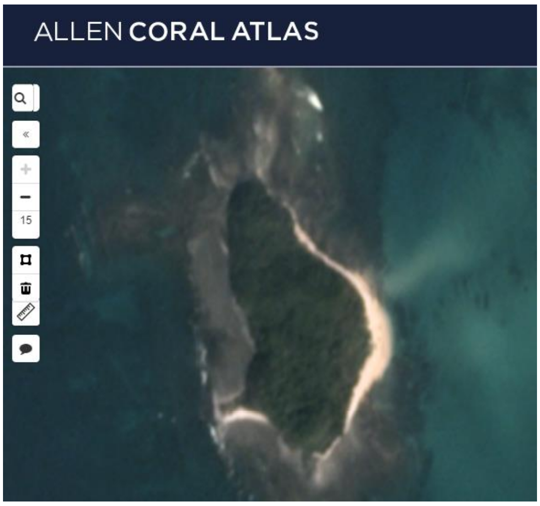


Figure 5. Gwa Island, Rakhine State, Myanmar, Allen Coral Atlas Imagery

What's coming next?

The Arizona State University team is currently creating a dynamic brightening alert layer that can detect changes in the spectral signature of coral reefs as a proxy for bleaching events. This could dramatically shorten how long it takes to detect bleaching events and can allow for more rapid response. Additionally, a turbidity layer is coming soon, which could help reef managers and researchers monitor their reefs and coastal areas for runoff events. The Atlas team is tackling the planet's reefs region-by-region, with a first draft of the full global coral reef map expected to be completed in the second half of 2021. Stay up to date on upcoming regions by subscribing to our Allen Coral Atlas newsletter (sent out less than once a month).

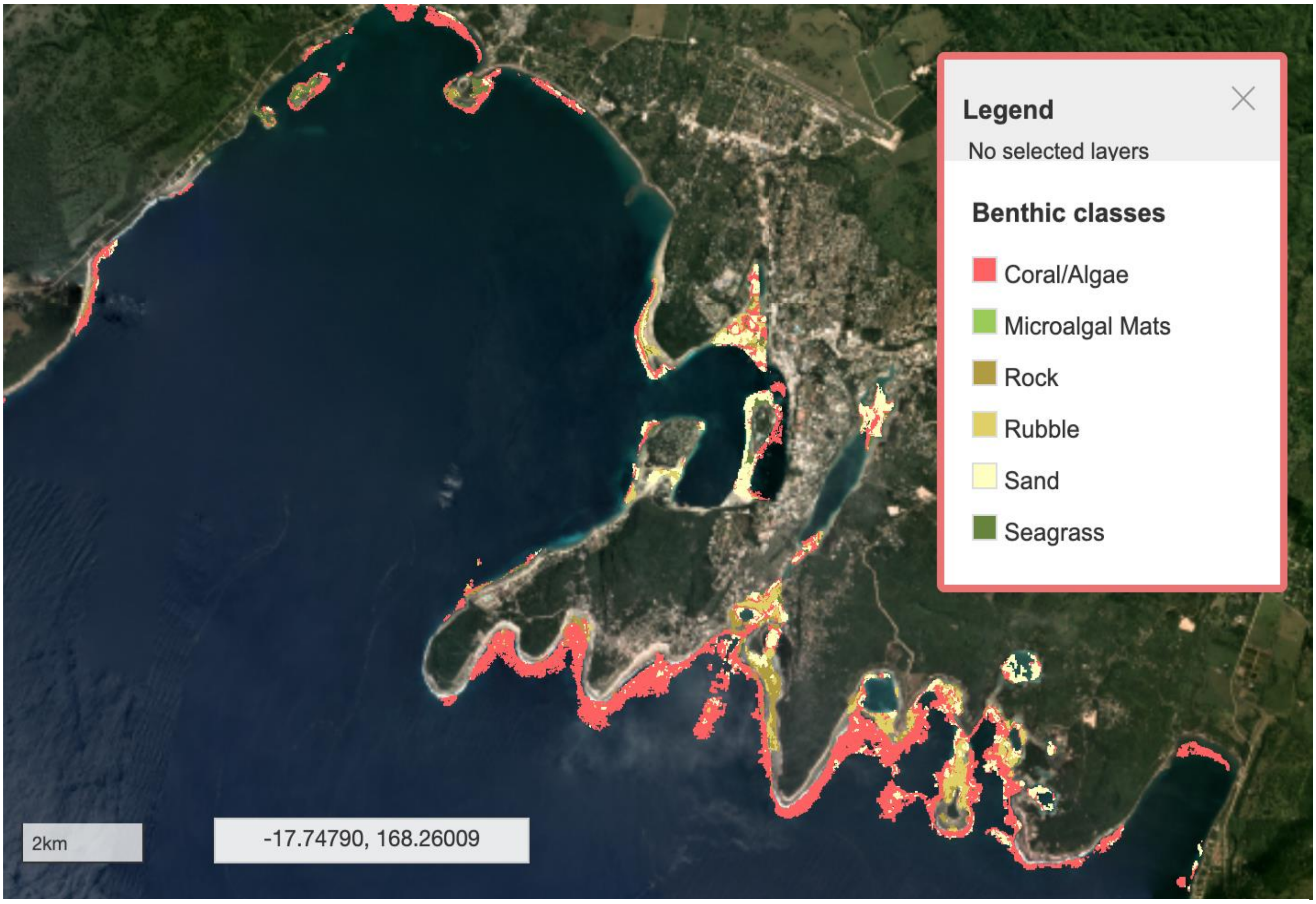


Figure 6. A watershed in Port Vila, Vanuatu. Allen Coral Atlas

Conclusion

Hundreds of years of foundational coral reef science and mapping, a technological revolution in remote sensing, and unprecedented computing capabilities have made the Allen Coral Atlas possible. It will be the first of a new generation of dynamic coral reef maps, made possible by cutting-edge satellite technology and cloud computing. But more than that, the Atlas can bring people together - stakeholders, scientists, conservation practitioners and lovers of coral reefs - creating a focal point for data-sharing and collaboration. By creating an open source, easy-access spatial visualization tool, the Atlas team hopes to increase the capacity of the coral reef conservation community to visualize, map, analyze, monitor, and protect one of the most biodiverse and vulnerable habitats on the planet.

The work of the Atlas team is made possible by the support of the coral reef community - please get in touch with us with questions or comments, or to let us know how you are planning to use this or other spatial tools in your work at support@allencoralatlas.org.

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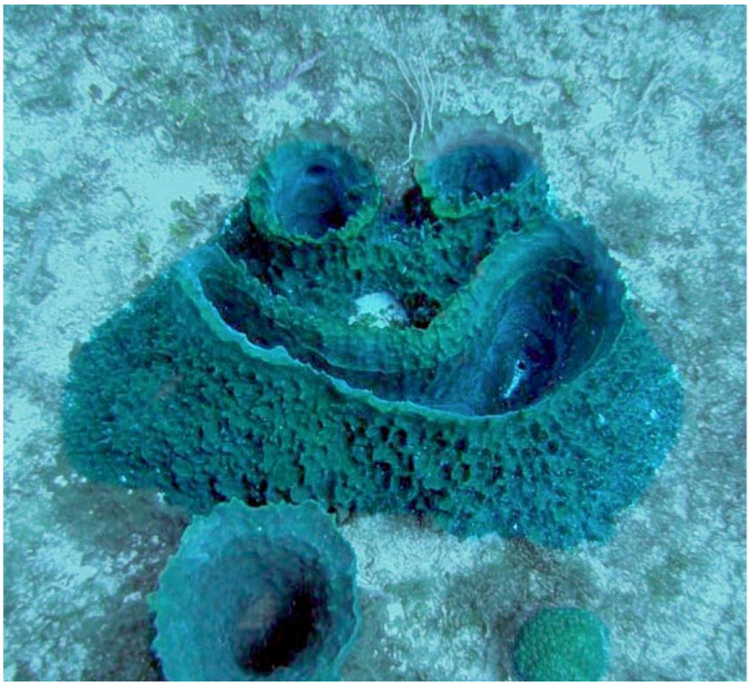

“Happy Sponge” – a giant barrel sponge *Xestospongia muta* encountered in the Virgin Islands Coral Reef National Monument, off the island of St. John; an illustration from the book “*Coral Reef Curiosities*” by Chuck Weikert (see book review section) – photo by Rob Waara.

4D-REEF: Past, present, and future of coral reefs in the Coral Triangle

Coral reefs are having a hard time. Reefs in the Coral Triangle stand out for their species richness, but they are in close proximity to areas with high human population densities. Ongoing anthropogenic environmental changes in the sea, on land and in the atmosphere have severely degraded many important coral reef environments. Will these reefs stand a chance in the future with ongoing climate change and pollution?

4D-REEF is a research programme funded by the European Union under the Horizon 2020 Marie Skłodowska-Curie Actions. The research consortium brings together researchers from 18 different organisations across Europe and southeast Asia.

Combining a variety of geological, biological and climate data, 4D-REEF investigates the hypothesis that turbid coastal environments provide a refuge for coral reefs in periods of warm climate. The key questions to be addressed are:

- What was the biodiversity of turbid reefs in the past, in what habitats did reefs grow during past warmer periods of the Earth's history, and how does this compare to the present?
- What are the environmental constraints on ecosystem functions of turbid reefs?
- How can we use information from past reefs to better understand the future trajectories of modern coral reefs, and apply this towards reef restoration actions?

18 Early Stage Researchers (ESRs) form the backbone of the 4D-REEF research programme. They are based at 10 different host institutions across Europe (Naturalis Biodiversity Center, Deltares, Natural History Museum London, University of Bristol, University of Granada, University of Aveiro, Goethe University Frankfurt, Max-Planck Institute for Marine Microbiology, Leibniz Centre for Tropical Marine Research, Ocean Maps) and Hasanuddin University in Makassar, Indonesia.

Pulau Badi island in the focus area of 4D-REEF, Spermonde Archipelago, south Sulawesi, Indonesia - photo by Willem Renema

The ESRs will provide a quantitative assessment of modern, Holocene (5-10 thousand years ago), and Pliocene (~3 million years ago) reef biota, and of their interaction with abiotic environmental gradients. Fieldwork will include both observations on present day reefs, including sediment cores, as well as geological analyses of fossil reef outcrops on land. Innovative techniques such as hyperspectral imaging and acoustics will be used to map the benthic composition and topography of large reef areas and to visualise these in 3D reef models. Several modelling techniques will be used to project coral distributions, to forecast trajectories of future climate change and to describe the functional relationships between environmental conditions and dominant carbonate producers. All quantifications of biota and reef functioning will ultimately be incorporated in a predictive model of turbid reef distribution for the 22nd century.

Besides the 18 ESRs, the following researchers are part of the 4D-REEF consortium:

- Naturalis Biodiversity Center, Netherlands: Willem Renema, Nicole de Voogd;
- Natural History Museum, UK: Ken Johnson, Jon Todd;
- University of Bristol, UK: Erica Hendy, Dan Lunt;
- University of Granada, Spain: Juan Carlos Braga;
- University of Aveiro, Portugal: Newton Gomes;
- Goethe University Frankfurt, Germany: Wolfgang Muller, David Evans;
- Leibniz Centre for Tropical Marine Research, Germany: Hildegard Westphal, Sebastian Ferse, Arjun Chennu, Sonia Bejarano;
- Ocean Maps, Austria: Klemens Svetitsch, Thomas Nemetz;
- Hasanuddin University, Indonesia: Jamaluddin Jompa, Rohani Ambo Rappe;
- Partners: Elena Couce, Susanna Jenkins, Alessio Rovere, Owen Wangensteen, Jody Webster.

Want to stay up to date? Please follow us on Twitter, or visit the website: www.4d-reef.eu

Divers conducting fieldwork on turbid reefs in the Spermonde Archipelago - photo by Willem Renema

REEF EDGE

Scientific letters or notes describing observations or data

Recent reports of *Astropyga magnifica* (the Magnificent Sea Urchin) in the US Virgin Islands

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There is limited natural history information on the Magnificent Sea Urchin *Astropyga magnifica* in the literature. Kier & Grant (1965) list the depth range as 80-85 feet in the Florida Keys. A cursory observation could mistake this species for *Diadema antillarum*, now common again on shallow-water reefs in the U.S. Virgin Islands (Miller et al. 2003). However, the specimens reported here had several distinguishing characteristics: iridescent blue spots and purplish-red coloration, and they held their spines in cone-shaped bundles, both as described by Kier & Grant (1965). We also noted orange-colored bands between the bundles.

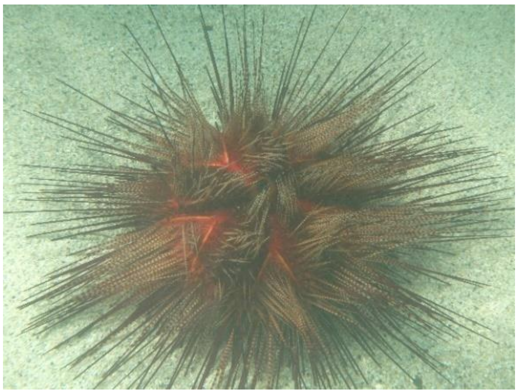

Figure 2. *First individual sighted near beach (2-3 ft of water), Coakley Bay St. Croix August 18, 2018*

Figure 3. *Second individual sighted in seagrass (10-12 ft of water), Coakley Bay St. Croix August 18, 2018*

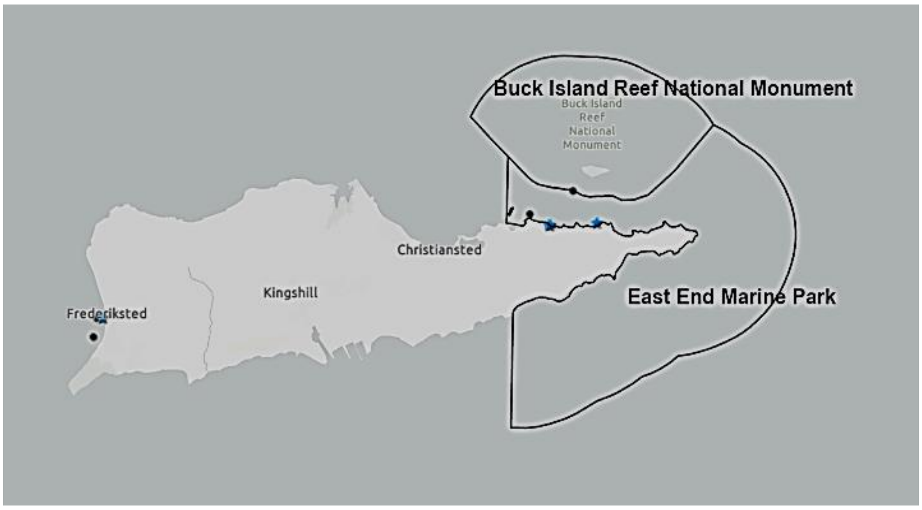

Figure 1. *Map of St. Croix showing sites of recent (this paper, blue star) and older (black dots) sightings of* Astropyga magnifica.

In 2018 and 2019, the authors observed and positively identified four individuals of this species in shallow-water, nearshore habitats on the island of St. Croix, US Virgin Islands (Fig. 1). We also asked resource managers and marine scholars in the territory about recent sightings of the species and report those here. Following the first report of an unusual sea urchin in shallow waters on St. Croix, the authors snorkeled to the site and confirmed the species. Two subsequent observations were made while performing other surveys or recreational dives. The first sighting was in 2-3 feet of water in Coakley Bay (East End Marine Park), St. Croix on August 21, 2018. The habitat was sand. The individual was approximately 6-7'' in diameter (body). This individual did not look healthy, as the color of its spines was faded to a brown color, however the striations on the spines were still clearly visible (Fig. 2). The second individual was in 10-12 feet of water nearby also in Coakley

Bay (East End Marine Park) on August 21, 2018. The habitat was a thick *Thalassia testudinum / Syringodium filiforme* seagrass bed. This individual was smaller than the first (4-5 ins diameter) and looked healthier, with good coloration (Fig. 3). The third individual was seen in 15-20 ft of water just south of the Frederiksted Pier (off the west end of St Croix) on September 1, 2018. The habitat was sand. This individual also did not look healthy, as the color of its spines and body was faded to a brown color. The striations on the spines were still clearly visible and they were grouped into cones. The fourth individual was observed in approximately 6 ft of water in Yellowcliff Bay (East End Marine Park), St Croix on January 15, 2019. The habitat was rubble/sand and sparse *T. testudinum* seagrass, near a shallow-water patch reef dominated by *Porites porites*, *Millepora spp*. and *Gorgonia ventalina*. This individual appeared to be in good condition.

Responses from marine resource managers and scholars in the US Virgin Islands indicated that the species is seen occasionally, including sometimes in shallow water. One report (2016) was of a single individual in approximately 6 ft of water on the east end of St. John (C. Rogers, pers comm.) also with bright colors and no fading. Two reports within the last decade refer to aggregations as described by Kier and Grant (1965) (Frederiksted Pier, 2009 and Buck Island Reef National Monument, 2013) (V. Brandtneris, pers comm; C. Pollock, pers comm). These were in deeper water (30-50 ft depth) in sand habitats and one (Buck Island) included faded individuals amongst them. Other reports of isolated individuals are provided on the map (W. Coles, pers comm; M. Taylor, pers comm).

In Puerto Rico, Williams et al. (1986) reported a mass mortality event of 68 *A. magnifica* in shallow water (2 – 4 ft), while nearby individuals of the same species at a greater depth were unaffected. Our observations were of single urchins. We were unable to observe adjacent, deeper waters concurrently to confirm or deny the presence of other individuals of the species at greater depths. We present these findings to increase the knowledge and documentation of this uncommon and little-known echinoid species in the shallow waters of the eastern Caribbean.

Acknowledgements: Many thanks to those in the natural resource community in the USVI who responded to my request for information: Victor Brandtneris, William Coles, Marcia Taylor, Clayton Pollock, and Caroline Rogers. Thanks are also due to Carmen Corradino who alerted us to the presence of the first urchin. The East End Marine Park is supported by the Coral Reef Conservation Program of the National Oceanic and Atmospheric Administration.

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Early observations of heat-induced coral bleaching in the Galápagos Islands

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Mass coral bleaching events have affected most of the world's tropical coral reefs in recent decades, bearing the signature of global warming (Hughes et al. 2018). Since the phenomenon was first described in the 1980s (Glynn 1983), most studies have interpreted that the first occurrence of widespread mass coral bleaching—when entire reef tracts or regions bleach at once—was associated with the 1982-83 El Niño (Glynn 1983; Coffroth et al. 1990; Hughes et al. 2018). The earliest published record of heat-induced coral bleaching was at Lowe Isles on the Great Barrier Reef in 1929 (Yonge and Nicholls 1931). However, since this event was potentially caused in part by subaerial exposure of reef-flat corals during low tides, and the observations were restricted to a small area of one reef, most studies have not considered this a "mass" bleaching event. Other early reports of coral bleaching were also localized events caused by freshwater stress, heated effluent from a power plant, or low-temperature stress (Goreau 1964; Jokiel and Coles 1974; Hudson et al. 1976). Given the lack of reported heat-induced, widespread bleaching events prior to the 1980s, scientists tend to describe coral reefs—at least those far from direct human impacts and not recently hit by a cyclone or disease outbreak—as being in "healthy" or generally undisturbed states before 1980 (but see *e.g.,* Bruno and Selig 2007; Cramer et al. 2020). Yet, since there were few systematic reef surveys prior to the 1980s (Bruno and Selig 2007), an absence of evidence should not necessarily be interpreted as an absence of bleaching.

One way to fill in the gaps when and where rigorous survey data are lacking is through the use of local ecological knowledge. Local and Indigenous Knowledge Systems (LINKS) are beginning to be recognized as a fundamental way of understanding, mitigating, and adapting to climate change, environmental degradation, and biodiversity loss by the United Nations Educational, Scientific and Cultural Organization (UNESCO). The Galápagos Islands are an ideal place to leverage local knowledge of past coral bleaching. Located at the confluence of warm and cold water currents, the Galápagos Islands naturally experience seasonal variations in water temperature of up to 10 °C and are strongly influenced by eastern Pacific El Niño events (Wellington et al. 2001). Previous studies have shown that some of the largest El Niño-related sea surface temperature (SST) anomalies occur in the vicinity of Galápagos and have profound effects on the patterns of coral bleaching and recovery in the region (Glynn 1991; Glynn et al. 2018). Furthermore, local settlers began fishing along the coasts in the Galápagos Islands in the late 1930s, the small artisanal boat industry began to develop in 1955, and the lobster fisheries in the 1960s, when Galápagos spiny lobster production contributed to more than 2/3 of Ecuadorian exports of lobster tails (Reck 1983). The onset of the lobster fishery was especially important because it required fishers to dive, and thus encouraged direct underwater observations of the Galápagos Islands reef environments for the past six decades.

During September 2018, we interviewed fishers in the Galápagos Islands who have been diving—almost daily—for more than fifty years across the archipelago. To comprehend the fisheries dynamics in conjunction with climate change in Galápagos, we gathered fishers' anecdotal information, perceptions, and testimonials about changes in fisheries and marine communities during past El Niño events. We used the snowball sampling method, where key informants help us to identify other individuals and these in turn led us to others, allowing a chain of information (Goodman 1961). We conducted semi-structured, in-depth, and exploratory interviews with 23 fishers from three populated areas in Galápagos (Fig. 1): Puerto Ayora in Santa Cruz Island, Puerto Villamil in Isabela Island, and Puerto Baquerizo Moreno in San Cristóbal Island. Open-ended questions were adapted to each fishers' knowledge or expertise, allowing each contributor to expand on topics they considered most interesting or important. Questions such as, "How does El Niño affect marine life?" and "How does El Niño affect your fishing activity?" were also aimed at understanding the personal perceptions of fishers regarding their work and their memories of past warm-water events. The interviews were between 30 and 200 minutes, summing up 31 hours of active conversation and mutual learning process with the local fishers.

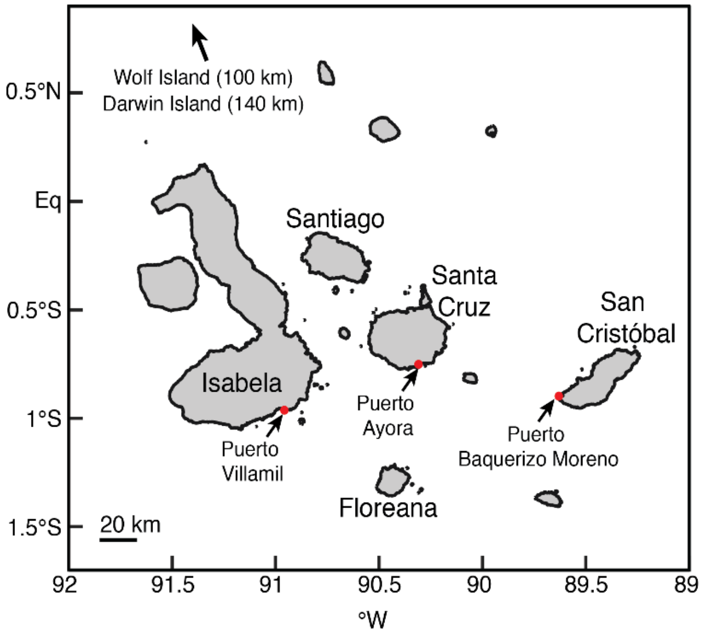

Figure 1. *Map of the Galapagos Islands*

Twelve fishers discussed specific El Niño events (*e.g.,* 1965-66, 1968-69, 1982-83, 1997-98 and 2015-16) and their effects on fisheries and marine life. Two traditional *hookah*-diving lobster fishers had specific recollections of coral bleaching in the 1960s. In Galápagos, *hookah* diving is a simple form of diving in which fresh air is drawn from the surface through a compressor on a fiberglass or wooden boat, and then sent down a hose for the diver to breathe freely underwater. The duration of the dives varies but can last up to six hours, which is the case for the spiny lobster fisheries. The oldest of these fishers told us that, "*When I arrived in Galápagos, in 1965, I was diving and I noticed that all the corals in the islands I fished were fully bleached.*" Another said, "*I was 6 or 7 years old when I began diving with my dad in 1968, and I observed there was a big bleaching of the corals in Santa Cruz Island*".

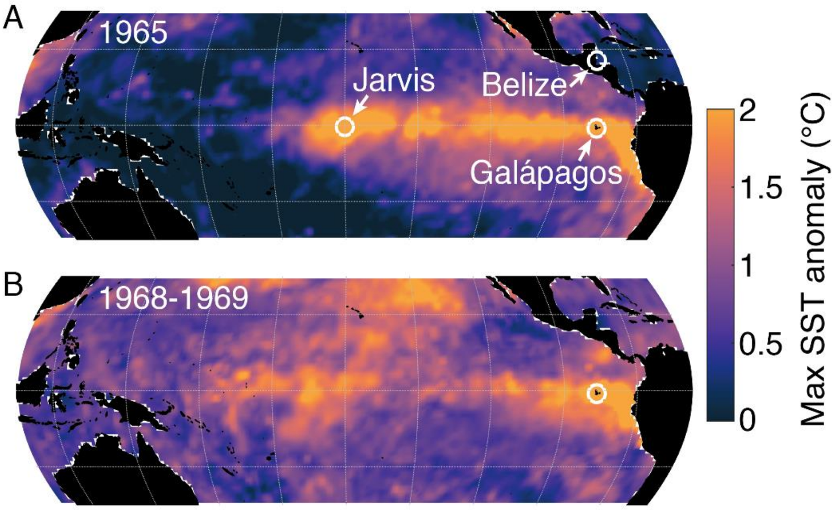

Figure 2. *Sea surface temperature (SST) anomalies during anecdotal reports of coral bleaching events in 1965 and 1968-1969. Colors show maximum monthly SST anomalies during the specified years, relative to the 1950-1980 climatology, calculated from HadISST data (Rayner et al. 2003). Labels show the Galápagos Islands as well as Jarvis Island and Belize, where coral cores showed stress bands corresponding to 1965.*

The first interviewee (#1) was 82 years old at the time we conducted a two-hour interview. He learned how to fish with his father when he was 8 years old and lived at the mainland port of Puerto López, Manabí Province. He had been fishing in the Galápagos Islands since 1962, but moved to live there permanently in 1965, being one of the first professional fishers to arrive on Santa Cruz Island. Between the 1960s and 1970s, he would free dive to ~10 meters depth to collect octopus, mollusks, and lobsters. At this time, he visited the islands of Santa Cruz, eastern Isabela, southern Santiago, northern Floreana, and some other small islets accessible during one- or two-day trips (Fig. 1). Fishing was his main economic activity for 74 years, until he retired. When asked how El Niño events have affected fisheries and marine life, he responded with observations that correspond to the scientific literature (*e.g.,* more precipitation, anomalously warm waters, migration of sea lions to deeper and further sites). Interviewee #1 continued to say that 1965 was an El Niño year because the water temperature and clarity were unusually high, and at this time the corals were "fully bleached". He also observed corals bleaching in later years (*i.e.,* El Niño events in 1982/83 and 1997/98). The other interviewee (#2) was also an experienced fisher, 58 years old at the time of our 90-minute interview. He began to fish when only about 6 years old. When asked how El Niño affected fisheries and marine life, he commented on many negative effects on sea lion populations (*e.g.,* increases of skin disease, higher mortality of pup and juvenile individuals, adult migration to deeper and further sites), but he also detected effects on marine birds and distributional shifts for sardines and herring local populations. Interviewee #2 recalled adamantly that the corals were bleached in 1968, as this was when he was first learning to fish and dive with his father.

Substantial variability exists in water temperatures around the Galápagos Islands. In particular, the northern Wolf and Darwin Islands are warmer, and the western side of Isabela Island is cooler, than most other islands due to the effects of equatorial upwelling (Karnauskas et al. 2015). The fishers that recalled coral bleaching in the 1960s did not travel to Wolf or Darwin Islands, but rather they visited several of the main islands (which may have included western Isabela, but not exclusively so). Although spatial and temporal variability in upwelling likely modulates bleaching responses in the Galápagos Islands (Riegl et al. 2019), the fishers' bleaching reports do not enable us to evaluate the role of upwelling during the 1960s bleaching events.

The fishers' testimonials of pre-1980s coral bleaching are supported by the anomalously warm waters around Galápagos at these times due to El Niño events, detected in both shipboard measurements (Fig. 2) and geochemical records from coral cores (Shen et al. 1992; Dunbar et al. 1994; Jimenez et al. 2018). Furthermore, multiple skeletal cores from *Porites* corals show coherent evidence of bleaching—indicated by distinct "stress bands"—in 1965 at Jarvis Island in the equatorial Pacific (Barkley et al. 2018). One stress band was also found corresponding to 1965 in a core from the Mesoamerican Reef of Belize, but the lack of replication in other cores suggests it may have been only a relatively weak event (Carilli et al. 2009). Although several studies have used coral skeletal cores from the Galápagos Islands (Glynn 1990, 1994; Shen et al. 1992; Dunbar et al. 1994; Manzello et al. 2014; Jimenez et al. 2018), no study has investigated stress bands or growth hiatuses in replicated *Porites* cores, preventing direct comparison to the Jarvis bleaching record. Considering that Jarvis Island, like the Galápagos, is highly sensitive to El Niño events, it is plausible that the records of bleaching in Jarvis Island skeletal cores represent the same widespread event in 1965 as seen in Galápagos by the lobster fisher. If so, to our knowledge, this is the earliest direct report of temperature-induced mass coral bleaching, pre-dating the anecdotal report of bleaching during 1972-73 in American Samoa (Glynn 1993). There is less corroborating evidence of the 1968 bleaching event mentioned by the second fisher, but nevertheless it remains plausible given the relatively high temperatures at the time and the lack of any direct contradictory evidence.

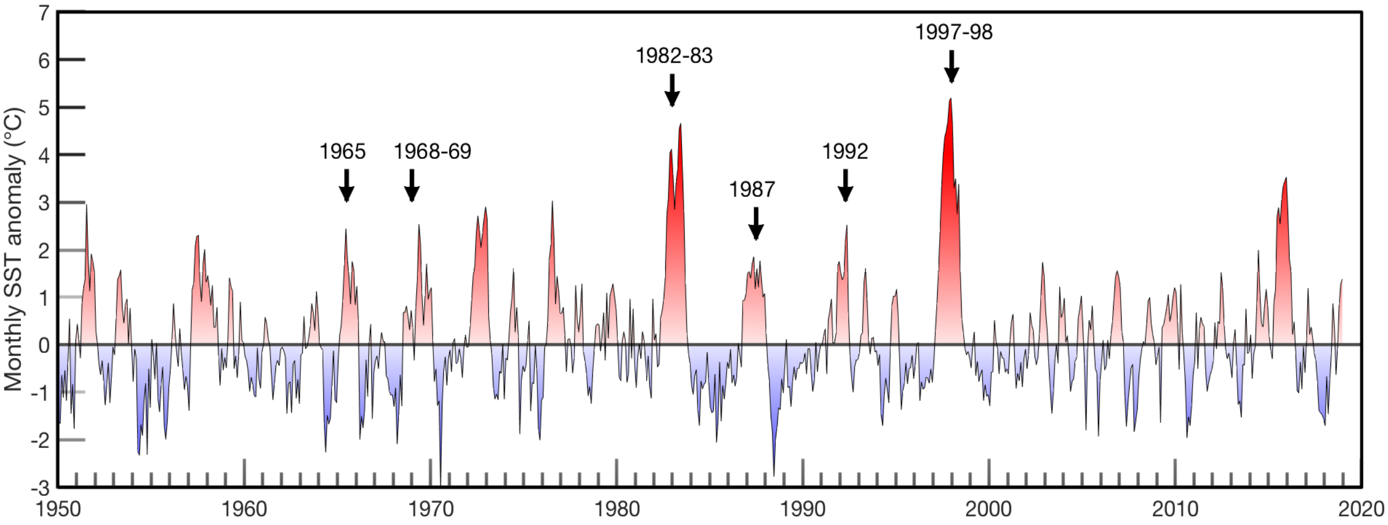

Figure 3. *Time series of monthly temperature anomalies for the HadISST grid-box nearest to the Galápagos Islands. Arrows indicate years of coral bleaching events recorded by scientists (1982 onwards) and those observed by fishers (1965 and 1968-1969). It is important to note that relatively few observations exist from the Galápagos Islands at these times, and that SST is reconstructed from sparse measurements across the Pacific Ocean (Deser 2010).*

The 1982/1983 El Niño imposed unprecedented heat stress on corals living in the Galápagos Islands, exceeded only by the El Niño event in 1997/1998 (Fig. 3). Extensive coral mortality occurred in 1982/1983, and some reef areas in Galápagos have yet to recover (Glynn et al. 2018). However, even though temperature anomalies were similar or greater in 1997-1998 than 1982-1983, less bleaching and mortality occurred in 1997-1998 (Glynn et al. 2001). Temperature anomalies in 1965 and 1968-1969 were 2-3 °C lower than in 1982-1983 and 1997-1998 (Fig. 3), but similar in magnitude to 1987 and 1992, both years when there were minor bleaching events in the Galápagos (Glynn et al. 2017). Thus, based on the observed record of bleaching in relation to temperature around the Galápagos Islands, it is not surprising that bleaching may have occurred in 1965 and/or 1968-1969. Perhaps more unexpected is that bleaching did not occur in 1972 (Glynn et al. 2017) or 2015 (Hughes et al. 2018) since temperatures were even higher than 1965, 1968-1969, 1987, and 1992 (Fig. 3). Regardless, it is compelling that the years in which fishers claim to have observed bleaching correspond to temperature anomalies comparable to minor bleaching events already recorded by scientists (1987 and 1992). Anecdotal reports of bleaching or expert opinion of scientists have already been incorporated in coral bleaching databases (Hughes et al. 2018), and reef users have broadly similar recollections of prior reef states as professional scientists (Eddy et al. 2018). The fishers that we interviewed in the Galápagos Islands also demonstrated acute knowledge of their local environment, as well as specific events in their own lives grounding their recollection of coral bleaching to the 1960s. Together, this leaves us with little reason to doubt their claims.

Recent declines in coral cover across the world's reefs (*e.g.,* Bruno and Selig 2007; De'ath et al. 2012) suggest that disturbance events have become (1) more severe, (2) more frequent, and/or (3) more widespread. However, local ecological knowledge provides evidence that at least some coral reefs may have bleached before scientific documentation of widespread, mass bleaching began in the 1980s. In the Galápagos Islands, for example, surveys conducted during the 1970s suggested the reefs were in "healthy states" (Glynn et al. 2018), despite the fishers' testimonies that these reefs had bleached within the previous decade. These observations suggest that some coral reefs may have a longer history of bleaching and recovery than previously recognized.

Acknowledgements: We are grateful to the artisanal fishers of Isabela, San Cristóbal and Santa Cruz Islands for their valuable observations, and to Solange Andrade and María José Barragán at the Charles Darwin Foundation for their field support and guidance. The Galápagos research was supported by the 2018 Tinker Field Research Grant and the Center for Iberian & Latin American Studies (CILAS) at UCSD. L.M.C. was supported by the National Council for Technological and Scientific Development –CNPq, Brazil (#213540/2014-2). Approval for ethical human research on social and behavioral sciences was obtained from the Institutional Review Boards (IRB) at the UCSD's Human Research Protection Program (Project # 181158SX). This publication is contribution number 2339 of the Charles Darwin Foundation for the Galápagos Islands.

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The Crown-of-Thorns Starfish in Espiritu Santo Archipelago National Park, Gulf of California, México – a first population outbreak in the Eastern Pacific

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The Crown-of-thorns starfish is among the most studied asteroids worldwide because it is an effective predator of scleractinian corals on Indo-Pacific reefs (Haszprunar *et al*. 2017). Its population outbreaks have been a major cause of coral mortality and reef perturbation, mainly in the Indo-West Pacific (Kayal et al. 2012). But this species also occurs in the Eastern Tropical Pacific Ocean, where it was first reported in the mid XIX Century from the Gulf of California, Mexico (Verrill 1869). Its known distribution in the Eastern Pacific extends in Mexico from Rasa Island (28°N) to Bahia Banderas (20°N) taking in several oceanic islands (Revillagigedo and Clipperton, Cocos, Malpelo and Galápagos), and also includes the Pacific coasts of Costa Rica, Panamá, Colombia and Ecuador (Glynn et al. 2001, Zapata et al. 2017).

In 2017, Rodríguez-Villalobos and Ayala-Bocos (2018), as well as other researchers including the authors of this note, noticed a surprising increase in population density of Crown-of-thorns in the Espiritu Santo Archipelago National Park, in the southern Gulf of California (Fig. 1). Previously in that area, De Alba (1978) reported 53 ind/ha and Herrero-Pérezrul (2008) recorded 220 ind/ha; nevertheless, there were no reports of significant damage to local coral colonies, probably because in this area the species has a varied diet within which corals are not always the main food

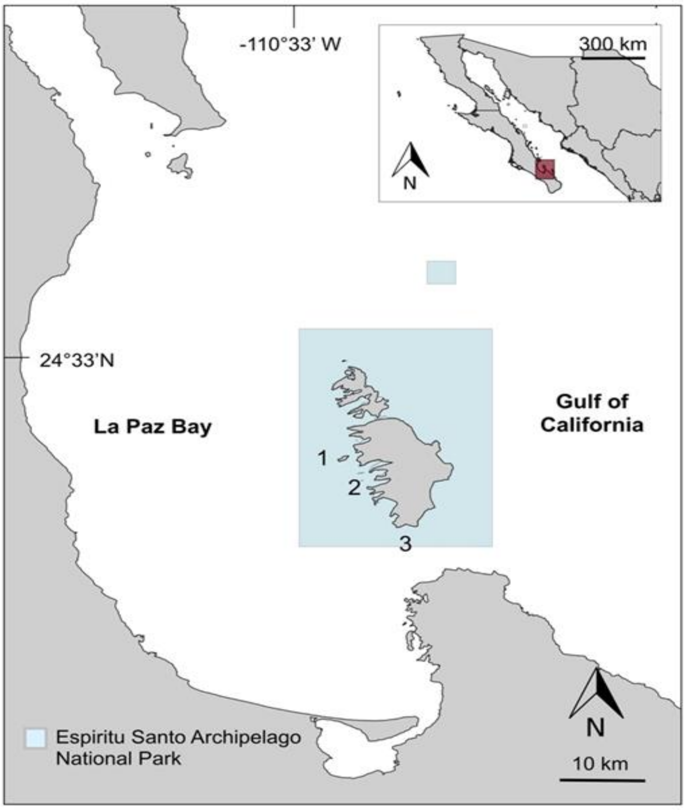

Figure 1. *Showing the extent of the Espiritu Santo Archipelago National Park in the Gulf of California, Mexico, and the locations of sites with the highest densities. (1) La Ballena, (2) Corralito, (3) Swany Rock.*

La Estrella Corona de Espinas en el Parque Nacional Archipiélago Espíritu Santo, Golfo de California, México – el primer brote poblacional en el Pacífico Oriental

Resumen
En los últimos años, en Parque Nacional Archipiélago Espíritu Santo se ha observado un evidente incremento en las densidades poblacionales de la estrella corona de espinas (*Crown-of-thorns starfish*). Este trabajo presenta los resultados del monitoreo poblacional de la especie realizado en el 2018 usando transectos en banda a profundidades de 2 a 20 m encontrando una densidad promedio de 122.52 ± 31.08 ind/ha de estrellas para el Parque. Los sitios Corralito (685.71 ± 198.25 ind/ha), isla La Ballena (222.22 ± 122.52 ind/ha) y Roca Swany (133.33 ± 65.06 ind/ha) describen las densidades más altas con el 40% de mortalidad en los corales. Los individuos de esta estrella fueron observados alimentandose principalmente de los géneros de coral *Pocillopora* (41%), *Porites* (35%) y *Pavona* (21%). Los valores de densidad observados podrían describir el primer *outbreak* de la estrella corona de espinas en el Pacífico Oriental Tropical.

item (Dana and Wolfson 1970; De Alba 1974; Herrero-Pérezrul 2008). Here we report the results of the Park's 2018 annual monitoring program (based on 25 x 2 m band transects, placed parallel to the coast and at depths of 2 to 20 m). The data showed a mean (±SE) Crown-of-thorns density of 122.5 ± 31.1 ind/ha over the entire Espiritu Santo Archipelago, although much higher values were recorded for small reef areas such as Corralito (685.7 ± 198.3 ind/ha), La Ballena Island (222.2 ± 122.5 ind/ha) and Swany Rock (133.33 ± 65.1 ind/ha) (Fig. 2). These figures are well within the range generally accepted as defining a population outbreak, so that this can be considered as the first outbreak known to have occurred in the Eastern Tropical Pacific region.

During the present survey we observed that the starfish had fed mostly on *Pocillopora* (41% of the affected specimens; N= 177) (Fig.3), followed by *Porites* (such as *P. panamensis*) (35%) and *Pavona* (such as *P. gigantea*) (21%), with occasional consumption of other prey, such as the coral *Psammocora*, gorgonians, black coral and assorted other invertebrates. The preference for the coral *Pocillopora* has been reported previously (Reyes-Bonilla and Calderón-Aguilera 1999) with the suggestion that this is due to its ramose morphology and higher nutritional value, compared to other coral genera (Pratchett 2007).

In association with this increase in the abundance of the asteroid, coral colony mortality in 2018 surpassed 40% in the three previously mentioned locations. The signs of attack by Crown-of-thorns were easily recognized because of the characteristic form of tissue loss in *Pocillopora* extending from the tips to the mid-portions of branches (Rodríguez-Villalobos *et al*. 2015), and in *Pavona* and *Porites* by the circular form of the predation lesions. It was also notable that a reef restoration project at Corralito and Roca Swan was severely affected by the outbreak, with over half of the fragments consumed by *Acanthaster*.

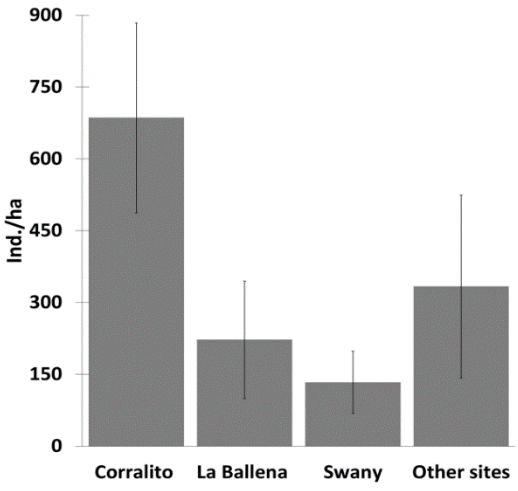

Figure 2. *Mean densities (±SE) of Crown-of-thorns starfish at sites within the Espiritu Santo Archipelago National Park in the Gulf of California, Mexico (Other sites N=11)*

Figure 3. *Individual Crown-of-thorns Starfish eating* Pocillopora *spp. colonies in Espiritu Santo Archipelago National Park in the Gulf of California, Mexico leaving a circular feeding scar in the branches. Photo: Frida Sánchez.*

The cause of this particular population outbreak remains unknown, but it has been suggested that the high positive thermal anomaly caused in the Gulf of California by the El Niño Southern Oscillation event of 2015 may have favored a higher fecundity in the adult starfish. In addition, the increase in primary productivity and nutrients caused by the La Niña in 2016 may have supported exceptional local larval survival and recruitment such as Birkeland proposed in the nutrient hypothesis (Birkeland 1982). However, the three sites with the highest abundance are also subject to excessive human use, so that some anthropogenic impact might also be a factor.

By 2019, two years after the start of the outbreak, there was still very poor recovery of coral cover because of continuing predation of *Pocillopora*, *Porites* and *Pavona*. A first apparent change, following the marked decrease in coral cover, was a surge of fleshy seaweeds, but to date a phase shift may have been avoided because of the presence in the area of numerous herbivorous fishes and sea-urchins. The reduction in live coral cover also appears to have reduced reef structural complexity (Sano 2000; Kayal et al. 2012), which could reduce biodiversity within Espiritu Santo Archipelago National Park.

Acknowledgments. We would like to thank Jenny Rodríguez Villalobos and Arturo Ayala Bocos from Ecosystems and Conservation (non-governmental organization), the Reef Systems Laboratory (Baja California Sur Autonomous University) team, the National Commission of Protected Natural Areas (CONANP) and Niparajá Natural History Society, for their continuing support and valuable help in the field.

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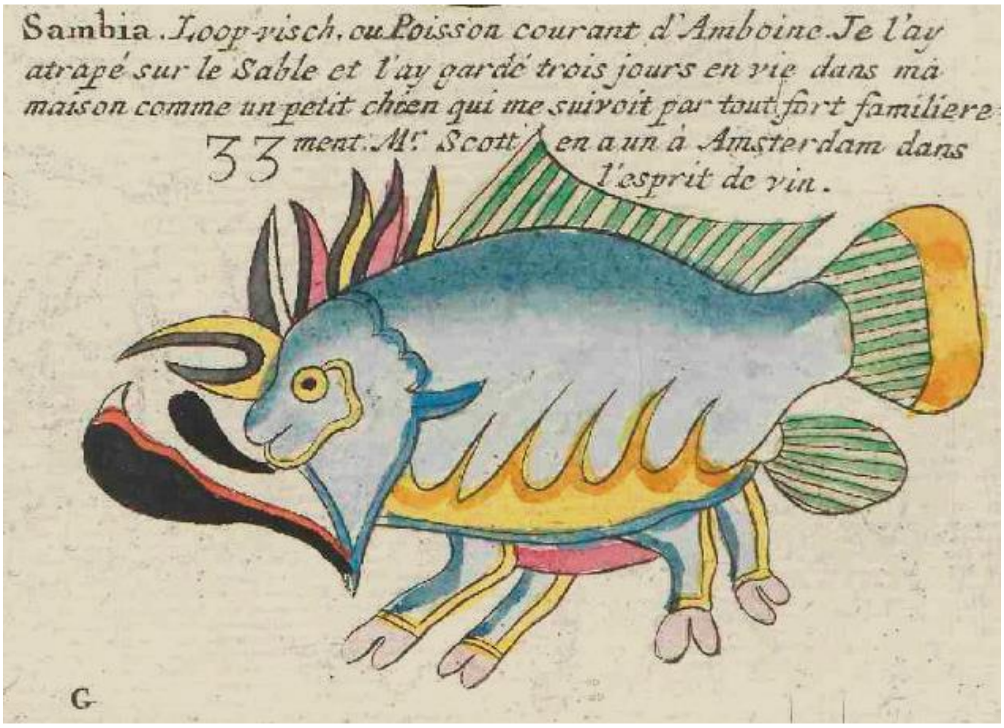
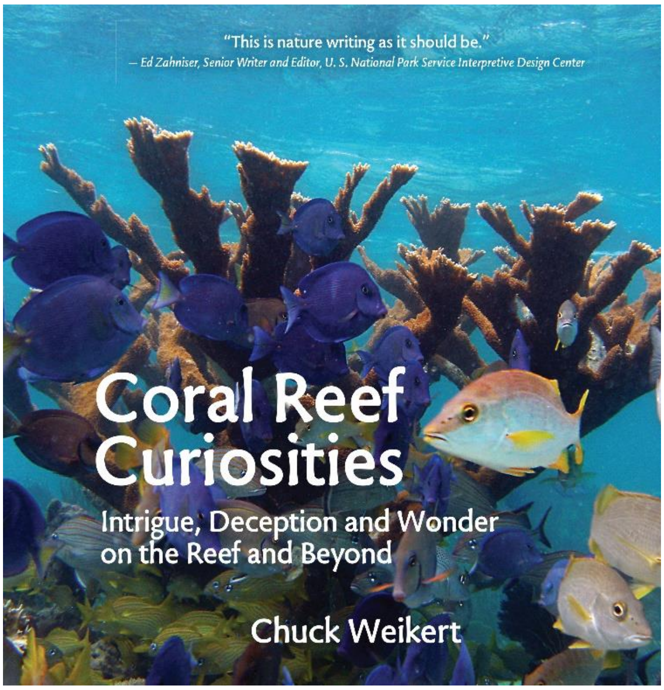


The "Sambia" or walking fish of Ambon, as painted by Samual Fallours in 1718. An illustration from the book *Coral Reef Curiosities* by Chuck Weikert. The author reveals the likely identity of this strange organism which the artist states he caught on the sand and kept alive in his house for three days!

REEF SHELF

Book and Equipment Reviews



Coral Reef Curiosities
a meander across space and time
Chuck Weikert

Dayton Publishing LLC (139 pages) 2020
$19.95 (paperback ISBN:978-1732526532),
$32.95 (hardcover ISBN:978-1732526549),
$4.99 (Ebook ISBN:978-1732526587)

This is a delightful and unusual book. Everyone with an interest in coral reefs - from the most sophisticated scientist, manager or conservationist to the well-traveled amateur naturalist and dive enthusiast; to the occasional snorkeler; to someone whose only reef experiences are through documentaries, aquaria and articles – will find many new and interesting secrets about organisms one thought one knew quite well. It will also trigger memories specific to each reader of how she/he became enamored of reefs and reef organisms through time. *Coral Reef Curiosities* is a modest length, only 139 pages, but its 25 beautifully illustrated chapters explore many of the most beautiful, odd, and remarkable coral reef organisms that many of us have been fortunate to encounter. However, it is far more than merely another natural history guide.

The author, a retired U. S. National Park Service Ranger who spent the better part of his career at Virgin Islands National Park, demonstrates that he is a renaissance man. He delves into the history of how reefs and their creatures were discovered and explored and described, as well as used by mankind in the past, going back to Aristotle, Darwin and Cuvier and other early giants of natural history, as well as Greek and South Pacific Island mythology. How did certain creatures get their common and scientific names? When people found or captured these creatures, what were they used for…food, of course, but also as sources of inspiration for scientific hypotheses, stories and myths, art, music and literature, and names for submarines…even as weights for butter scales, a purpose for which fossilized urchins were used well into the 18th century. How did different cultures relate to these animals? How did these creatures end up in art and literature, ranging from Shakespeare to Melville to modern television, Dali to graphic arts, musical instruments to fashion? Reading this book will make one eager to explore the wonder of coral reefs once again, now armed with new ways to look at and appreciate this extraordinarily rich and complex world, and to discover how reef organisms have inspired art and architecture, music and literature, myth and science through the centuries.

What prompted Chuck Weikert to engage in his wide ranging research? It all started in New York City at a museum exhibit, Grant and Lee in War and Peace, at the New York Historical Society. He saw a Bowie knife, once owned by the abolitionist John Brown, who was captured by Robert E. Lee in 1859, and subsequently put to death. It was the "mottled gold and brown pattern on the knife handle that had the look of the familiar." The handle was made from a Hawksbill turtle, of course, but what was the provenance of the knife? Although Weikert never solved this mystery, it led him into a web search, to this and then that, and "I found myself entangled in a thicket of natural and cultural history." That fortuitous exercise led to a different way to think about reef creatures: "I had never considered

The Psychedelic Frogfish, Histiophryne psychedelica, one of many entertaining images from the book. Photo: Waterframe - Alamy.

the realm of a coral reef beyond the magical diversity of life it harbored. But there were untold reef stories I had never thought about."

Each chapter of the book focuses on a related group of animals – Cnidaria (corals, of course, and sea anemones), sponges, molluscs (squids, octopuses, nudibranchs), echinoderms (sea cucumbers, sea urchins, starfish), tunicates, cartilaginous fishes (sharks, stringrays), and bony fishes (12 chapters), and sea turtles. For me, some stories elicited memories of my own history of learning about marine organisms. For instance, Chapter 2 on "Animal Blossoms" has a sidebar "Farewell to 'Granny'", a story from the November 2, 1887 issue of the New York Times about the demise of a many-decades-old sea anemone from the Botanic Gardens in Edinburgh. This reminded me of my fascination with the "touch tank" at Friday Harbor Laboratories when I was 19, where I discovered that at least one of the anemones was reputed to be many decades old. That was also where I first saw *Stomphia.* Who ever would have thought that a sea anemone could swim?

"Aristotle's Sponges," Chapter 3, reminds us that scientific dogma can be turned on its head with new information. Aristotle gathered sponges brought to the surface by commercial sponge divers from their attachment on the sea bottom. He placed them in terra cotta pots filled with sea water and watched as they pumped water through their pores. He mused, "…as regards certain things in the sea, one would be at a loss to know whether they are animals or plants…how to classify them is unclear." For two thousand years the thinking was that since they are sessile and don't appear to move their body parts, they must be plants. In the 19th century, due to many new fossil discoveries, there was "spirited debate focused on the age of the earth and how its creatures came to be." The puzzle about whether a sponge was plant or animal continued until a "Scotsman Robert Grant wrote, 'All facts known about the sponge have remained where Aristotle left them'." Grant was the first to describe "how sponge eggs disperse, propelling themselves about with tiny whiplike structures called flagella." Thus, we now take it as fact that sponges are animals, although the modern tools of molecular biology have yet again required us to question how the many animals we know about are related to one another. The classification that some of us learned in the 1960s and 1970s has been upended by a completely different way to assess relationship among organisms.

Finally, among my favorite fish is the trumpetfish, discussed in Chapter 18, "A Reef Fish That Does Headstands." Trumpetfish were first described by the French zoologist Achille Valenciennes in 1837. He was a protégé of George Cuvier, and worked with him on *Histoire Naturalle des Poissons,* an 11,000 page, 22 volume opus describing 4,055 species. Although Cuvier's goal was to describe all the planet's known fishes, he died before the work was finished. What he did produce was beautifully illustrated as demonstrated by drawings of trumpetfish from that book that are included in this chapter.

The above are merely a small selection of the stories that delighted me, and brought back memories of first learning about marine animals and my subsequent reef experiences; other readers will bring to the book their own experiences with reefs and their organisms. Reading it will make one eager to explore the wonder of coral reefs once again, now armed with new ways to look at and appreciate this extraordinarily rich and complex world.

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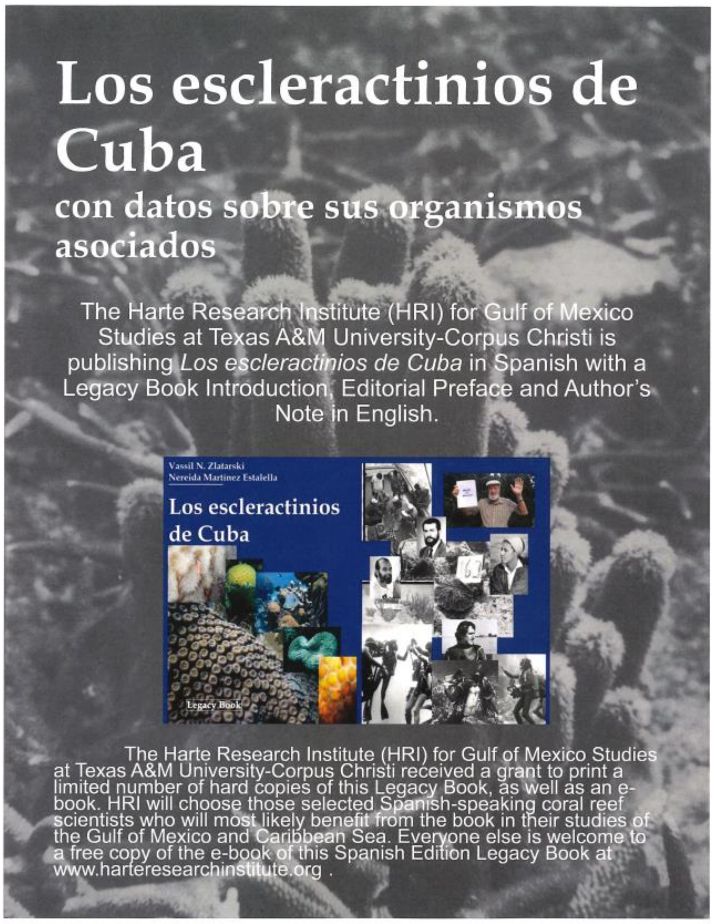

Los escleractinios de Cuba
con datos sobre sus organismos asociados

The Harte Research Institute (HRI) for Gulf of Mexico Studies at Texas A&M University-Corpus Christi is publishing *Los escleractinios de Cuba* in Spanish with a Legacy Book Introduction, Editorial Preface and Author's Note in English.

Vassil N. Zlatarski
Nereida Martinez Estalella
Los escleractinios de Cuba
Legacy Book

The Harte Research Institute (HRI) for Gulf of Mexico Studies at Texas A&M University-Corpus Christi received a grant to print a limited number of hard copies of this Legacy Book, as well as an e-book. HRI will choose those selected Spanish-speaking coral reef scientists who will most likely benefit from the book in their studies of the Gulf of Mexico and Caribbean Sea. Everyone else is welcome to a free copy of the e-book of this Spanish Edition Legacy Book at www.harteresearchinstitute.org .

Los escleractinios de Cuba:
con datos sobre sus organismos asociados

Vassil N. Zlatarski and Nereida M. Estalella

(Spanish translation)

2018. Harte Research Institute for Gulf of Mexico Studies at Texas A&M University, Corpus Christi, TX, USA. 471 pp.

Originally published in Russian (1980) and later translated into French (1982), this is the long-awaited Spanish translation of this seminal work. Although the title implies a faunistic account of the corals of Cuba, this book can be used for the taxonomy and identification of stony corals for the entire Caribbean, the work including full accounts of 63 scleractinian taxa and 4 milleporid taxa. Indeed, this is the most thorough and well-illustrated revision of the western Atlantic stony corals ever published, notwithstanding the legendary works of A.E. Verrill, T.W. Vaughan, F.G.W. Smith, and J. W. Wells. The account of each species begins with a complete and often lengthy synonymy of the species, followed by a full description of the taxon, a section on variation, microstructure, comments on ecology and pathology, and then both fossil and living records of the species or form, accompanied by detailed maps. Each species and form is copiously illustrated, showing the range of variation encompassed by that taxon. It is not unusual for the material examined section for a species to contain over 200 coralla, most of which are still curated at the National Aquarium of Havana.

The underlying foundation of the book, and its primary intellectual contribution, is that the authors have sampled large numbers of specimens from around Cuba, allowing them to literally see the range of variation of a species and how it may transition to other similar species. This has allowed the authors to suggest that previously described, purportedly distinct "species" are, in fact, just variants or forms of the primary species. This has led to "lumping" of taxa and the establishment of many formae; however I do not use the word "lumping" in a pejorative sense, since this is the way a good morphologist would proceed. It is not unusual for a coral taxonomist to describe a new species or even a new genus based on one specimen, if he thinks it distinctive enough. I am guilty of this type of typology. But looking at large suites of specimens allows for an analysis of intraspecific variation, regional variation, and the exclusion of aberrant morphology. Furthermore, the authors sampled specimens much deeper than the conventional 40 m usually considered to be the depth limit of reef corals, collecting and/or observing specimens as deep as 90 m. This is all painstaking and time-consuming work, and an effort that may never be repeated.

It should be noted that the Spanish edition includes an update for the taxonomy of various coral species and an interesting collage of photographs of the authors and photographer on the back cover. Because this book was originally published in Russian and French, it unfortunately has not had the full audience that it merited over the years. It is hoped that the Spanish translation will help to highlight the significance of this landmark contribution to coral taxonomy and make it more accessible to a larger community.

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REEF VIEWS

Public knowledge and coral reef conservation: a lesson from the COVID-19 pandemic

Dear Reef Encounter,

A lesson is playing out for us right now on the global stage: the public holds the power to direct the outcome of a crisis. Our current global crisis is the COVID-19 pandemic. For many years, however, a predominant world-wide crisis has been and continues to be Earth's declining ecosystems, affected by global climate change and other anthropogenic stressors. For us reef scientists, the ongoing pandemic is the effect of these stressors on coral reef conservation.

We understand the critical importance of an informed public and in the present pandemic we see that much of the public is not on the same page with scientists. As our understanding of SARS-CoV-2 builds, we hear pushback from the general populace in response to almost every safety recommendation made. Today, I sit quarantined in my side yard / garden listening to undergraduate students walking by chattering about their excitement to break city curfew rules to attend a party, balking at the embarrassing idea of wearing a mask in public. These students are earning college degrees, and while their education may not be focused on disease ecology, that is the topic on which everyone across the globe currently needs basic knowledge. However, we cannot expect everyone to study of their own volition fields like epidemiology or ecology, even though such fields are broadly critical to the continuation of our species.

The challenge is figuring out how to engage all members of the public, especially those resistant to learning or to believing in science, in order for us to share foundational knowledge and inspire curiosity about crucial topics such as public health, ecosystem management, or in our case, the science and value of coral reefs. We must do so in a way that discourages people from then falling into the misleading comfort of confirmation bias, which can distort and malign the scientific knowledge we aim to disseminate[1,2]. As well, if we are to reach truly broad audiences and move them to action, we must work to decouple the knowledge we present from our audiences' political views and other biases while, inspiring excitement for and enjoyment of nature and science[1,2].

Science as a whole, in particular coral reef science, is starting to see the immense value of broad education and engagement as evidenced by the growing presence of requirements for broader impact or outreach statements in grant applications over the last two decades. We must put the immense creativity of our scientific minds to the tasks of local, national, and global education of the general population, so that when we call on communities to save their local coral reefs or alter the trajectory of the climate, people from all backgrounds, political affiliations, and levels of schooling, will rise to the challenge. "Thus, via widespread and effective communication, as scientists we can support the notion of social responsibility"[3].

Based on observations made during my experiences with scientific education targeting a wide diversity of audiences encompassed in my work for universities, study-abroad programs, a municipal government, dive centers and outreach organizations, I pose 5 parameters to consider in designing innovative and broad reaching community engagement: 1) Attract Everyone, 2) Be Accessible, 3) Inspire, 4) Provide Physical/Digital Take-aways, and please let's not forget science should 5) Be Fun. My thoughts are mirrored and greatly elaborated on within Bruce J. MacFadden's 2019 book 'Broader Impacts of Science on Society'. Rather than elaborate further here, I would like to recommend this timely work.

I intend for this letter to promote conversation within the reef science community on how we can continue to grow and strengthen our engagement efforts across all societal scales. Our scientific discoveries provide the knowledge to protect the natural world, but the public provides the power.

Bobbie Renfro, M.Sc.
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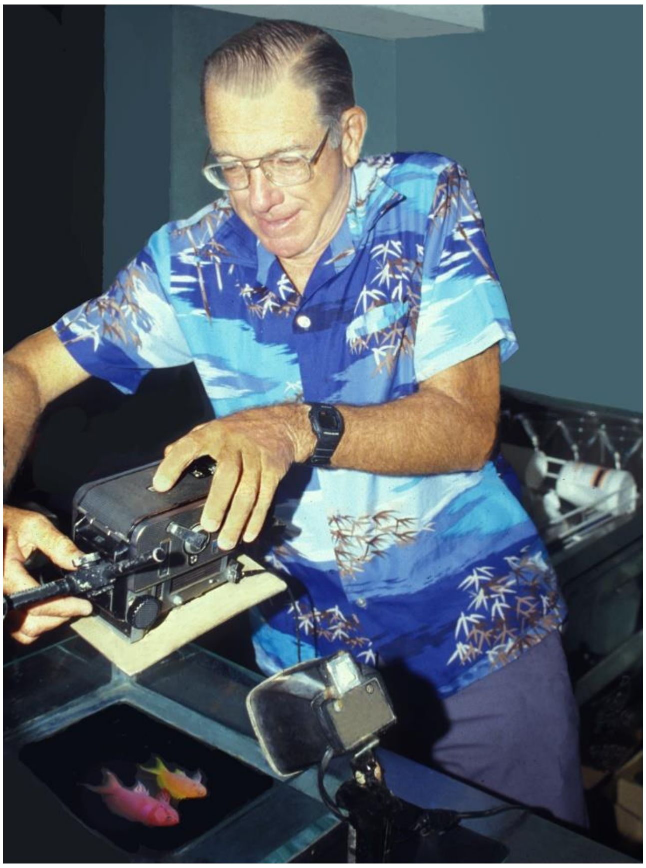
REEF DEPARTURES

Tributes to recently departed members and reef scientists

The Charles Darwin Medal is presented every four years to a member of ICRS in recognition of a record of sustained, highly significant contributions to reef studies and the dissemination of scientific knowledge to secure coral reefs for future generations. In this issue of Reef Encounter, we sadly mark the passing of two of our most eminent Darwin Medalists: Ian Macintyre and Jack Randall. We extend our gratitude and sympathies to their families, colleagues and friends.

John E "Jack" Randall

The field of marine biology, and in particular the study of coral reefs, has lost one of its true giants. Dr. John E. "Jack" Randall passed away peacefully in his sleep on April 26, 2020, with his wife Helen, daughter Lori and granddaughter Sandra by his side. He was 95 years old; less than a month shy of his 96th birthday.



Jack using the photographic system he developed to obtain publication quality images of freshly caught specimens.

The name "Jack Randall" is legendary among ichthyologists. By several metrics, he was among the greatest ichthyologists in history, and perhaps even ***the*** greatest. He was best known for his work discovering and describing new species of fishes, almost all of them from coral reefs. The current total for new species names that he authored hovers at 834, of which 809 represent valid species – an astonishing number. But even among the all-time greats of ichthyological history, going back to the time of Linnaeus (who started the modern scientific naming game in the 1750s), he was only exceeded by one in terms of actual fish species named. Among all the ichthyologists in history, only the great Dutch naturalist Pieter Bleeker, who forged his career during the mid- to late nineteenth century, has more valid species names (839) to his credit.

Historically, there are of course other prolific fish "namers", but for most of these the proportion of currently "accepted names" (i.e. names representing valid species) lies in the range of 40-60%. For example, the great David "Super Starr" Jordan, one of the most prolific ichthyologists of the late nineteenth and early twentieth centuries, established some 1,380 fish names, but only about 51% of these are today considered legitimate species. By contrast, an astonishing ***97%*** of the scientific names of fishes established by Jack are still regarded as representing valid species, and most of the remaining 3% were sunk into synonymy by Jack himself.

Furthermore, the final verdict is not yet in. The astute reader will have noticed that I referred above to the "current" total of Jack's new names. He had been working on several manuscripts right up until his final days, and these will be published in the coming months and years as his co-authors and colleagues complete this work. There are at least two dozen new species to be described, so that when the dust finally settles on the life legacy of Jack Randall, he may well surpass Pieter Bleeker as the most prolific namer of fish species (in any environment) in all of history. As if this were not impressive enough, he also established thirty new genus names and two new families of fishes.

But this is only one of many metrics. His publication record also eclipses that of his predecessors. "Pieter the Great" authored (amazingly) well over 500 scientific publications in his lifetime, David Starr Jordan produced more than 350 and another great ichthyologist of the twentieth century, Carl Hubbs, bested the rest with a remarkable 797 publications. At the time of his death, Jack's publication list tipped the scales at more than ***940,*** a number that will grow as more of his work is published posthumously. And before I move on from these rather dry metrics, it is worth mentioning one more number: the 61 species that Jack's colleagues have named in his honor, not to mention the two genera named for him: *Randallichthys* and *Johnrandallia*. Most of these were so named because Jack discovered them himself. However rather than horde his discoveries for himself, Jack was a model of professional generosity and sent specimens of his own discoveries to his colleagues, allowing them an opportunity to build up their own scientific track records. Only a small fraction of these new species he relinquished to others ended up bearing his name. When we finally analyze the total number of discoveries Jack made over his career, named by him, named for him, and named otherwise by others, it will be well in excess of 1,000 species.

Jack Randall with diving gear in 1963

This leads us to that aspect of Jack's professional career that is truly extraordinary: the quality of his contributions. Jack was a true ***explorer*** – so much more than just a good scientist. He began SCUBA diving in the 1940s – before Cousteau and Gagnon co-invented and popularized it – and his final SCUBA dive took place on the occasion of his 90th birthday, marking the end of a mind-boggling 68 years as a diver (almost certainly among the longest in history). Jack began his career in an era when the practice of ichthyology had remained more or less the same for at least a century and he witnessed a transformation that included the advent of not only SCUBA diving but global air travel, vastly improved photography and computer technology, and the development of molecular tools which led to a dramatic change in the field of taxonomy. In many respects, Jack was a true pioneer of many of these advances, resulting in his much richer and more diverse career than his predecessors. In many ways, the latter had a much easier time discovering new things than he did, because in their time there were many more un-named species to be found. Although modern technology helped him, Jack's ability to immerse himself on a coral reef gave him direct access to species that those before him could never have seen. On top of this, his spirit of adventure and bold willingness to push the envelope, so to speak, of undersea exploration was what really drove his astonishing success.

Spending all those thousands of hours underwater allowed Jack to uncover many more mysteries about coral reefs than simply adding to the reef fish list. In addition to his 120 taxonomic revisions and reviews, 17 major regional checklists and 25 "new records" papers, Jack also published profusely on the broad patterns of species distribution that laid the ground work for much of modern marine biogeography. He also pioneered several aspects of coral-reef ecology. In 1960, with his wife Helen, he published the first major study of mimicry in coral-reef fishes. He wrote many papers on reef-fish hybridization, and published on the trophic patterns of fishes, including a hypothesis about the "halos" of sand that separate patch reefs from seagrass beds. His monumental *Food habits of reef fishes of the West Indies*, published in 1976, is still today regarded as the key base-line study of trophic patterns in reef fishes. Furthermore, his research was not limited to reef fishes or even to fish in general. He published an article on the maximum size of the Great White Shark (*Carcharodon carcharias*) in the journal *Science,* did some groundbreaking work on the biology of conch, and co-described several new species of crustacean. He made several key early discoveries about Ciguatera and other fish poisons, and he invented new methods for collecting, photographing, and describing fishes that are still cited and followed to this day. Perhaps his most important legacy in marine science will prove to be his tireless efforts to protect coral-reef habitat through marine protected areas, which Jack himself regarded as among his most vital efforts.

John "Jack" E Randall: above, sharing a fish specimen with a whitetip reef shark (Triaenodon obesus); *and below, on his 90th birthday dive, with Gordon Tribble (left) and Richard Pyle (right)*

All of these details only scratch the surface of Jack's contributions to our understanding of the marine environment. The many decades he spent as senior ichthyologist at the Bernice Pauahi Bishop Museum in Honolulu, where he forged most of his career, led to a body of research that had a profound impact on his field of study. His memoirs, which will be published later this year by Reef to Rainforest Media LLC and Bishop Museum, run to some 800 pages. They chronicle the amazing track of his personal and professional life, and document not only his countless discoveries but also amazing, harrowing, hilarious, and sometimes tragic stories.

What he does not mention in his memoirs is the extent to which he influenced so many lives. Although technically he was senior advisor to only two PhD students, the memorial website set up in his honor (http://marineexploration.org/jack) shows, from the over 320 contributions from friends, colleagues, students, and a surprising number of people who met him only briefly (or even not at all), the extent of his influence. Several themes clearly emerge, notably his incredible humility and generosity. He responded to every inquiry (letter, email, phone call) with equal earnestness, regardless of whether it came from global luminaries like Sylvia Earle and Paul Ehrlich, or from amateur naturalists, students and children. He was humble to a fault, always disparaging praise and claims about the magnitude of his own efforts, and utterly relentless in his work ethic. He was willing to share credit for work with others to an astonishing degree, enthusiastically adding others as co-authors, and even sometimes relinquishing senior authorship even when he had done most of the work.

He was a friend to many, and admired by all. Those of us who study coral reefs stand upon the shoulders of many giants; but few, if any are as broad and far-reaching as those of Jack Randall.

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Ian G. Macintyre

Ian Macintyre receiving his Darwin medal from David Stoddart at the 1996 ICRS meeting in Panama

On May 14, 2020 the coral reef scientific community lost one of its true pioneers, Dr. Ian G. Macintyre. Ian's career as a renowned coral reef researcher lasted for almost 50 years, and will have a permanent legacy, not just in his publications but more importantly in all the lives he touched through his words and deeds. He was a colleague and mentor to many and a friend to all.

He was a member of the International Society for Reef Studies (ISRS) - now of course the International Coral Reef Society - from its inception and proudly displayed his blue and yellow ISRS t-shirt while working in the field. He was immensely active in ISRS, serving as the Society's President (1983-1986) and also as editor of our journal, *Coral Reefs*. While he was deeply committed to our organization, he was driven by the need to advance the burgeoning, multi-disciplinary field that is coral reef science, and was also the long-time editor of the Atoll Research Bulletin (from 1979-2013).

Ian worked as a research scientist in the Smithsonian Institution's Department of Paleobiology for 45 years, during which time he supported many students and post docs, and collaborated with numerous colleagues and reef enthusiasts. Between 1971 and 2012, Ian undertook 67 field trips, all involving extensive diving, to pursue his research goal of elucidating Holocene coral-reef history and exploring the internal structure of coral reefs. He pioneered a new approach in the 1970s - a submersible diver-operated hydraulic drill, which sparked similar studies of Holocene reef growth worldwide. He was one of the first to recognize the key role of submarine lithification in coral reefs. His numerous scientific contributions provided new and important understanding in the areas of sea-level history, bioerosion, diagenesis of reef carbonates, sclerochronology, coral growth in relation to water motion and irradiance fields, and skeletal diagenesis in calcareous algae; also the formation of stromatolites, mangrove peat deposits and algal ridges, and much more.

Ian coring the unconsolidated reefs of the Belize lagoon (photo by Richard Aronson)

Ian was one of the founders of the Smithsonian's Caribbean Coral Reef Ecosystem program, and helped to identify the location for its base: Carrie Bow Cay in Belize. The Smithsonian field station was established here in 1972 and to this day continues to provide field support for studies on coral reef, seagrass, and mangrove systems. And one of his lesser known achievements was to spearhead a move to persuade the U.S. Postal Service to issue coral-reef commemorative stamps in 1980.

Ian felt that one of the great rewards of his career was the opportunity to participate in a period of major new discoveries in coral reef research working with colleagues from multiple disciplines. A detailed personal account of his illustrious career can be found in the Golden Issue of the Atoll Research Bulletin[1]. I implore young coral reef scientists to look at the stories throughout this volume, as these are the stories of the scientists upon whose shoulders we stand.

In June 1996 Ian became the third recipient of the Charles Darwin Medal. The night that Ian received his medal, Dr David Stoddart said of him that "Ian was a gentleman and a gentle man." This perfectly sums up Dr. Ian Macintyre: a true gentleman and a scholar. Ian is survived by his wife, Vicky, three children and seven grandchildren.

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Ian, above, diving on his favorite reef at Carrie Bow Cay, Belize, and below, performing coral reef probing studies on the reefs in the southern Belize lagoon

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[1] Macintyre, I.G., 2001. Atoll Research Bulletin Golden Issue (1951-2001). Atoll Research Bulletin. 494: 161-176.

David Bellamy

photo by Allan Warren via http://commons.wikipedia.org

The British botanist, television presenter, author and environmental campaigner, David Bellamy, died in December 2019. Known to many as Dave, he was very popular as a TV marine scientist some 40 years ago, and very distinctive with his large frame and big bushy beard. He was enormously skilled at getting viewers interested in wildlife and natural science – using comedy liberally to lighten programmes that were rich in botany, natural history and ecology.

While his main enthusiasm and academic expertise was in the ecology of mires and peat bogs, he also had a major interest in reef ecology research through SCUBA diving, an aspect of his life that has been omitted from most other obituaries. Those of us who are interested in reefs and who knew and worked with David are also aware of other important characteristics that should be remembered. The first was his general enthusiasm for bringing ecology and science generally to the public, and this has had important consequences. In the 1970s, it was not really considered very ‘respectable’ to popularise science, and during his professorship at Durham University, this caused problems. For example when a BBC helicopter landed in the grounds near his Department to whisk him off for another half day filming, some colleagues were not only jealous but also critical, considering this sort of thing ‘frivolous’. This would upset him sometimes as, correctly, he believed in the merits of communication with the public, at which he was a complete natural. When colleagues were asked whether his over-the-top ebullient style was an act or really him, the answer was clear: he was indeed like that!

Dave Bellamy in his diving days; among other achievements he organised (in 1968) the first citizen science project for divers, and was a co-founder (in 1977) of the UK Marine Conservation Society.

Dave’s recognition as a marine scientist started with the Torrey Canyon’s disastrous oil spill in 1967, which led to his work on marine pollution for which he became well known in the British diving fraternity. In terms of reefs, his first major encounter was conducting the first underwater survey of Aldabra Atoll in the Indian Ocean in 1972. In the 1970s he had begun to champion, with one of us (Brian Rosen), application of by then well-established phytoecological methods to coral ecology: using classic Braun-Blanquet survey methods with reef corals and subsequently other marine benthic organisms. At this time, the UK military ran adventure training diving expeditions and asked Dave for a good place to go, and also invited him to take part. Dave could rarely say no, and selected the Chagos Archipelago, the islands in the Indian Ocean that had recently become the British Indian Ocean Territory.

Dave had the scientific project that the military needed to justify their trip, and the military possessed the massive logistics necessary for diving in such a remote location. Following an initial three months on Egmont Atoll (1972) the team then spent a couple of months on the Great Chagos Bank in 1975. These trips led to another visit lasting eight months starting in 1978, in which Dave did not participate, but that was led by Charles Sheppard, one of Dave's previous research students. Dave did not return to Chagos until 1996, his last trip there, but his work there had an enormous lasting legacy. These early expeditions set the scene for an ever-increasing series of visits, culminating in today's massive programme of annual expeditions involving hundreds of scientists from numerous countries, and the ongoing efforts to protect the Chagos reefs. That early reef work was just one facet of his notable conservation advocacy, mostly with terrestrial habitats, an advocacy that would even lead to him being imprisoned on one occasion - for protesting in Tasmania about a planned scheme for an unnecessary dam.

Dave at a relatively recent scientific meeting on the Chagos Archipelago, with (left) Charles Sheppard

Dave was inspirational, urging on his postgraduate students, with his natural enthusiasm and ebullience, whether they were terrestrial botanists or budding coral reef ecologists. As a PhD supervisor he was superb from the student's point of view: setting up projects; finding the money; getting the student started; and then staying out of the way and letting the students (of which he sometimes had many at a time) work in their own way until or unless they asked him for help. This is the best way to learn how to do research! He was warm, friendly and always sympathetic to his students and research assistants, and gave accommodation to one of us (Zena Dinesen) in his and his family's home for months.

Dave in television presenter mode; his entertaining style attracted a mass following.

It is impossible to ignore the one quite baffling aspect that Dave later became infamous for: his denial of climate change, which became evident after about 1990. This was important in that he was a well-known TV personality by then (few TV comedians could resist imitating his distinctive accent). His climate stance mystified all of us, and prolonged conversations with him about it did not explain much at all; although he did admit at one point that he was probably being fool-hardy to take this view.

But all of us who knew Dave were very fond of him, and feel now we would prefer to just ignore this quirky aspect. He was a superb supervisor with a very warm personality, and later on, an endearing and helpful colleague. The world needed many more like him, and does so even more today.

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with additions from Zena Dinesen, Brian Rosen
and Anne Sheppard

ICRS MEMBERSHIP

ICRS membership is open to all persons interested in any aspect of the science of coral reefs. While the society's membership consists principally of researchers, managers and students with interests in coral reefs and associated ecosystems, other people with genuine interests in or concern for reefs, of any type, are welcome. The benefits of membership include:

- Receipt of the Society's scientific journal *Coral Reefs* (either on-line or hard copy)
- Receipt of the Society's newsletter/magazine *Reef Encounter* (by email or on-line)
- Access to the Society's on-line membership services, including the on-line Membership Directory
- Reduced registration fees for the International Coral Reef Symposium and other meetings sponsored by the Society.

Full / Individual Member
Membership includes all the benefits listed above, but rates vary depending on whether a hard-copy subscription or on-line access to the Society's academic journal Coral Reefs is preferred, and according to the mean income level of the member's country.

Student Membership
The benefits are the same as for a Full / Individual Member, and include hard copy or on-line access to Coral Reefs at a much reduced rate.

Family Membership
Family memberships are available for partners who live at the same address. Each receives the same benefits as Full Individual Members, but only one hard copy of any journal is supplied.

Sustaining Membership
Sustaining Membership is for those Members who would like to contribute extra to support the work of the Society. They receive additional minor benefits and their support is acknowledged in Society publications.

Honorary Membership
Honorary Membership has been conferred on a small number of members who have rendered special service to the society or otherwise distinguished themselves in the field of reef science.

Membership services are now operated by Schneider Group which provides such services to academic societies. They may be contacted at:

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5400 Bosque Blvd, Suite 680
Waco, Texas 76710-4446 USA
Phone: 254-399-9636
Fax: 254-776-3767
email: icrs@sgmeet.com

The membership subscription varies considerably depending on the type of membership selected and the primary country of residence of the member. Very generous membership rates are available for students and residents of developing countries. For low to low-middle income countries, full membership costs only $40 (US) per year, and student membership only $20 (US) per year.

For details of current rates and to complete the on-line membership form or download a hard copy please go to the society’s membership portal at: https://icrs.memberclicks.net/

NOTES FOR CONTRIBUTORS

Reef Encounter welcomes in particular (1) general overview articles (3-5 pages) about aspects of reef science and (2) short communications / scientific letters (1-2 pages) reporting recent observations. It also carries Announcements, Conference Reports and Book and Product Reviews. 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 references should be cited and listed using the style of the ICRS academic journal *CORAL REEFS*. For further details please see http://www.springer.com/life+sciences/ecology/journal/338. Items should be submitted by email to a relevant editor (see page 2).

Spotted cleaner shrimp (*Periclimenes yucatanicus*) on a giant Caribbean sea anemone (*Condylactis gigantea*), an illustration from the book "*Coral Reef Curiosities*" by Chuck Weikert (see book review section) – photo by Caroline Rogers.