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Sent: Friday, August 7, 2020 5:13 PM
To: Clerks Office
Cc: Rennae Meno
Subject: Messages and Communications

08-07-20	2:30 PM	08-04-20	Revenue Bonds Capital Improvement Status Report for the periods covering October 1, 2019 through July 31, 2020.	Port Authority of Guam	35GL-20-2139

Sinseru yan Minagåhet,

Office of the Speaker • Tina Rose Muña Barnes
Committee on Public Accountability, Human Resources & the Guam Buildup

35th Guam Legislature
I Mina'trentai Singko na Liheslaturan Guåhan

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Gumai pribilehu yan konfedensia este siha na mensåhi. Solo espesiåtmente para hågu ma entensioña pat ma aturisa para unrisibi. Sen prubidu kumu ti un ma aturisa para manribisa, na'setbe, pat mandespåtcha. Yanggen lachi rinisibu-mu nu este na mensåhi , put fabot ago' guatu gi I numa'huyong gi as speaker@guamlegislature.org yan despues destrosa todu siha I kopian mensåhi. Si Yu'os ma'åse'.

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Lourdes A. Leon Guerrero
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August 4, 2020

The Honorable Tina Muña Barnes
Speaker
35th Guam Legislature
163 Chålån Santo Papa
Hagåtña, Guam 96910

35GL-20-2139
Speaker Tina Rose Muña Barnes

AUG 0 7 2020
Time 2:30 ( )AM (X)PM
Received By: Matt

Dear Speaker Muna Barnes:

Håfa Adai!

Pursuant to Public Law 34-70, Section 6. Reports, transmitted herewith, is the Port Authority of Guam's Revenue Bonds Capital Improvement Status Report for the periods covering October 1, 2019, through July 31, 2020. Also transmitted is the H-Wharf Coral Relocation Compensatory Mitigation and the ECO Magazine on the "Relocating Corals in Guam".

If you have any questions regarding this matter or need additional information, please contact my office at 477-5931/35, extension 303 or 302.

Si Yu'os Ma'ase!

Respectfully,

RORY J. RESPICIO
General Manager

Attachment

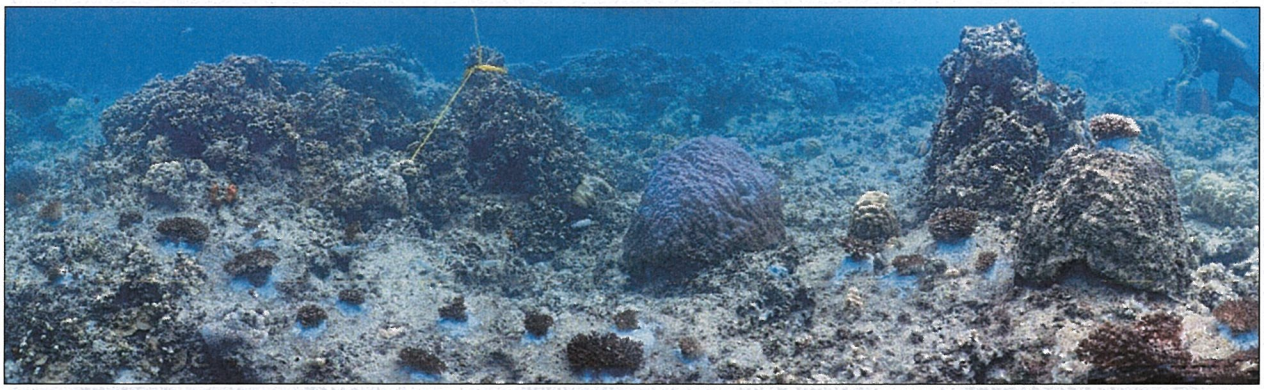
Cc: Senator Clynton Ridgell
Public Utilities Commission of Guam

Doc. No. 35GL-20-2139.

2018 Port Revenue Bonds Status Report
As of July 31, 2020

Bond Project	Total Award Amount	Total Draw Down	Total Remaining Balance	PROCUREMENT IFB/RFP/PO Number	Status
Rehabilitation of "H" Wharf (Federal Share & Port Share)	$10,000,000.00 $13,774,255.00	$0.00 $300,136.75	$10,000,000.00 $13,474,118.25	PO No. 16332-OF - Coral Relocation at $482,700.00 to WSP awarded on February 18, 2020. RFP No. 2020-002 - CM Services	Construction Management Services proposals pending review. 3rd Quarter Progress report submitted to MARAD.
Golf Pier Repairs and Improvements	$2,000,000.00	$354,876.53	$1,645,123.47	RFP No. 2019-02: A&E Design for $484,000.17 awarded to NC Macario	Final design submitted to the PAG on June 5, 2020.
Waterline Replacement and Relocation and EQMR Building and Warehouse 1 Repairs and Upgrades	$11,628,800.00	$0.00	$11,628,800.00	RFP No. 2019-03: A&E Design for $1,406,427.48 awarded to NC Macario	NC Macario assessment ongoing; additional work required for 35% design submittal.
Other Priority Projects - Repair of F-1 Fuel Pier - Repair of F-3, F-4, F-5, and F-6 waterfront facilities - Installation of connectivity fuel line connecting Golf Pier and F-1 - Upgrade of the Port's IT system and integration of TOS and FMS	$7,480,745.00	$0.00	$7,480,745.00		EnterpriseOne purchase order currently pending acknowledgement from vendor. F1 wharf repair and Terminal Operating System upgrades pending.
New Admin. Annex Building	$10,445,000.00	$0.00	$10,445,000.00		Status Quo - Of the six (6) original bond-funded projects, this was deemed as the lowest priority. No ongoing activity performed on this project.
Grand Total	**$55,328,800.00**	**$655,013.28**	**$54,673,786.72**		

Coral Relocation Compensatory Mitigation for the Hotel Wharf and Access Road Maintenance and Repair Project, Apra Harbor, Guam



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Doc. No. 35GL-20-2139.*

CSA Ocean Sciences Inc.

Coral Relocation Compensatory Mitigation for the Hotel Wharf and Access Road Maintenance and Repair Project, Apra Harbor, Guam

DOCUMENT NO. CSA-WSP-PAG-FL-20-80159-3550-03-REP-01-FIN-REV01

Version	Date	Description	Prepared by:	Reviewed by:	Approved by:
01	04/24/2020	Initial draft for review	K. Spring	C. Baumberger	K. Spring
02	05/01/2020	Revised draft	K. Spring	K. Metzger	K. Spring
FIN	05/12/2020	Final	K. Spring	Client	K. Spring
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1.0 Introduction

Hotel Wharf is under the control of the Port Authority of Guam (PAG) and is located on the northern side of Outer Apra Harbor, between Pier Dog (Dog Leg Pier) to the west and Pier A to the east (**Figure 1**). Maintenance and repair work is proposed for the structure and will include removal of the cap, driving new sheet piles outside of the existing piles (wharf face), backfilling, and re-capping of the structure. As a result, all marine biota attached to the wharf face and on the seafloor within approximately 3 m of the wharf (Direct Impacts Zone) will be lost unless removed.

Biological surveys of the wharf face and adjacent seafloor were conducted in January-February of 2019 (Burdick, 2019) and documented significant hard coral populations, as well as macroalgae and various sponge species growing within the direct impacts area. Corals observed on the wharf face comprised 35 coral taxa and averaged approximately 5 cm diameter, while 29 coral taxa were noted on the immediately adjacent seafloor and were slightly larger at about 11 cm average diameter. The most abundant coral taxa in order of decreasing abundance included *Leptastrea purpurea*, *Pocillopora damicornis*, massive *Porites* sp., *Stylocoeniella armata*, and *Lobophyllia hemprichii*.

A Compensatory Mitigation Plan was prepared by Duenas, Camacho & Associates, Inc. (DCA) (2019) to present measures to minimize and offset adverse effects to resources within the project area. The plan primary objective was to mitigate for the loss of ecological functions and services due to direct impacts from the proposed construction activities on coral reef habitat.

Permits include:

- Guam Environmental Protection Agency (Guam EPA) 401 Water Quality Certification (WQC) Order #2020-03;
- U.S. Army Corps of Engineers Permit No. POH-2017-253;
- Department of Agriculture Special Permit for Scientific Coral Relocation, License No. SC-20-003; and
- Federal Consistency Certification, GCMP FC No. 2018-0011.

The proposed measures included the movement of corals feasible for relocation from the Hotel Wharf face and immediately adjacent seafloor to an acceptable nearby recipient site, and a post-relocation monitoring program. Based upon the results of the 2019 survey it was estimated there were potentially 636 corals on the wharf face and 194 colonies within the direct impact zone at the base of the wharf that were healthy enough and of a size suitable for relocation. Coral relocation criteria included:

1. Coral colonies located within the Direct Impacts Zone;
2. Coral size between 10 cm and 100 cm;
3. All coral species, excluding encrusting forms, small dendrophyliids, or any other corals that would not survive relocation; and
4. Healthy coral colonies with no bleaching or major paling.

Post-relocation monitoring was to include health assessments of selected relocated and reference corals during an immediate post-relocation baseline survey, and at 6-months, 18-months, and 36-months after relocation.

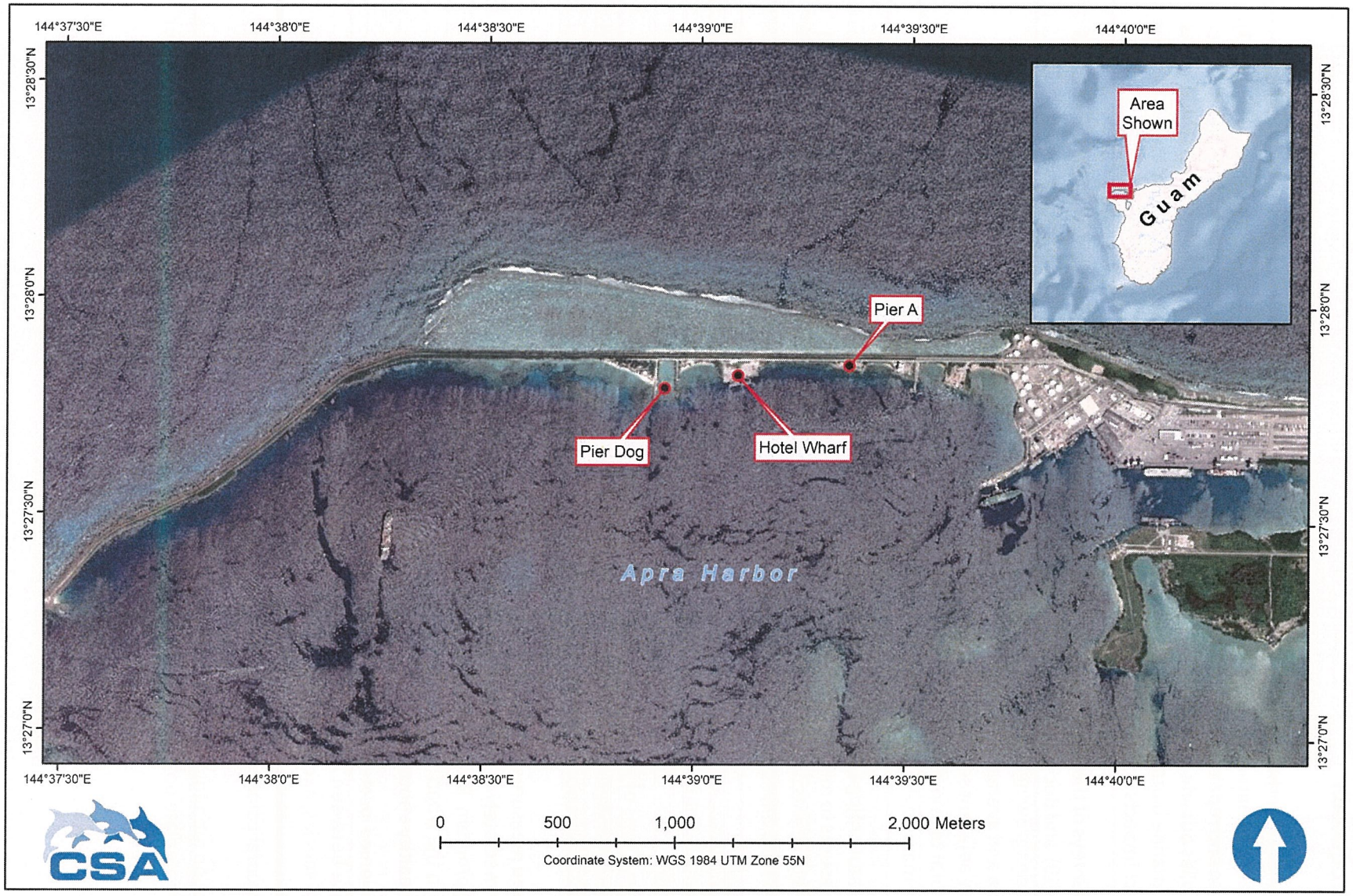


Figure 1. Location of Hotel Wharf along the northern edge of Apra Harbor, Guam.

CSA Ocean Sciences Inc. (CSA) was contracted by WSP USA Inc. to prepare a coral relocation and monitoring plan, complete the coral relocation effort, and conduct subsequent monitoring activities. An additional task was to conduct an assessment for the invasive octocoral species *Carijoa riisei*, reported to be growing along the southern wharf face. In mid-March 2020 CSA staff mobilized to Guam, participated in a kick-off meeting with Port officials, conducted an initial survey of the wharf face, identified suitable coral reattachment sites, relocated all healthy corals within the required size range to the reattachment sites, tagged representative numbers of relocated and reference corals, and completed baseline health assessment monitoring. This report describes the methods of the coral relocation effort and the results of the coral relocation and baseline monitoring survey.

The coral relocation effort was undertaken just prior to the implementation of COVID-19 quarantine measures in Guam. When initial quarantine measures were announced, CSA field staff implemented social distancing measures, minimizing contact with other persons, and initiated frequent hand washing and use of hand sanitizers. Staff avoided all restaurants and, as possible, minimized visits to grocery stores and other retail outlets. Following the completion of the coral relocation and monitoring field effort all staff were able to return safely home and no one has developed any symptoms of COVID-19 infection.

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2.0 Methods

2.1 VESSEL AND DIVING

CSA field operations were conducted from the *Sea Spinner*, a 40-ft long local dive vessel provided by Poseidon's Maidens Charters. In addition, Poseidon's Maidens Charters provided additional dive support including Nitrox scuba bottle fills and required dive safety equipment.

Coral relocation activities and monitoring surveys were performed by a five-person field team, including a Dive Safety Officer and four scientific divers. All divers were certified by an internationally recognized dive association, in good standing with the CSA member organization (American Academy of Underwater Sciences [AAUS]), and current with all required safety certifications. Divers were covered by Maritime Employers Liability Insurance (coverage for divers and crew personnel while in navigable waters, including Jones Act).

2.2 INITIAL SITE SURVEYS

Prior to the start of diving activities, discussions were conducted with Port officials, Port Police, and on-site vessel repair supervisors regarding coordination of efforts and scheduling to prevent and minimize operational conflicts. Notes were made of positions of barges and vessels at the wharf, and potential locations for the mooring of the dive support vessel were identified. Daily communication plans were established with the Port Control, repair supervisors, and Port Police.

Initial dive surveys of the wharf face were then conducted to familiarize dive team members with the wharf structure, identify any potential safety hazards, and delineate general coral distribution within the Direct Impacts Zone. Divers collected video with GoPro Hero 7 cameras and still photographs with multiple DSLR cameras in underwater housings of the wharf face and adjacent seafloor prior to the relocation of coral colonies. Observations were made of coral sizes and abundance to allow planning of subsequent removal efforts. A dive was also conducted to assess the presence and abundance of the invasive octocoral *Carijoa riisei* along the upper wharf face.

Dive teams then made dives at the potential coral reattachment area described in the Compensatory Mitigation Plan to assess suitability of the location for the receipt of corals observed on the wharf. Dives included areas to the east, south, and west of the Dog Leg Pier (**Figure 2**).

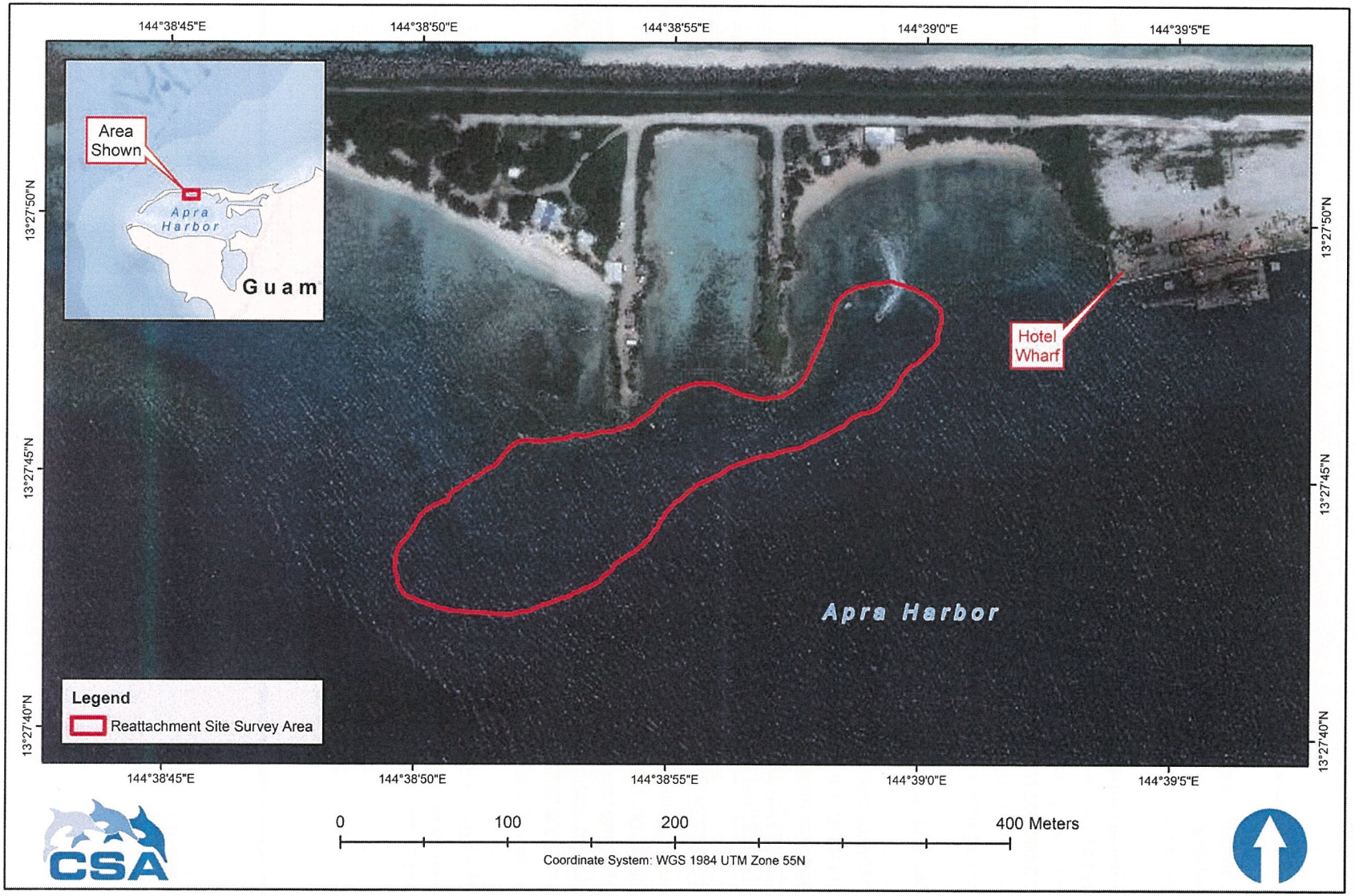


Figure 2. Area surveyed to identify coral reattachment sites for corals removed from Hotel Wharf and adjacent seafloor.

2.3 CORAL RELOCATION

2.3.1 Reattachment Site Selection

Suitable reattachment sites were selected based on site-specific conditions, including relative proximity to the wharf, similar water depth, available exposed substrate for coral attachment, and the presence of other healthy corals of the same species. The available substrate at the potential reattachment area off the Dog Leg Pier identified in the Compensatory Mitigation Plan was deemed to be insufficient for the number of corals to be relocated, as well as being covered with layers of surficial sediments with fairly heavy *Padina* (macroalgae) growth. Additionally, the bottom between the Dog Leg Pier jetties at water depths up to nearly 6 m was heavily disturbed, with exposed rock and rubble, as well as significant amounts of loose sediments settling out on corals and cascading down the slope. This may be partly due to jet skiing and flyboarding in this area, as mentioned in the mitigation plan. Because of these conditions, reattachment sites were identified slightly to the west in an area to the southwest of the western Dog Leg Pier at depths ranging from about 2 to 13 m. A total of 11 distinct reattachment and reference sites or areas were ultimately selected and were marked with centrally positioned fiberglass rods cemented into the bottom. The three shallowest sites were along the reef flat and slope at water depths of from 2 to 4.5 m. The other 8 sites were on individual reef rock outcrops and along the base of the reef slope at depths ranging from 9.5 to 12.8 m (**Figure 3**). **Table 1** lists coordinates of marker rod for each reattachment site.

Table 1. Reattachment site marker rod coordinates.

Reattachment Site	Latitude (N)	Longitude
1	13°27'45.46558"	144°38'52.07670"
2	13°27'45.25702"	144°38'52.43957"
3	13°27'44.79200"	144°38'51.66757"
4	13°27'43.11477"	144°38'51.36902"
5	13°27'43.25019"	144°38'51.19476"
6	13°27'43.52936"	144°38'51.00813"
7	13°27'43.62555"	144°38'50.81039"
8	13°27'43.57431"	144°38'50.51960"
9	13°27'43.66108"	144°38'50.45960"
10	13°27'43.31863"	144°38'50.30608"
11	13°27'43.52299"	144°38'51.79439"

Coordinate System: WGS 1984 UTM Zone 55N.

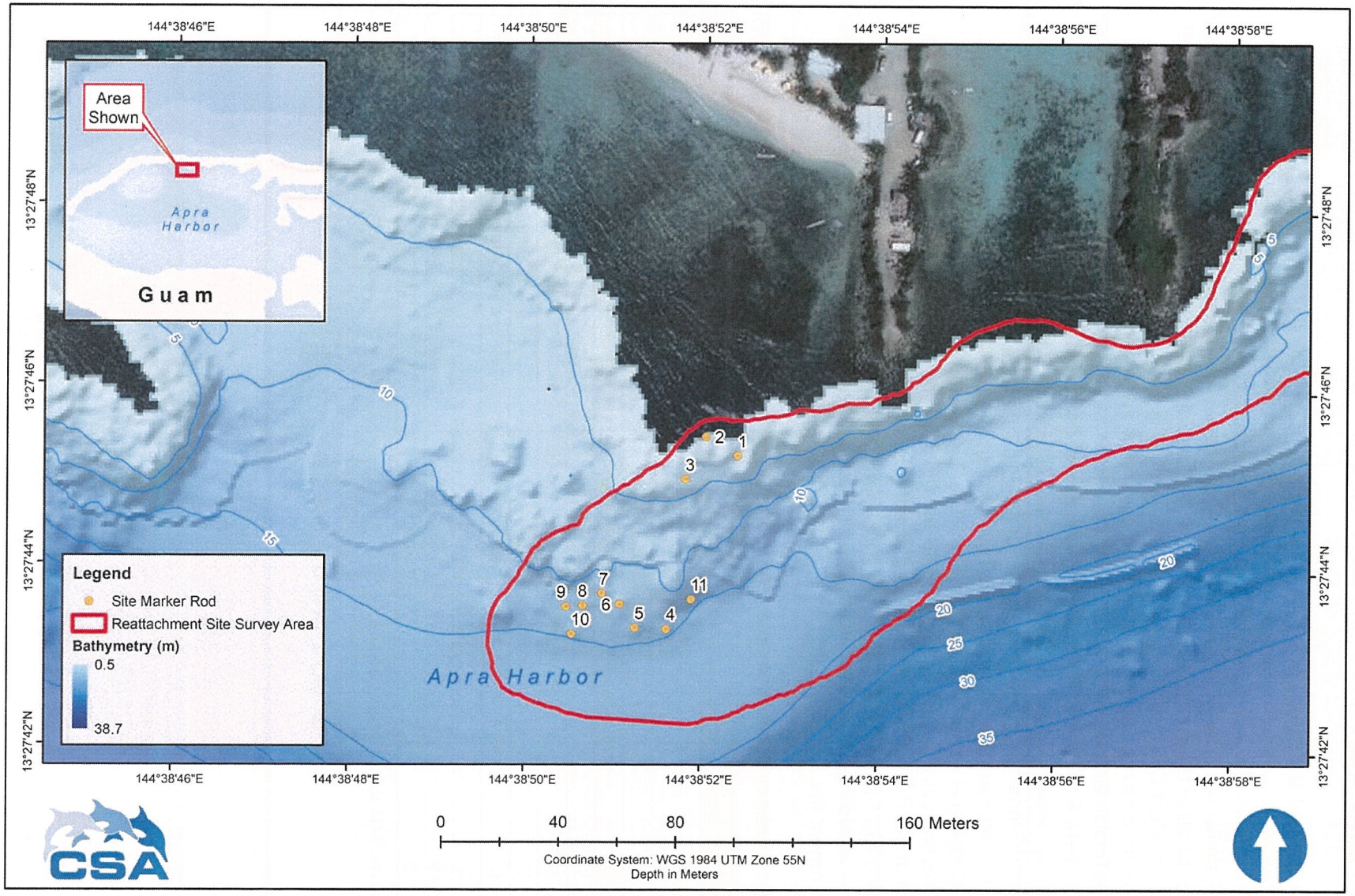


Figure 3. Locations of marker rods demarcating the approximate centers of selected coral reattachment sites.

2.3.2 Coral Removal and Transport

Coral colonies selected for relocation were removed by chipping the living portion of the colony from the point of attachment on the wharf face, debris, or rock substrate using a hammer and masonry chisel. Detached colonies were placed in perforated plastic collection crates that were cached on the bottom pending movement to the reattachment site. While transiting to the reattachment site the crates were covered with cloth sheets dampened with seawater to protect the corals from direct sunlight and overheating. Upon arrival at the reattachment sites the crates of corals were immediately returned to the water and cached on the seafloor by divers.

2.3.3 Coral Reattachment

Prior to attaching relocated corals, the specific reattachment surfaces were prepared by removing any loose sediment and surficial biota (i.e., algae and fouling organisms). A concrete mixture of Portland cement and sand was prepared in individual 5-gal buckets for reattaching corals. The concrete was mixed to yield a thick or "stiff" mixture to lessen the cement plume released in the water. Half-full buckets of concrete were lowered from the vessel to near bottom with lift lines and transported by divers to specific reattachment sites. Sufficient amounts of concrete were placed directly on the pre-cleaned substrate, and the coral to be reattached was pressed firmly into the concrete mixture until stable and secure. Reattached corals were intermittently checked during reattachment operations to ensure stability, address the aesthetic quality of the reattachment matrix, and dissipate cement residue that may have settled on adjacent biota. Coral colonies were reattached with a spatial distribution that mimicked the surrounding benthic habitat.

2.4 BASELINE MONITORING

Baseline and subsequent monitoring events will be used to determine the relative success of the coral relocation effort. During the future monitoring events, comparisons will be made between relocated and reference corals to determine the success of the relocation efforts. Baseline monitoring tasks included:

- Permanently marking center of reattachment and reference sites with fiberglass rods;
- Selection and tagging of relatively healthy monitored corals with uniquely numbered markers;
- Recording distance and compass bearing from central rods to all tagged corals;
- Assessment of relocated coral colony bonding status;
- Visual assessment of reattached and reference coral health conditions; and
- Collection of still photographs for all monitored corals.

Monitored coral colonies included an experimental group of 132 relocated corals and 101 reference corals. Reference corals were selected based on health condition, proximity to the reattachment site, and good representation of the relocated coral species. **Appendix A, Tables A-1** and **A-2** provide documented coral condition, size, and location during the baseline survey.

2.4.1 Site Establishment

Reattachment and reference sites were demarcated by permanently installed, geo-referenced site markers (fiberglass rods) to facilitate monitoring site reoccupation and to serve as a benchmark for mapping corals for monitoring activities. Monitored coral colonies were marked with a unique numeric

identification tag (width of 7.6 cm and length of 10.8 cm) and mapped by recording distances and compass bearings from the site marker rods (**Appendix, Tables A-1** and **A-2**).

2.4.2 Bonding Status of Relocated Colonies

Monitored coral colonies were visually assessed to determine reattachment status by inspecting the base for cracks or gaps between the coral colony and the natural rock substrate. If the attachment point (base of colony) appeared compromised in any way, it was manually tested (diver with gloved hand) for stability and attachment security.

2.4.3 Coral Condition

Direct *in situ* observations of relative conditions were made for relocated and reference coral colonies. For each coral colony, a visual assessment was made recording any adverse health or stress conditions. Some of the monitored coral colonies were affected by, and assigned, more than one condition during the assessment. However, only the primary condition that appeared to be responsible for the greatest percentage of affected tissue for each monitored coral was presented in coral health assessment comparisons and discussion. Additionally, the observer estimated the percentage of the entire colony (0% to 100%) covered by living tissue. Physical damage to the monitored corals, including abrasions and broken branches, was also noted.

2.4.4 Coral Size

Coral size was measured as the maximum length of living tissue on the colony. Size measurements were collected along the longest axis (vertical or horizontal) for each colony, depending on growth form. Most coral measurements were collected along a horizontal axis and notes were made for each monitored coral measured along a vertical axis to allow precise method replication during future monitoring events.

2.4.5 Photographs

Photographs were collected of all monitored coral colonies using a Nikon D810 high-resolution digital camera within an underwater housing unit with dual strobes. The camera was held perpendicular to the colony to collect a plan view image to qualitatively compare with imagery from future monitoring events. Additional photographs were collected at various oblique angles to document the condition of the colony or the proliferation of non-coral biota such as algae or sponges.

3.0 Results and Discussion

Field operations, including initial site survey, coral removal and relocation, and baseline monitoring were conducted from 19 to 27 March 2020. Weather conditions during the survey were good with winds ranging from about 5 to 15 kn, partly cloudy skies, and occasional showers. Sea state was relatively calm with small wind chop from the east. Subsurface visibility ranged from 10 to 15 m and was variable based on tidal exchange.

3.1 INITIAL SITE SURVEYS

Dive teams systematically assessed the face of Hotel Wharf from east to west, making notes relative to coral size, relative abundance, distribution, and species, and collecting video and still photographs. Hotel Wharf was fully utilized during the site survey and coral relocation timeframe, with four large barges as well as an offshore supply vessel tied alongside (**Photo 1**). This caused a nearly total shading of the face of the wharf and adjacent seafloor out at least 15 m from the base of the wharf, aside from small areas within two gaps between the barges/vessels.

During the assessment dive teams recorded areas of higher coral abundance for the subsequent focus of collection efforts. Higher densities of healthy stony corals occurred along the eastern and western ends of the wharf and adjacent shallow rock shelves than on the long southern wharf face. These healthy corals included *Pavona decussata*, *Pocillopora damicornis*, *Porites cylindrica*, *Porites rus*, and several species of "massive" *Porites*. Along the southern side of the wharf the density of living corals was much lower and dominant species included *Pocillopora damicornis*, *Astreopora cucullata*, *Astreopora gracilis*, *Lobophyllia hemprichii*, *Lobophyllia corymbosa*, and several massive *Porites* species. The *P. damicornis* colonies were nearly all found within the upper 2 m depths on the wharf face. The *Astreopora* and massive *Porites* colonies were observed along the deeper sections of the wharf face and attached to debris on the surrounding seafloor, while the *Lobophyllia* occurred primarily on the deeper face of the wharf. More than 2 dozen dead or nearly dead colonies of *Lobophyllia* spp. were observed on the wharf face along with numerous other unidentified dead and bioeroded coral colonies. Most of these dead or dying colonies were covered with varying amounts of silt and encrusting sponges (**Photos 2** and **3**).



Photo 1. Barges and cranes tied up at Hotel Wharf during coral relocation project.



Photo 2. An 80% dead colony of *Lobophyllia hemprichii* on wharf face.



Photo 3. Unidentified dead coral encrusted with sponge.

A clump of the invasive octocoral *Carijoa riisei* was identified at the southeastern corner of the wharf below the upper ledge at about 1.5 m depth (**Photo 4**). As its distribution was limited to this specific area, divers carefully detached all visible pieces of the colonies, placed them in a fine-mesh bag, and delivered the colonies to DCA for appropriate disposal.



Photo 4. The invasive octocoral *Carijoa riisei* on southeastern corner of wharf.

Following the wharf assessment, dives to identify reattachment sites were conducted along the shallow reef to the immediate east, south, and then west of the Dog Leg Pier, two parallel rock jetties about 75 m apart and extending out approximately 152 m (east pier) and 170 m (west pier) from shore (**Figure 2**). Divers swam parallel to shore along the base of the reef at about 6 to 7.5 m depths as well as just offshore of the shallower reef crest at 3 to 5 m depths to identify potential coral reattachment sites.

Several widely separated small areas free of corals were observed in the vicinity of the eastern pier but there also was an abundance of surficial sediments along with significant amounts of the macroalgae *Padina* sp. at these locations, making them less than optimal reattachment sites. In the area between the ends of the piers a large amount of exposed rock and rubble bottom was present at depths of about 3 to 5 m, however, it appeared to be heavily disturbed and free of any attached epifauna. It was surmised this could be due to heavy use of personal watercraft (jet skis) and flyboarding in the area, which has the potential to scour bottom sediments. As the jet ski rental operations were closed due to the COVID-19 quarantine this could not be verified firsthand, although the dive vessel crew mentioned there was heavy jet ski usage in this area.

The Compensatory Mitigation Plan mentioned there was habitat suitable for the reattachment of the larger *Lobophyllia* sp. colonies, which were present in lower light areas at the base of the wharf, in slightly deeper waters just to the southwest of the western Dog Leg Pier. Dives in this area identified a series of small rock outcrops just south of the base of the reef ranging in size from about 3 m to 8 m diameter at water depths of 9 to 13 m. These outcrops harbored coral species similar to those identified on the wharf and could provide sufficient free space for the reattachment of a large number of the corals slated for removal. Additionally, three shallower locations were identified about 45 to 55 m to the northeast of these deeper outcrops that had available open space for the reattachment of the coral colonies to be removed from the upper sections of the wharf and from the two shallow rock ledges at the east and west ends of the wharf. These areas were marked with surface floats for use as reattachment sites.

3.2 CORAL RELOCATION

Dive teams carefully removed corals from the face of Hotel Wharf, starting at the eastern end and working to the west over a 2-day period. This was done both to ensure a complete and thorough removal of all acceptable corals as well as to lessen the impact to ongoing vessel and barge repair activities occurring along the wharf, as no repair work could be conducted in the vicinity of active dive operations. Divers detached all non-encrusting coral colonies that were greater than 10 cm diameter. Most colonies of small encrusting species such as *Leptastrea purpurea* could not be removed intact due to their very thin morphology, causing them to fracture and crumble. Following detachment, coral colonies were placed in perforated plastic crates on the seafloor, grouped by species, as possible.

After each collection of approximately 300 corals the crates were raised to the surface, placed on the deck of the vessel, and covered with cotton sheets dampened with seawater to prevent coral tissue damage from exposure to direct sunlight and desiccation. During the loading process and vessel transit to the reattachment site, corals were identified to species and counted. The corals were immediately returned to the water after the vessel anchored at the reattachment site, and the colonies were spread out over the available rock substrate prior to being attached. **Table 2** lists the number of colonies of each species relocated and reattached at the shallow sites 1 to 3 and the deeper sites 4 to 11.

Coral colonies removed from the shallow upper section of the wharf and from the shallow ledges at the eastern and western ends of the wharf were placed at reattachment Sites 1, 2, and 3, located in water depths of 2 to 4.5 m. These included approximately 228 colonies from the species *Favia favus*, *Pavona decussata*, *Pocillopora acuta*, *Pocillopora damicornis*, *Porites cylindrica*, *Porites lichen*, *Porites lobata*, *Porites lutea*, *Porites monticulosa*, *Porites murrayensis*, *Porites rus*, *Porites solida*, and *Psammocora nierstrozi* (**Table 2**). In addition to the relocated corals, more than 30 small colonies and fragments of

Porites cylindrica and *Porites rus* ("corals of opportunity") found broken loose at the three shallow reattachment sites were reattached to the reef.

Table 2. Number of coral colonies by species reattached at shallow versus deep reattachment sites, and numbers of reattached corals tagged for monitoring.

Coral Species	Coral Colonies Reattached at Sites 1–3	Coral Colonies Reattached at Sites 4–11	Total Reattached Corals	Reattached Coral Colonies Tagged for Monitoring
Pocillopora damicornis	149		149	17
Astreopora cucullata		62	62	11
Porites ~lutea	9	46	55	4
Lobophyllia hemprichii		44	44	12
Pavona decussata	43	1	44	10
Porites ~lobata	8	36	44	12
Lobophyllia corymbosa		35	35	7
Astreopora gracilis		29	29	6
Favia matthaii		27	27	8
Porites rus	2	24	26	5
Lobophyllia hataii		21	21	6
Porites ~solida	2	14	16	3
Pocillopora acuta	4	1	5	2
*Herpolitha limax**		4	4	3
Porites murrayensis	4		4	2
Leptoseris incrustans		3	3	3
Porites cylindrica	3		3	2
Porites horizontalata		2	2	2
Porites monticulosa (*convexa* sensu R&M 1983)	1	1	2	2
Porites sp (*P. lichen* sensu R&M 1983)	1	1	2	3
Astreopora elliptica		1	1	2
Astreopora listeri		1	1	1
Astreopora myriophthalma		1	1	1
Astreopora randalli		1	1	0
Cyphastrea chalcidicum		1	1	1
Favia favus	1		1	1
Leptastrea purpurea		3	3	3
Leptastrea transversa		1	1	0
Leptoseris mycetoseroides		1	1	0
Phymastrea valenciennesi (*Favites russelli* sensu R&M 1983)		1	1	1
Psammocora haimeana (*P. profundicella* sensu R&M 1983)		1	1	1
Psammocora neirstrazi	1		1	1
"Corals of opportunity" (*Porites cylindrica* and *Porites rus*)	30		30	
Total	**258**	**363**	**621**	**132**

* colonies were not cemented to reef (free-living species).

Corals removed from deeper areas on the wharf as well as from the adjacent seafloor were distributed on rock features subsequently marked as Sites 4 through 11 in water depths of 9.5 to 12.8 m. These included approximately 363 colonies dominated by *Astreopora cucullata*, *Porites lutea*, *Lobophyllia hemprichii*, *Porites lobata*, *Lobophyllia corymbosa*, *Astreopora gracilis*, *Favia matthaii*, *Porites rus*, *Lobophyllia hataii*, and *Porites solida*.

After corals were transported to the reattachment locations dive teams began the reattachment process, using wire brushes and metal scrapers to remove surficial sediments and any biofouling from the recipient rock surfaces to enhance cement adhesion. Divers also used the wire brushes to remove encrusting tunicates and sponges from the undersides of the coral colonies to be reattached. Colonies were reattached using methods described in **Section 2.3.3**. During the coral attachment process divers were careful to minimize concrete contact with living coral tissue on both the reattached colonies and on surrounding naturally-occurring corals. Any cement residue settling on corals was hand-fanned off at regular periods during the dives.

3.3 BASELINE MONITORING

After completion of coral reattachment activities, each of the reattachment sites was marked with a 2 cm diameter, 50 cm long, fiberglass rod cemented into the reef rock at the approximate center of each distinct site (**Photo 5**). Coral colonies representative of the species and relative numbers relocated were then selected and tagged for subsequent monitoring. Department of Agriculture Special Permit for Scientific Coral Relocation, License No. SC-20-003, specified the number of coral colonies of each relocated species to be monitored. For coral species with 50 or more individual colonies relocated, 20% were to be monitored; for species with 10 to 50 individual colonies relocated, 10% were to be monitored; and for species with less than 10 individuals, 100% were to be monitored.

A total of 149 small colonies of *Pocillopora damicornis,* nearly 24% of the total number of relocated corals, were removed from the shallow areas on the wharf and adjacent shallow hard bottom substrate and relocated. Because of the higher than expected number of colonies of this species, which is a relatively fast growing early colonizer, the number of *P. damicornis* colonies selected for monitoring was reduced from 30 colonies (20% of the total relocated) down to 17 colonies (11.4%). This allowed additional numbers of colonies of slightly less abundant and more rare species such as *Lobophyllia corymbosa*, *L. hataii*, and *L. hemprichii* to be selected for monitoring.

Additionally, the species *Porites lutea* may be under-represented in the monitoring, with only 4 colonies tagged of the estimated 55 relocated colonies. This was due to the visual similarity of this species to the species *Porites lobata* in small-sized colonies. The specified 11 colonies of *P. lutea* (20% of the total 55 colonies) were initially tagged, but upon closer inspection during the health assessment it was determined that 7 of these colonies were more likely to be the species *P. lobata*. As a result there are 12 colonies of what appear to be *P. lobata* and only 4 colonies of what may be *P. lutea* in the set of monitored relocated corals. Colonies from three species, *Astreopora randalli*, *Leptastrea transversa*, and *Leptoseris mycetoserioides*, each represented by only single small colonies, could not be relocated to be tagged for monitoring following reattachment.

A total of 132 relocated corals (**Table 2**) and 101 reference corals of similar species were tagged using colored plastic livestock ear tags secured to the substrate adjacent to the monitored colonies (**Photo 5**). Complete listings of monitored reference corals and relocated corals along with health assessment data are presented in **Appendix A**. Photographs of each tagged and monitored reference and relocated coral

colony are provided in **Appendices B** and **C**. Relocated corals were marked with light blue tags while reference coral tags were yellow. Distance and compass bearings were then recorded from the center rod to each tagged coral at each of the monitoring sites to allow easier location of monitored colonies during subsequent monitoring surveys.

Baseline monitoring of reattached and reference corals included attachment status (secureness) of relocated corals, measurement of maximum diameter (length or height) of colony (living tissue), and a health assessment including level of tissue paling or bleaching, recent tissue loss, sponge or macroalgae overgrowth, predation, and disease. Photographs were also taken of each tagged coral.

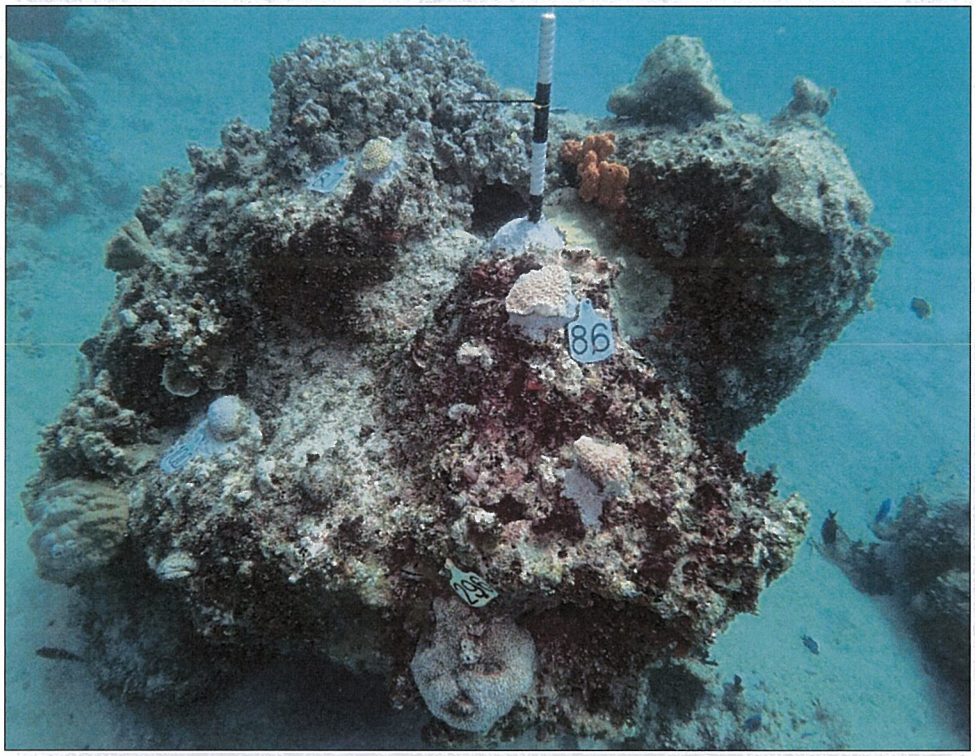


Photo 5. Marker rod embedded in rock at Site 7 along with corals tagged for monitoring.

3.3.1 Relocated Colony Bonding Status

Divers visually assessed all relocated corals to determine reattachment status by inspecting the base for cracks or gaps between the coral colony and the cement/substratum. All monitored relocated corals and numbered monitoring tags were noted as secure during the survey.

3.3.2 Coral Size and Condition

In situ observations of coral health identified six conditions as potential sources of coral stress (**Table 3**). Algal overgrowth or encroachment was the most commonly observed condition during the survey, recorded in similar frequency on 82 relocated corals (62.1%) and 69 reference corals (68.3%). It was unclear whether the algae were causing partial coral mortality, or merely growing over previously dead portions of coral colonies, and in most cases the growth was relatively minor. Algal overgrowth observed on coral colonies was typically comprised of turf algae species or in some cases the leafy brown algae *Padina*.

Table 3. Number of monitored coral colonies affected by the observed coral conditions recorded during the Baseline Monitoring Survey.

Condition	Coral Type	
	Relocated Number/ (% of total)	Reference Number/ (% of total)
Algal overgrowth	82 (62.1%)	69 (68.3%)
Paling	52 (39.4%)	22 (21.8%)
Bioerosion (fish grazing or *Lithophaga* intrusion)	36 (27.3%)	24 (23.8%)
Sponge overgrowth	12 (9.1%)	24 (23.8%)
Tissue loss	6 (4.6%)	4 (4.0%)
Tunicate overgrowth	3 (2.3%)	3 (3.0%)

Paling tissue was the second most frequently recorded condition on monitored corals and was observed on 52 relocated corals (39.4%) and only 22 reference corals (21.8%). The paling was most commonly observed as isolated areas on colony tissues (**Photo 6**), although large portions of nearly all of the *Pocillopora damicornis* reference colonies in shallow water were pale (**Photo 7**).



Photo 6. A reattached colony of *Favia matthai* with patches of pale tissue.

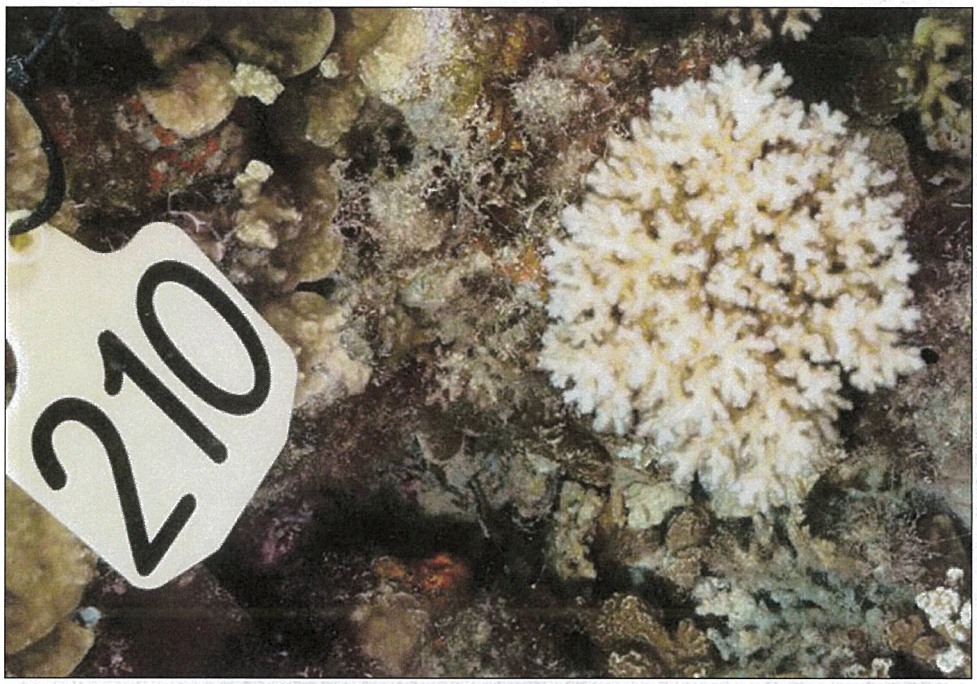


Photo 7. A reference colony of paling *Pocillopora damicornis* in shallow water.

Bioerosion included two different types of damage - the grazing of coral tissue by parrotfish and the intrusion of the boring bivalve *Lithophaga* sp. Relocated colonies of *P. damicornis* were noticeably impacted by parrotfish nipping the tips off of branches shortly after reattachment (**Photo 8**). *Lithophaga* was observed in nearly all colonies of massive *Porites* sp. greater than approximately 15 to 20 cm diameter, with abundance generally increasing with colony size (**Photos 9** and **10**).



Photo 8. A reattached colony of *Pocillopora damicornis* with branch tips eaten by parrotfish.



Photo 9. A small colony of *Porites lobata* with the boring bivalve *Lithophaga* sp. (small dark dumbbell-shaped holes).

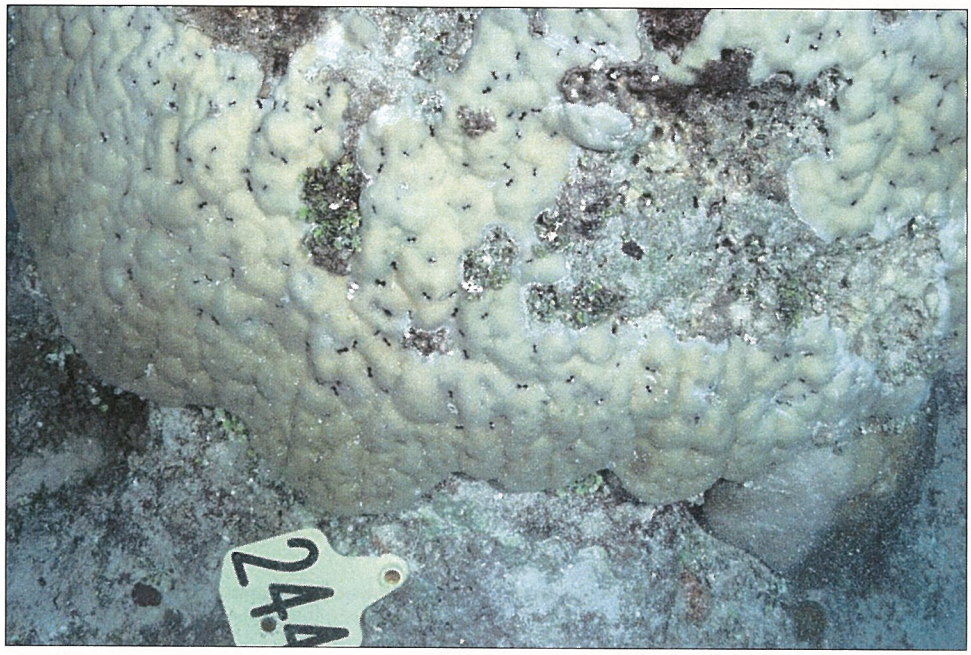


Photo 10. A large colony (71 cm diameter) of *Porites lobata* with high abundance of *Lithophaga* sp.

Sponge overgrowth was twice as prevalent in reference colonies as in relocated colonies. As encrusting sponges were abundant on the face of the wharf, this difference could be partially due to those sponges encroaching on the relocated corals either not being collected along with the coral colony during detachment or being removed by wire brushes prior to reattachment. The sponge *Clathria eurypa* was

observed in high abundance on reef substrate at the deeper reattachment sites, in many cases overgrowing healthy coral colonies (**Photo 11**).



Photo 11. The sponge *Clathria eurypa* (brown) overgrowing the top of a colony of *Porites lobata*.

Tissue loss was primarily due to branch or column breakage/fragmenting during the removal process. In most cases the branch fragments were also relocated. Tunicate overgrowth was observed but uncommon for both relocated and reference corals. Reference coral #294 (**Photo 12**) exhibited sponge (*Liosina granularis*) and algae (*Caulerpa serrulata*) overgrowth, as well as the yellow tunicate (*Phallusia julinea*).



Photo 12. The coral *Porites lutea* with a yellow tunicate (*Phallusia julinea*; left), the beige-colored sponge *Liosina granularis* (right), and the green algae *Caulerpa serrulata* (center).

Percent living tissue on monitored relocated colonies ranged from as low as 40% up to 100%, with 97 of the 132 relocated colonies (73.5%) having 90% or greater living tissue. The average percent living tissue for all monitored relocated corals was 89.7%. Percent living tissue observed on reference corals ranged from 10% up to 100%, with 64 of 101 tagged corals (63.4%) having 90% or greater living tissue. The average percent living tissue for all reference corals was 82.3%. A total of eight reference corals with less than 50% living tissue were selected for monitoring due to the rarity of individuals of several species occurring naturally in the vicinity of the reattachment sites. If these 8 colonies are excluded, the average percent living tissue for reference corals was 87.0%.

4.0 Summary

4.1 CORAL RELOCATION

All relatively healthy coral colonies greater than 10 cm diameter, as well as several smaller healthy colonies, were removed from the face of Hotel Wharf and from the seafloor and debris within 3 m of the base of the wharf, and relocated to reattachment areas to the southwest of Dog Leg Pier. This included a total of approximately 591 coral colonies, as well as more than 30 "corals of opportunity" found detached or broken loose at the shallow reattachment sites. The corals were reattached at a total of 11 sites – 3 sites located in shallow depths of 2 to 4.5 m and 8 sites in depths of 9.5 to 12.8 m. A total of 132 relocated coral colonies and 101 reference coral colonies were identified, tagged, and mapped for subsequent health monitoring.

The invasive octocoral *Carijoa riisei* was identified from the shallow southeastern corner of the wharf. All colonies of the species were carefully removed from the wharf, taking care to collect all visible pieces, and delivered to DCA for disposal.

4.2 CORAL HEALTH

Overall, the baseline monitoring observations of the conditions of the relocated and reference corals showed similar levels of both minor algae overgrowth and bioerosion; with the bioerosion either by parrotfish predation on *P. damicornis* branch tips or intrusion by the boring bivalve *Lithophaga* on massive *Porites* sp.

A higher percentage of the tagged relocated corals showed tissue paling (39.4%) compared to the tagged reference corals (21.8%). This could be partially due to declining health conditions of the corals removed from the southward-facing side of the wharf where four large barges and an offshore supply vessel have been tied off for an extended period, causing a significant reduction in sunlight reaching corals. The shading caused by the vessels, and possible resultant stress to shaded corals, could be a contributing factor in the lower number of corals identified and relocated from the project area compared to the higher number estimated as available for relocation in the Compensatory Mitigation Plan. There were several dozen nearly dead colonies observed on the wharf face, especially from mid-depths down to the seafloor, which were not relocated because of their poor condition. Many other dead colonies, fouled with silt, encrusting sponges and algae, were also observed on the face of the wharf.

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5.0 Literature Cited

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Appendices

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Table A-1. Coral baseline health assessment data for relocated and reference colonies.

Tag	Type	Taxa	Coral Condition			Coral Location				Notes
			Percent Living Tissue	Stress Condition	Maximum Diameter (cm)	Depth Zone	Stake Number	Distance (m)	Bearing (°)	
1	Relocated	*Porites cylindrica*	90	A	15.6	Shallow	3	2.5	018	cyanobacteria and coral overgrowth at base
2	Relocated	*Porites cylindrica*	95	A	12.5	Shallow	3	2.7	010	dead at tips of some branches; do not assess *Pavona* sp. portion
3	Relocated	*Porites* aff. *lichen*	95	P,Bio	16.4	Shallow	3	3.3	020	dead around perimeter; *Lithophaga*; pale tissue throughout; not *P. lichen*; but in Randall & Meyers 1983 as *P. lichen*
4	Relocated	*Porites monticulosa*	95	A,TL,Bio	62.0	Shallow	3	3.1	032	assess large colony only; several broken branches; *Lithophaga*
5	Relocated	*Porites monticulosa*	85	A,TL	23.2	Shallow	3	3.4	060	one broken branch
6	Relocated	*Porites* cf. *murrayensis*	98	P,Bio	13.7	Shallow	3	4.5	025	pale tissue throughout; *Lithophaga*; do not assess dead area around edge of colony; could also be *P. lutea*
7	Relocated	*Porites* cf. *murrayensis*	90	P,A,Bio	24.5	Shallow	1	4.5	245	*Lithophaga*; pale tissue throughout; could also be *P. lutea*
8	Relocated	*Porites rus*	95	A,P	25.4	Shallow	2	2.6	355	pale tissue around edge
9	Relocated	*Porites rus*	98	P,TL	12.4	Shallow	2	1.9	050	assess large colony only; broken branch; pale tissue at edge
10	Relocated	*Porites rus*	85	A	17.0	Shallow	2	2.3	225	--
11	Relocated	*Porites lobata*	85	A,P,Bio	28.6	Shallow	1	3.8	213	pale tissue in areas; *Lithophaga*; grazing scars
12	Relocated	*Psammocora neirstrazi*	90	TL,A	7.5	Shallow	1	4.0	162	broken branches

Table A-1. (Continued).

Tag	Type	Taxa	Coral Condition			Coral Location				Notes
			Percent Living Tissue	Stress Condition	Maximum Diameter (cm)	Depth Zone	Stake Number	Distance (m)	Bearing (°)	
13	Relocated	*Porites solida*	98	Bio,P	23.5	Shallow	1	1.6	165	pale tissue spots; *Lithophaga*; grazing scars
14	Relocated	*Porites solida*	65	A,Bio,P	36.8	Shallow	1	5.9	210	bivalves
15	Relocated	*Porites lobata*	98	TL,Bio,P	22.9	Shallow	1	6.1	205	*Lithophaga*
16	Relocated	*Porites lobata*	99	P,A	16.5	Shallow	1	4.2	180	vertical measurement; grazing scars
17	Relocated	*Porites lobata*	99	A,Bio	12.4	Shallow	1	4.1	225	grazing scars
18	Relocated	*Porites lutea*	60	A,P,Bio	16.4	Shallow	1	4.1	212	*Lithophaga*; grazing scars
19	Relocated	*Pocillopora damicornis*	97	P,Bio	26.4	Shallow	1	1.5	265	grazing scars
20	Relocated	*Pocillopora damicornis*	100	P	20.5	Shallow	1	1.3	318	--
21	Relocated	*Pocillopora damicornis*	98	P,Bio	17.9	Shallow	1	1.6	318	grazing scars
22	Relocated	*Pocillopora damicornis*	100	P	15.9	Shallow	1	5.7	045	--
23	Relocated	*Pocillopora damicornis*	98	P,Bio	19.6	Shallow	1	5.9	042	grazing scars
24	Relocated	*Pocillopora damicornis*	95	A,P	15.8	Shallow	1	5.5	038	--
25	Relocated	*Pavona decussata*	60	A	17.6	Shallow	1	1.8	095	--
26	Relocated	*Pavona decussata*	95	A	10.2	Shallow	1	1.8	115	--
27	Relocated	*Pavona decussata*	70	A	24.9	Shallow	1	1.9	125	--
28	Relocated	*Pavona decussata*	95	A,P	15.5	Shallow	1	2.6	140	pale tissue throughout
29	Relocated	*Pocillopora damicornis*	90	A,Bio	12.3	Shallow	1	3.9	155	grazing scars
30	Relocated	*Pocillopora damicornis*	95	A,P,Bio	17.0	Shallow	1	4.7	152	grazing scars
31	Relocated	*Pocillopora damicornis*	95	Bio,P	15.8	Shallow	1	4.8	162	assess large colony only; grazing scars; pale tissue throughout
32	Relocated	*Pocillopora damicornis*	97	Bio	11.4	Shallow	1	4.7	175	grazing scars

Table A-1. (Continued).

Tag	Type	Taxa	Coral Condition			Coral Location				Notes
			Percent Living Tissue	Stress Condition	Maximum Diameter (cm)	Depth Zone	Stake Number	Distance (m)	Bearing (°)	
33	Relocated	*Porites lutea*	50	A,P,Bio	20.0	Shallow	3	3.4	075	pale tissue in spots; *Lithophaga*; worm tubes
34	Relocated	*Porites lutea*	99	P,Bio	11.1	Shallow	3	3.1	072	pale tissue in spots; *Lithophaga*; could be *F. murrayensis*
35	Relocated	*Favia favus*	70	A,Bio	18.0	Shallow	3	2.7	260	assess large colony only; *Lithophaga*; worm tubes; could be *F. murrayensis*
36	Relocated	*Pocillopora acuta*	99	P,Bio	24.2	Shallow	3	4.6	250	grazing scars
37	Relocated	*Pocillopora acuta*	80	A,P,Bio	14.2	Shallow	3	5.1	238	grazing scars
38	Relocated	*Pocillopora damicornis*	98	A,Bio,P	15.4	Shallow	3	4.0	248	grazing scars
39	Relocated	*Pocillopora damicornis*	95	A,P,Bio	25.5	Shallow	3	3.6	248	grazing scars
40	Relocated	*Pocillopora damicornis*	98	Bio	24.7	Shallow	3	1.8	238	grazing scars
41	Relocated	*Pocillopora damicornis*	98	Bio,P	8.4	Shallow	3	1.3	242	grazing scars
42	Relocated	*Pocillopora damicornis*	95	A,Bio	18.5	Shallow	3	0.5	210	grazing scars
43	Relocated	*Pocillopora damicornis*	100	-	12.3	Shallow	3	2.7	350	--
44	Relocated	*Pocillopora damicornis*	99	Bio	17.2	Shallow	3	3.7	335	grazing scars
45	Relocated	*Pavona decussata*	98	P,A	17.6	Shallow	3	3.6	015	--
46	Relocated	*Pavona decussata*	90	A,P	20.3	Shallow	3	6.9	012	--
47	Relocated	*Pavona decussata*	85	A	15.8	Shallow	2	6.4	218	--
48	Relocated	*Pavona decussata*	98	A	14.7	Shallow	2	0.6	230	*Padina* algae
49	Relocated	*Pavona decussata*	60	A	12.6	Shallow	2	1.7	025	do not assess base of colony
50	Relocated	*Porites lutea*	95	A,P,Bio	32.8	Deep	4	1.2	335	pale tissue in spots; *Lithophaga*
51	Relocated	*Porites solida*	95	A	19.9	Deep	4	0.4	340	assess large colony only

Table A-1. (Continued).

Tag	Type	Taxa	Coral Condition			Coral Location				Notes
			Percent Living Tissue	Stress Condition	Maximum Diameter (cm)	Depth Zone	Stake Number	Distance (m)	Bearing (°)	
52	Relocated	*Leptoseris incrustans*	90	A,S	21.6	Deep	4	0.9	315	--
53	Relocated	*Porites rus*	98	A,P	14.8	Deep	4	1.3	315	pale tissue at edge
54	Relocated	*Favia matthaii*	95	A,P	14.2	Deep	5	1.7	140	--
55	Relocated	*Lobophyllia hemprichii*	85	A	24.4	Deep	5	1.7	150	--
56	Relocated	*Lobophyllia hemprichii*	85	A,S	17.6	Deep	5	0.3	090	--
57	Relocated	*Pavona decussata*	95	A	26.5	Deep	5	1.7	332	*Halimeda* algae
58	Relocated	*Astreopora cucullata*	90	A	18.1	Deep	5	1.5	028	--
59	Relocated	*Favia matthaii*	40	A	23.3	Deep	5	5.7	125	--
60	Relocated	*Favia matthaii*	100	-	4.6	Deep	5	5.7	135	assess large colony only
61	Relocated	*Astreopora cucullata*	90	A	24.3	Deep	4	7.2	332	--
62	Relocated	*Astreopora listeri*	100	P	12.2	Deep	4	7.3	340	assess large colony only, pale tissue throughout
63	Relocated	*Lobophyllia hemprichii*	55	A	36.2	Deep	4	6.9	345	encrusting red algae
64	Relocated	*Lobophyllia hemprichii*	95	A	15.8	Deep	4	6.5	340	--
65	Relocated	*Leptastrea* cf. *purpurea*	90	A,P	14.2	Deep	4	6.8	335	pale tissue throughout; likely L. purpurea
66	Relocated	*Lobophyllia hemprichii*	75	A	18.6	Deep	6	2.4	088	--
67	Relocated	*Porites horizontalata*	99	A,P	8.7	Deep	6	1.9	118	pale tissue throughout
68	Relocated	*Lobophyllia hemprichii*	98	A	35.0	Deep	6	0.5	110	--
69	Relocated	*Favia matthaii*	75	A	16.6	Deep	6	0.5	062	--
70	Relocated	*Lobophyllia corymbosa*	95	A	15.2	Deep	6	0.8	228	dead area in center of colony

Table A-1. (Continued).

Tag	Type	Taxa	Coral Condition			Coral Location				Notes
			Percent Living Tissue	Stress Condition	Maximum Diameter (cm)	Depth Zone	Stake Number	Distance (m)	Bearing (°)	
71	Relocated	*Lobophyllia hemprichii*	100	-	17.7	Deep	6	1.3	348	--
72	Relocated	*Favia matthaii*	100	-	11.4	Deep	6	1.6	355	tunicate at base of colony
73	Relocated	*Porites ~lichen*	98	A,P	15.3	Deep	6	1.7	345	assess colony above (southeast) tag; two colonies; combined; not *P. lichen* but in Randall & Meyers 1983 as *P. lichen*
74	Relocated	*Herpolitha limax**	100,100,100	-	10.5,14.4,30.2	Deep	6	2.0	328	three colonies, assess all
75	Relocated	*Astreopora gracilis*	85	A	23.3	Deep	6	2.3	000	three colonies around tag; two small, one large
76	Relocated	*Lobophyllia hemprichii*	65	A	24.5	Deep	6	3.0	358	pink tissue coloration; turf algae on dead areas
77	Relocated	*Lobophyllia corymbosa*	90	A	31.0	Deep	6	3.5	015	turf algae on dead areas
78	Relocated	*Astreopora cucullata*	95	-	10.0	Deep	6	3.3	020	--
79	Relocated	*Lobophyllia hataii*	95	A	16.2	Deep	6	2.9	028	turf algae on dead areas
80	Relocated	*Lobophyllia corymbosa*	100	-	17.8	Deep	6	3.0	045	--
81	Relocated	*Porites lobata*	75	Bio	9.5	Deep	6	3.9	042	a few *Lithophaga*
82	Relocated	*Astreopora gracilis*	75	-	26.5	Deep	6	2.0	015	tissue paling in areas; tissue growing over dead areas
83	Relocated	*Lobophyllia hemprichii*	65	A	28.0	Deep	7	2.1	122	turf algae on dead areas
84	Relocated	*Leptoseris incrustans*	97	-	15.5	Deep	7	1.8	138	areas of green endolithic algae
85	Relocated	*Lobophyllia hemprichii*	85	-	26.8	Deep	7	2.4	155	--
86	Relocated	*Astreopora myriophthalma*	100	-	12.5	Deep	7	0.2	225	--
87	Relocated	*Favia matthaii*	98	A	10.6	Deep	7	0.4	002	turf algae and *Halimeda*

Table A-1. (Continued).

Tag	Type	Taxa	Coral Condition			Coral Location				Notes
			Percent Living Tissue	Stress Condition	Maximum Diameter (cm)	Depth Zone	Stake Number	Distance (m)	Bearing (°)	
88	Relocated	*Astreopora cucullata*	98	P	12.0	Deep	7	0.8	060	small area of pale tissue
89	Relocated	*Lobophyllia corymbosa*	80	S,T	22.5	Deep	7	1.0	060	sponge; tunicates; bivalves
90	Relocated	*Favia matthaii*	95	A,P	14.5	Deep	7	1.0	072	turf algae; some pale tissue
91	Relocated	*Lobophyllia hemprichii*	90	S	21.2	Deep	7	1.1	100	--
92	Relocated	*Porites lobata*	100	Bio	13.8	Deep	7	1.3	090	*Lithophaga*
93	Relocated	*Cyphastrea chalcidicum*	65	-	8.2	Deep	7	1.4	008	--
94	Relocated	*Favia matthaii*	95	S,A	24.5	Deep	7	3.0	005	turf algae around edge of colony
95	Relocated	*Astreopora gracilis*	90	-	10.0	Deep	7	2.8	010	--
96	Relocated	*Astreopora cucullata*	90	A	19.0	Deep	7	4.0	342	turf algae on dead areas
97	Relocated	*Astreopora cucullata*	75	S,A	24.6	Deep	7	3.8	330	--
98	Relocated	*Lobophyllia hemprichii*	98	-	19.6	Deep	7	7.0	342	--
99	Relocated	*Astreopora cucullata*	90	S	13.5	Deep	7	6.4	346	encrusting sponge on side of colony
100	Relocated	*Astreopora cucullata*	100	P	11.9	Deep	7	0.6	317	pale tissue throughout
101	Relocated	*Phymastrea valenciennesi*	60	A,T	27.9	Deep	8	0.4	228	assess entire complex
102	Relocated	*Lobophyllia hataii*	100	-	14.6	Deep	8	0.8	225	--
103	Relocated	*Astreopora elliptica*	100	P	11.6	Deep	8	1.2	125	pale tissue throughout
104	Relocated	*Porites lobata*	90	A,P,Bio	17.9	Deep	8	0.9	175	*Lithophaga*; pale tissue in spots

Table A-1. (Continued).

Tag	Type	Taxa	Coral Condition			Coral Location				Notes
			Percent Living Tissue	Stress Condition	Maximum Diameter (cm)	Depth Zone	Stake Number	Distance (m)	Bearing (°)	
105	Relocated	*Astreopora cucullata*	90	A,S	14.9	Deep	8	1.7	240	--
106	Relocated	*Astreopora gracilis*	80	A,T	19.3	Deep	8	1.7	265	--
107	Relocated	*Astreopora elliptica*	100	P	16.2	Deep	8	1.7	298	pale tissue in spots
108	Relocated	*Astreopora gracilis*	95	A	11.6	Deep	8	1.5	328	--
109	Relocated	*Astreopora gracilis*	65	A	23.7	Deep	8	1.3	330	--
110	Relocated	*Astreopora cucullata*	80	A	16.2	Deep	8	2.5	022	--
111	Relocated	*Astreopora cucullata*	95	A,P	17.6	Deep	8	0.1	270	pale tissue in spots
112	Relocated	*Porites lobata*	100	P,Bio	21.1	Deep	8	1.1	032	pale tissue in spots; *Lithophaga*
113	Relocated	*Lobophyllia corymbosa*	85	S,A	22.4	Deep	10	2.4	260	assess entire complex; yellow sponge
114	Relocated	*Lobophyllia corymbosa*	70	S,A	23.7	Deep	10	2.0	320	black sponge
115	Relocated	*Lobophyllia corymbosa*	65	A,S	30.1	Deep	10	1.0	346	assess entire complex; black sponge
116	Relocated	*Porites horizontalata*	90	A,P	22.1	Deep	9	0.8	158	pale tissue in spots
117	Relocated	*Porites lobata*	95	A,P	12.4	Deep	9	0.6	085	pale tissue in spots
118	Relocated	*Leptastrea purpurea*	100	-	10.1	Deep	9	1.9	040	--
119	Relocated	*Porites lobata*	90	A,P	9.0	Deep	9	1.5	115	pale tissue throughout
120	Relocated	*Porites lobata*	100	P	9.6	Deep	9	2.0	115	some tissue discoloration
121	Relocated	*Lobophyllia hataii*	85	TL,P	13.9	Deep	8	1.2	135	recent tissue loss and tissue paling
122	Relocated	*Lobophyllia hataii*	100	-	11.4	Deep	8	1.5	280	--

Table A-1. (Continued).

Tag	Type	Taxa	Coral Condition			Coral Location				Notes
			Percent Living Tissue	Stress Condition	Maximum Diameter (cm)	Depth Zone	Stake Number	Distance (m)	Bearing (°)	
123	Relocated	*Porites* aff. *lichen*	97	A,P,Bio	34.6	Deep	8	2.7	010	pale tissue in spots; *Lithophaga*; not *P. lichen*, but in Randall & Meyers 1983 as *P. lichen*
124	Relocated	*Porites rus*	98	A	10.9	Deep	7	6.4	022	--
125	Relocated	*Psammocora profundicella*	98	A	9.4	Deep	6	7.6	210	*Halimeda* algae; sensu Randall & Meyers 1983 - Veron still accepts this ID, but has recently been redone and this beast is not *P. haimeana*
126	Relocated	*Leptastrea purpurea*	90	S,A,P	21.5	Deep	6	5.3	200	some pale tissue; boring sponge
127	Relocated	*Leptoseris incrustans*	90	A	22.9	Deep	6	6.0	200	--
128	Relocated	*Lobophyllia hataii*	90	A	16.1	Deep	6	7.6	205	--
129	Relocated	*Lobophyllia hataii*	100	-	16.4	Deep	6	8.5	208	sponge at base of colony; perhaps Burdick's *L.* cf. *hataii*
130	Relocated	*Porites lobata*	95	A,Bio,P	19.8	Deep	6	1.6	298	*Lithophaga*; pale grazing scars
Reference										
200	Reference	*Pocillopora damicornis*	100	P, A	12.5	Shallow	2	3.8	292	--
201	Reference	*Pocillopora damicornis*	98	P,A	4.8	Shallow	2	2.0	310	--
202	Reference	*Pocillopora damicornis*	100	P	10.8	Shallow	2	4.9	345	--
203	Reference	*Pocillopora damicornis*	100	P	6.8	Shallow	2	5.7	012	--
204	Reference	*Pocillopora damicornis*	100	P	12.2	Shallow	2	5.3	010	--

Table A-1. (Continued).

Tag	Type	Taxa	Coral Condition			Coral Location				Notes
			Percent Living Tissue	Stress Condition	Maximum Diameter (cm)	Depth Zone	Stake Number	Distance (m)	Bearing (°)	
205	Reference	*Pocillopora damicornis*	55	A,P	20.4	Shallow	2	4.8	330	--
206	Reference	*Pocillopora damicornis*	100	P,A	16.0	Shallow	2	7.7	315	--
207	Reference	*Pocillopora damicornis*	100	A	17.5	Shallow	2	2.3	152	located in a hole
208	Reference	*Pocillopora damicornis*	100	P	7.5	Shallow	2	3.3	155	--
209	Reference	*Pocillopora damicornis*	100	-	18.0	Shallow	2	2.6	140	--
210	Reference	*Pocillopora damicornis*	100	P	13.6	Shallow	2	8.4	195	--
211	Reference	*Pocillopora damicornis*	100	-	12.9	Shallow	2	7.5	198	on vertical wall
212	Reference	*Pocillopora damicornis*	100	P	9.6	Shallow	2	8.2	185	--
213	Reference	*Porites cylindrica*	100	-	19.4	Shallow	3	4.3	082	--
214	Reference	*Porites cylindrica*	100	-	15.5	Shallow	3	4.4	122	*P. monticulosa* overgrowth
215	Reference	*Astreopora cucullata*	90	Bio,A	43.5	Deep	5	2.8	235	bivalves; *Lithophaga*
216	Reference	*Porites monticulosa*	100	-	56.0	Shallow	3	3.7	105	--
217	Reference	*Porites monticulosa*	100	A	19.4	Shallow	3	2.8	272	vertical measurement
218	Reference	*Porites rus*	100	A	11.5	Shallow	3	4.2	240	--
219	Reference	*Porites rus*	100	-	11.3	Shallow	3	5.6	252	--
220	Reference	*Psammocora neirstrazi*	90	A	22.6	Shallow	3	2.0	118	--
221	Reference	*Porites lutea*	99	S	19.5	Shallow	3	1.8	045	sponge at edge of colony
222	Reference	*Porites lutea*	95	A	21.2	Shallow	3	3.2	018	--
223	Reference	*Porites lutea*	100	-	35.5	Shallow	3	3.7	002	--
224	Reference	*Porites lutea*	99	A	40.5	Shallow	3	5.0	015	--

Table A-1. (Continued).

Tag	Type	Taxa	Coral Condition			Coral Location				Notes
			Percent Living Tissue	Stress Condition	Maximum Diameter (cm)	Depth Zone	Stake Number	Distance (m)	Bearing (°)	
225	Reference	*Porites lutea*	75	Bio,A,P	38.0	Shallow	3	5.8	010	vertical measure; heavy *Lithophaga*; some algal cover; slight paling
226	Reference	*Porites murrayensis*	80	A,Bio	25.5	Shallow	2	3.7	335	cyanobacteria film; *Lithophaga*
227	Reference	*Porites murrayensis*	30	A	33.0	Shallow	2	4.5	008	seven areas of living tissue
228	Reference	*Porites solida*	100	Bio	20.0	Shallow	2	2.9	152	brown color colony, located under another colony; vertical measurement; *Lithophaga*
229	Reference	*Porites solida*	98	A	37.5	Shallow	3	3.1	120	--
230	Reference	*Astreopora cucullata*	95	A,Bio	24.0	Deep	5	2.0	228	*Lithophaga*; vertical measurement
231	Reference	*Astreopora gracilis*	100	-	16.9	Deep	5	1.9	190	--
232	Reference	*Porites lutea*	95	A,Bio	22.2	Deep	5	2.1	172	*Lithophaga*
233	Reference	*Leptastrea purpurea*	60	TL,A	18.8	Deep	5	1.8	105	vertical measurement; recovering dead area
234	Reference	*Astreopora gracilis*	95	A,Bio,P	23.8	Deep	5	1.5	010	some pale tissue; *Lithophaga*
235	Reference	*Astreopora cucullata*	100	-	19.6	Deep	5	2.3	010	--
236	Reference	*Astreopora cucullata*	98	A	14.7	Deep	4	2.1	060	assess large colony only
237	Reference	*Astreopora gracilis*	100	-	15.4	Deep	4	2.4	050	--
238	Reference	*Astreopora myriophthalma*	70	A,Bio,S	60.5	Deep	4	2.3	045	*Lithophaga*; bivalves; *Clathria* sponge
239	Reference	*Astreopora gracilis*	99	A,Bio,P	15.5	Deep	4	0.7	335	some pale tissue and discoloration; *Lithophaga*
240	Reference	*Porites rus*	70	A,S,T	55.8	Deep	4	1.8	332	--

Table A-1. (Continued).

Tag	Type	Taxa	Coral Condition			Coral Location				Notes
			Percent Living Tissue	Stress Condition	Maximum Diameter (cm)	Depth Zone	Stake Number	Distance (m)	Bearing (°)	
241	Reference	*Astreopora cucullata*	70	A,Bio	25.7	Deep	4	1.4	305	bivalves; *Lithophaga*
242	Reference	*Porites horizontalata*	60	A,TL,P	25.0	Deep	4	0.9	288	--
243	Reference	*Porites lutea*	90	A,Bio	17.4	Deep	4	0.6	262	*Lithophaga*
244	Reference	*Porites lobata*	60	A,Bio	71.0	Deep	4	2.5	210	cyanobacteria
245	Reference	*Leptoseris incrustans*	100	-	11.2	Deep	4	2.9	202	--
246	Reference	*Astreopora cucullata*	97	A	34.4	Deep	4	0.9	120	--
247	Reference	*Porites* aff. *lichen*	100	Bio	24.0	Deep	4	6.6	332	*Lithophaga*; not *P. lichen*, but in Randall & Meyers 1983 as *P. lichen*
248	Reference	*Porites* aff. *lichen*	99	Bio	22.3	Deep	4	6.7	342	*Lithophaga*; previous damage to rock; not *P. lichen*, but in Randall & Meyers 1983 as *P. lichen*
249	Relocated	*Porites horizontalata*	90	S,Bio	23.8	Deep	5	1.1	190	*Lithophaga*
250	Reference	*Psammocora profundicella*	30	A,S	14.7	Deep	5	0.9	282	sensu Randall & Meyers 1983 - Veron still accepts this identification, but has recently been redone and this is not *P. haimeana*
251	Reference	*Phymastrea valenciennesi*	50	A	11.0	Deep	6	7.0	208	assess area to right (southwest) of tag
252	Reference	*Astreopora cucullata*	98	A	29.5	Deep	6	7.5	200	--
253	Reference	*Astreopora cucullata*	50	A,S	41.7	Deep	6	2.0	205	--
254	Reference	*Lobophyllia corymbosa*	20	A,S	49.0	Deep	6	2.9	226	appears part of larger dead colony; assess as portion of original colony

Table A-1. (Continued).

Tag	Type	Taxa	Coral Condition			Coral Location				Notes
			Percent Living Tissue	Stress Condition	Maximum Diameter (cm)	Depth Zone	Stake Number	Distance (m)	Bearing (°)	
255	Reference	*Astreopora cucullata*	95	A,Bio	24.2	Deep	6	3.4	040	*Lithophaga*
256	Reference	*Lobophyllia hemprichii*	99	A,P	16.0	Deep	9	1.8	045	pale tissue throughout
257	Reference	*Lobophyllia hemprichii*	90	A,S	19.6	Deep	9	2.6	020	--
258	Reference	*Lobophyllia corymbosa*	40	A,S	40.5	Deep	10	7.4	302	living tissue around perimeter of original colony
259	Reference	*Leptastrea transversa*	60	A,S	26.4	Deep	10	4.6	105	assess entire end of rock edge
260	Reference	*Lobophyllia corymbosa*	95	A,S,T	49.9	Deep	6	11.7	200	--
261	Reference	*Herpolitha limax*	100	P	12.5	Deep	8	0.1	118	near site stake; "J" shaped
262	Reference	*Favia favus*	80	A	12.5	Deep	8	0.8	185	assess large colony under tag only
263	Reference	*Porites lutea*	100	-	37.8	Deep	7	7.6	355	--
264	Reference	*Porites lobata*	65	A,TL	31.8	Deep	7	7.8	355	areas of sedimentation within colony
265	Reference	*Porites lobata*	95	A	29.4	Deep	7	6.9	000	reattached *Porites rus* colony on top; *Lithophaga*, cyanobacteria
266	Reference	*Porites lutea*	65	A,P	31.2	Deep	7	5.4	010	--
267	Reference	*Porites lobata*	90	A	38.6	Deep	6	1.4	225	assess end of rock near tag
268	Reference	*Astreopora listeri*	85	A,S	59.4	Deep	6	1.0	090	--
269	Reference	*Astreopora cucullata*	98	A,Bio	34.5	Deep	6	2.4	058	*Lithophaga*
270	Reference	*Porites solida*	98	P	49.5	Deep	6	2.5	050	pale tissue spots
271	Reference	*Lobophyllia corymbosa*	100	-	36.0	Deep	11	7.5	185	--
272	Reference	*Leptastrea purpurea*	60	A,S	30.0	Deep	11	7.6	195	turf algae

Table A-1. (Continued).

Tag	Type	Taxa	Coral Condition			Coral Location				Notes
			Percent Living Tissue	Stress Condition	Maximum Diameter (cm)	Depth Zone	Stake Number	Distance (m)	Bearing (°)	
273	Reference	*Lobophyllia hemprichii*	100	-	18.3	Deep	11	1.7	215	--
274	Reference	*Favia favus*	25	S	26.0	Deep	11	8.0	055	--
275	Reference	*Favia matthaii*	10	S,A	5.0, 8.0, 9.5	Deep	11	6.6	042	three colonies; 22 cm of colony dead with sponge and algal cover
276	Reference	*Lobophyllia hemprichii*	50	A	24.5	Deep	11	10.4	025	--
277	Reference	*Lobophyllia corymbosa*	95	S,A	73.0	Deep	11	21.8	005	--
278	Reference	*Astreopora gracilis*	45	A	16.5	Deep	11	2.5	235	turf algae; cyanobacteria
279	Reference	*Lobophyllia hemprichii*	100	-	6.0	Deep	11	1.7	235	located under ledge
280	Reference	*Astreopora cucullata*	95	A	22.5	Deep	11	3.5	230	turf algae; cyanobacteria
281	Reference	*Astreopora gracilis*	90	A	20.0	Deep	11	4.1	250	turf algae; *Porites monticulosa* overgrowth
282	Reference	*Favia* cf. *matthaii*	20	A	14.5	Deep	11	3.0	028	turf algae and cyanobacteria on mostly dead original coral colony; primary septa are more enlarged than normal for *F. matthaii* giving star-like appearance
283	Reference	*Porites lobata*	100	P	43.0	Deep	4	2.8	215	pale tissue spots; grazing scars; sponge at base of colony
284	Reference	*Astreopora cucullata*	60	A,Bio	29.6	Deep	4	3.1	215	*Lithophaga*
285	Reference	*Astreopora gracilis*	100	-	23.2	Deep	4	1.0	225	--

Table A-1. (Continued).

Tag	Type	Taxa	Coral Condition			Coral Location				Notes
			Percent Living Tissue	Stress Condition	Maximum Diameter (cm)	Depth Zone	Stake Number	Distance (m)	Bearing (°)	
286	Reference	*Astreopora cucullata*	60	A,S	36.7	Deep	5	3.5	075	assess area to left (north) of tag
287	Reference	*Astreopora cucullata*	70	A	51.0	Deep	5	4.0	355	--
288	Reference	*Porites lobata*	50	S,P	25.3	Deep	5	3.3	015	*Clathria* sponge; pale tissue spots
289	Reference	*Astreopora cucullata*	60	A,S	37.5	Deep	5	3.0	018	--
290	Reference	*Astreopora cucullata*	90	A,Bio	31.5	Deep	6	2.3	112	*Lithophaga*
291	Reference	*Porites lutea*	90	A,TL,P	51.8	Deep	6	2.3	125	recent tissue loss; black coloration at edge of colony
292	Reference	*Astreopora gracilis*	50	A	33.0	Deep	6	1.6	105	assess entire rock
293	Reference	*Astreopora cucullata*	70	A	35.2	Deep	6	2.0	060	assess area to north of tag
294	Reference	*Porites lutea*	60	A,S,T	77.5	Deep	6	1.2	035	--
295	Reference	*Porites lobata*	99	A,Bio	26.5	Deep	7	2.0	155	*Lithophaga*
296	Reference	*Astreopora cucullata*	90	S,A,Bio	26.6	Deep	7	0.7	238	vertical measurement; bivalves
297	Reference	*Porites lobata*	95	Bio,P,A	59.5	Deep	7	2.1	305	*Porites rus* colony on top; pale tissue spots; *Lithophaga*
298	Reference	*Porites lobata*	85	A,S,Bio	49.4	Deep	7	6.2	005	bivalves; *Lithophaga*
299	Reference	*Porites lutea*	50	A,S	82.5	Deep	10	1.3	218	assess entire rock; *Astreopora* colony attached
300	Reference	*Astreopora cucullata*	85	A,Bio,S	35.5	Deep	10	1.9	200	vertical measurement; bivalves; *Lithophaga*

* three colonies of *Herpolitha limax* at Tag **74**.
-- = no stress condition observed.

Appendix B

Photographs of Tagged Relocated Corals

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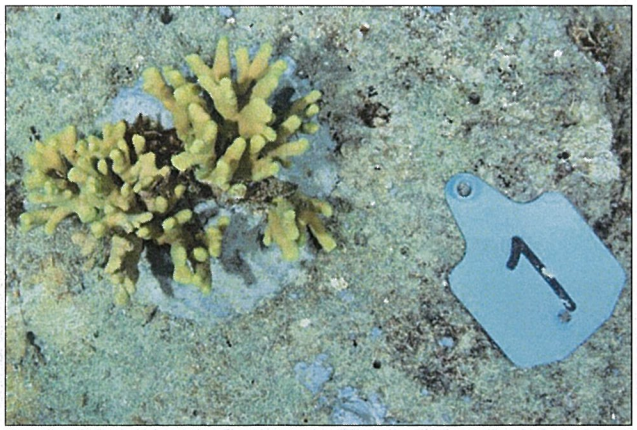


Photo B-1. *Porites cylindrica*

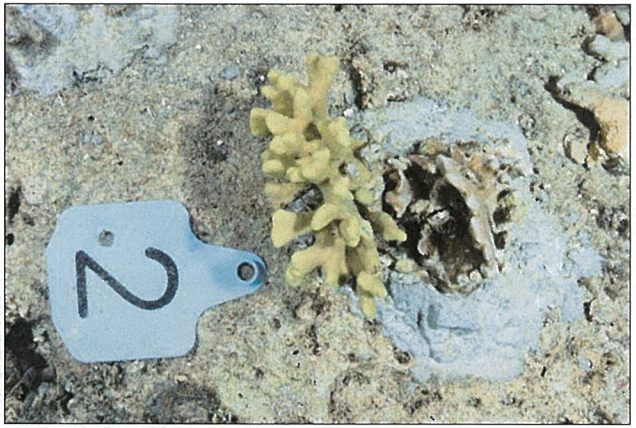


Photo B-2. *Porites cylindrica*



Photo B-3 *Porites* aff. *lichen*

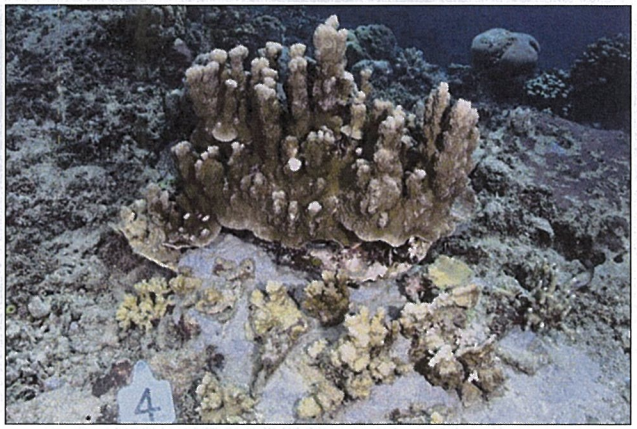


Photo B-4. *Porites monticulosa*

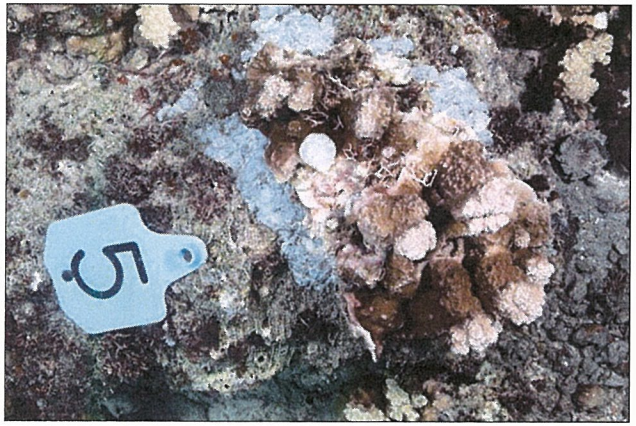


Photo B-5. *Porites monticulosa*

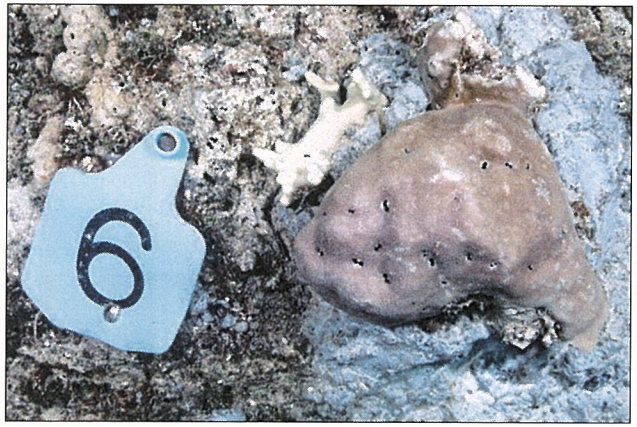


Photo B-6. *Porites* cf. *murrayensis*

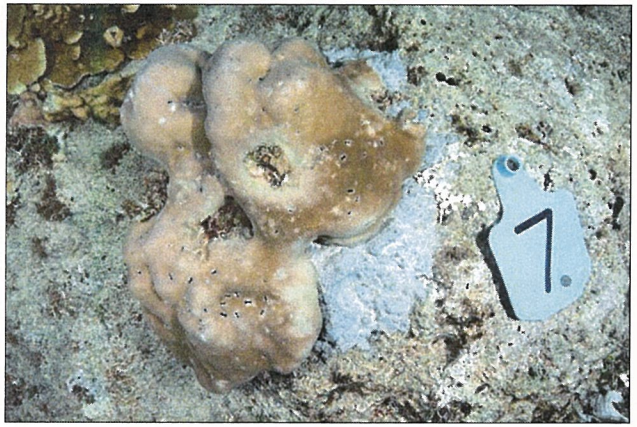


Photo B-7. *Porites* cf. murrayensis



Photo B-8. *Porites rus*



Photo B-9. *Porites rus*

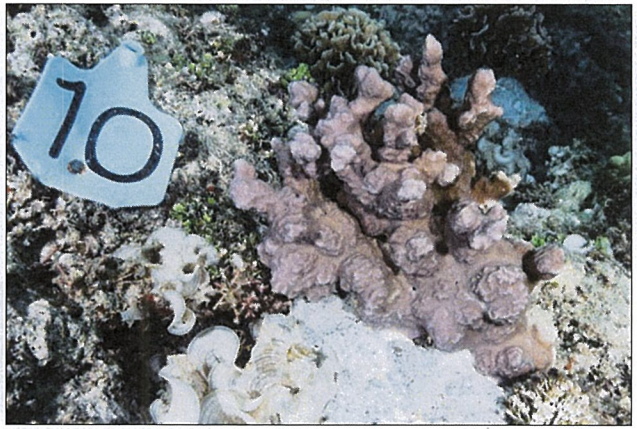


Photo B-10. *Porites rus*

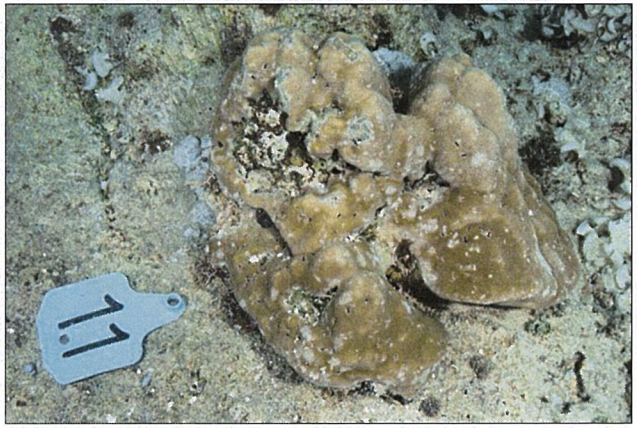


Photo B-11. *Porites lobata*

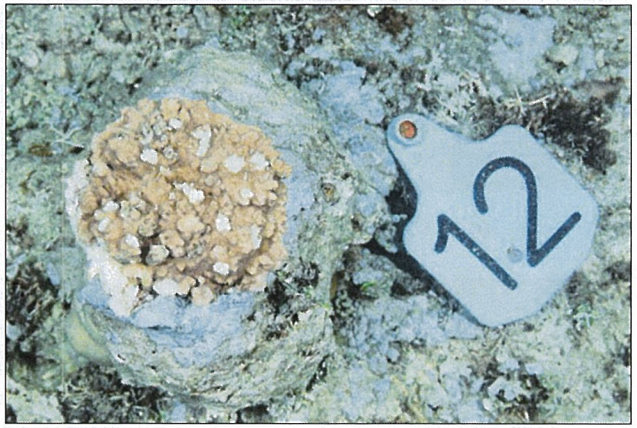


Photo B-12 *Psammocora neirstrazi*

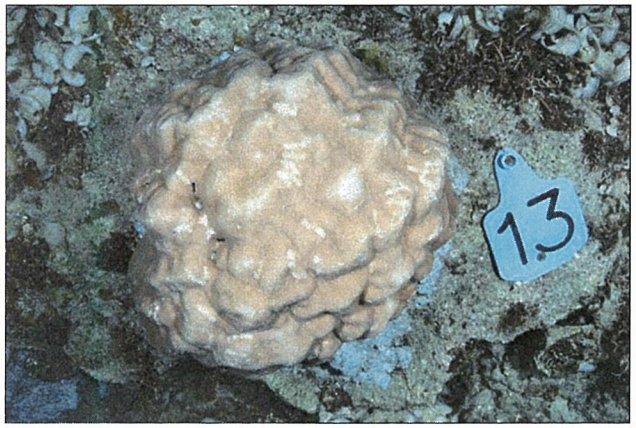


Photo B-13. *Porites solida*

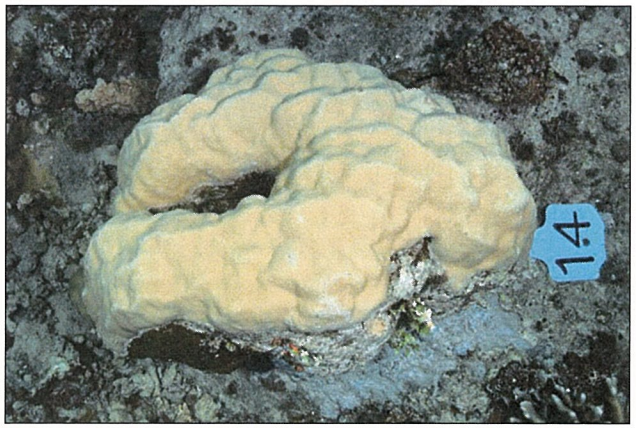


Photo B-14. *Porites solida*



Photo B-15. *Porites lobata*

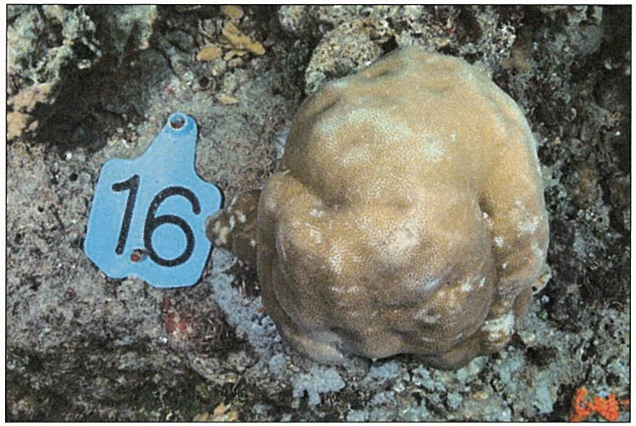


Photo B-16. *Porites lobata*

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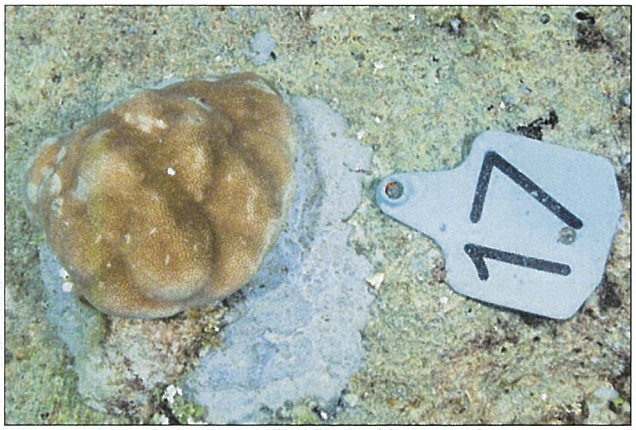


Photo B-17. *Porites lobata*

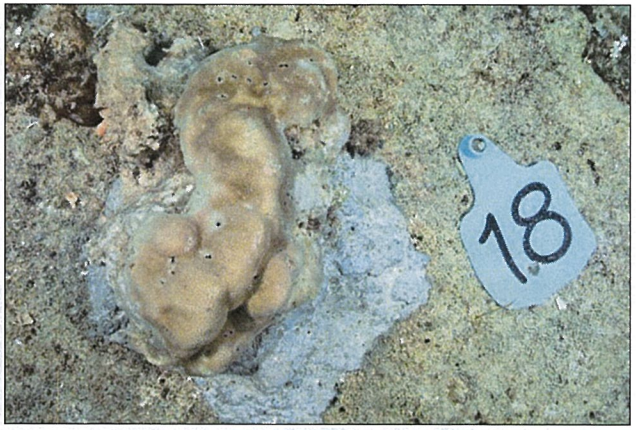


Photo B-18. *Porites lutea*



Photo B-19. *Pocillopora damicornis*



Photo B-20. *Pocillopora damicornis*



Photo B-21. *Pocillopora damicornis*

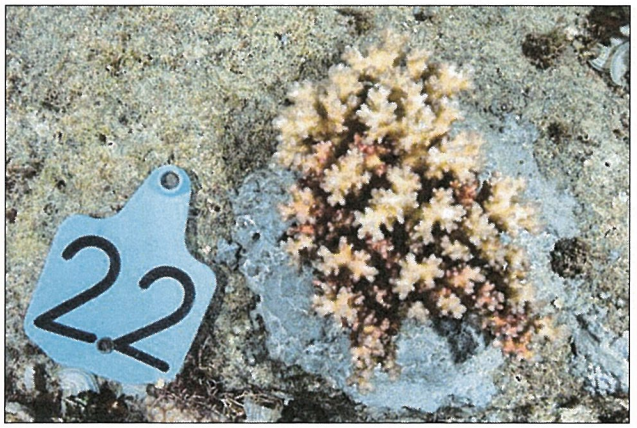


Photo B-22. *Pocillopora damicornis*



Photo B-23. *Pocillopora damicornis*



Photo B-24. *Pocillopora damicornis*



Photo B-25. *Pavona decussata*



Photo B-26. *Pavona decussata*



Photo B-27. *Pavona decussata*

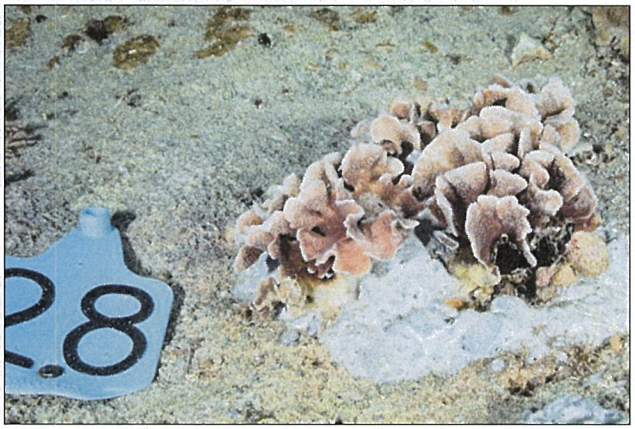


Photo B-28. *Pavona decussata*



Photo B-29. *Pocillopora damicornis*



Photo B-30. *Pocillopora damicornis*

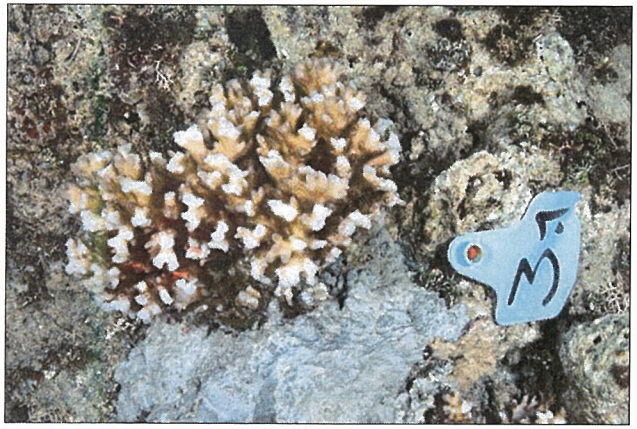


Photo B-31. *Pocillopora damicornis*

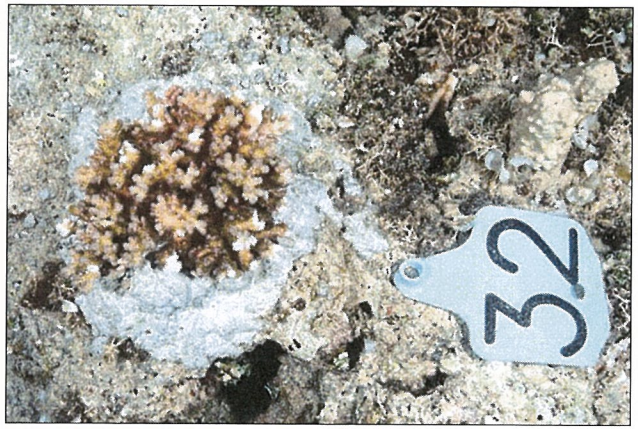


Photo B-32. *Pocillopora damicornis*



Photo B-33. *Porites lutea*



Photo B-34. *Porites lutea*



Photo B-35. *Favia favus*

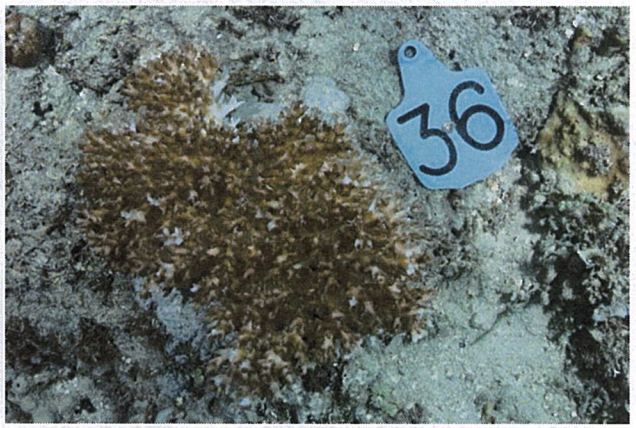


Photo B-36. *Pocillopora acuta*

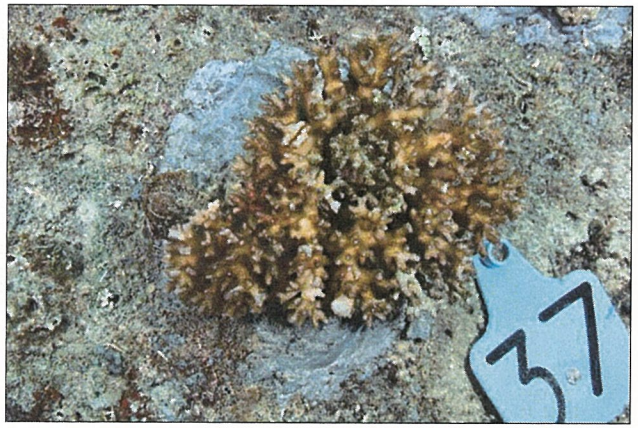


Photo B-37. *Pocillopora acuta*



Photo B-38. *Pocillopora damicornis*

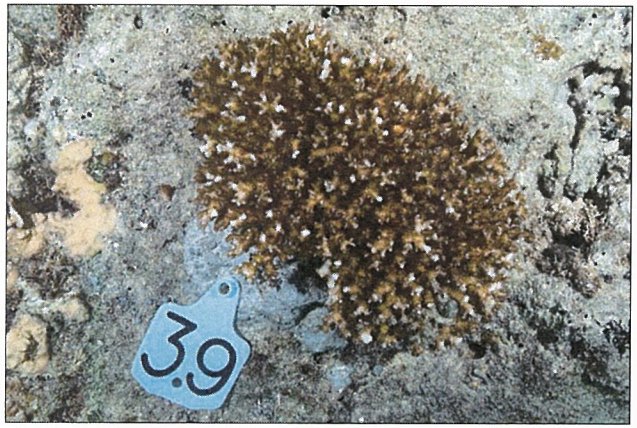


Photo B-39. *Pocillopora damicornis*



Photo B-40. *Pocillopora damicornis*

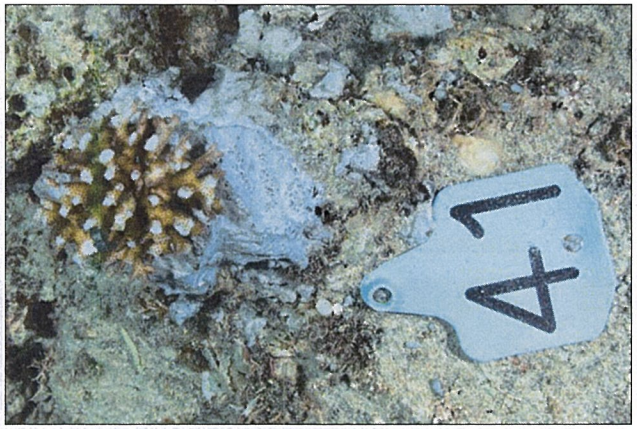


Photo B-41. *Pocillopora damicornis*



Photo B-42. *Pocillopora damicornis*

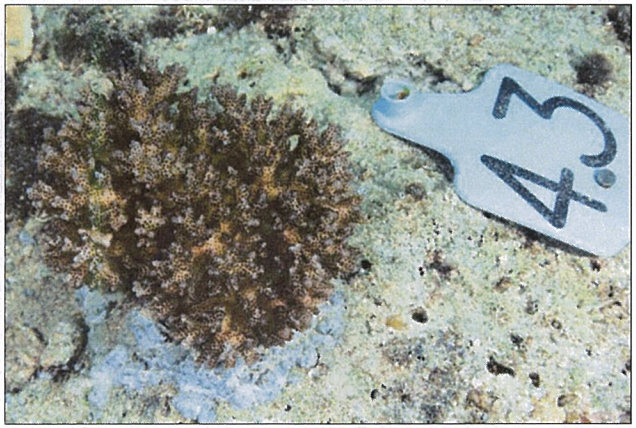


Photo B-43. *Pocillopora damicornis*

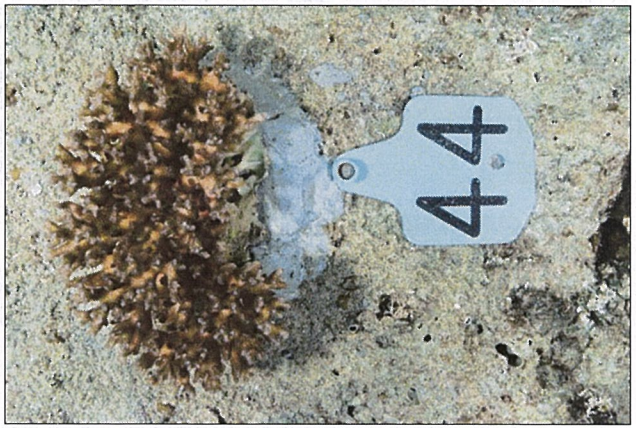


Photo B-44. *Pocillopora damicornis*

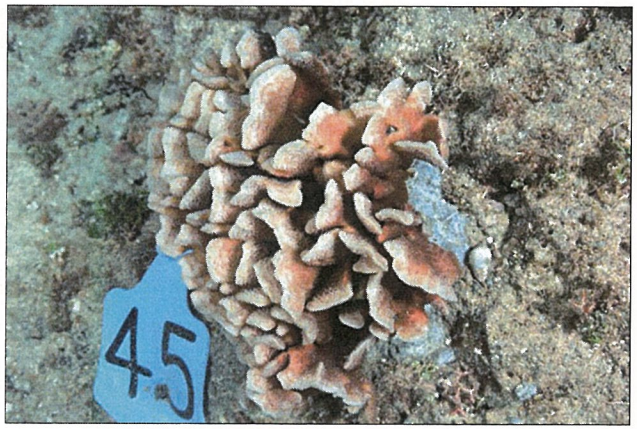


Photo B-45. *Pavona decussata*



Photo B-46. *Pavona decussata*



Photo B-47. *Pavona decussata*

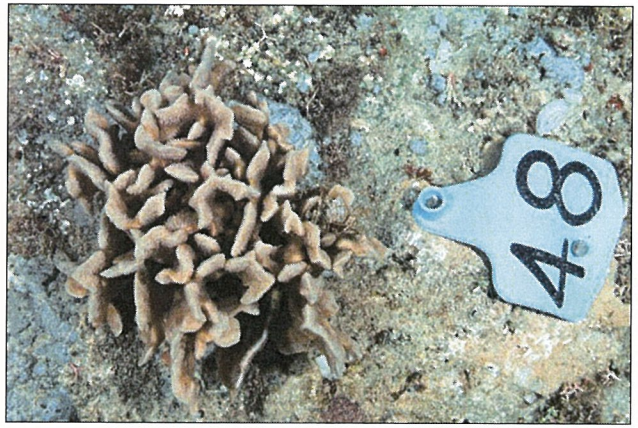


Photo B-48. *Pavona decussata*



Photo B-49. *Pavona decussata*



Photo B-50. *Porites lutea*

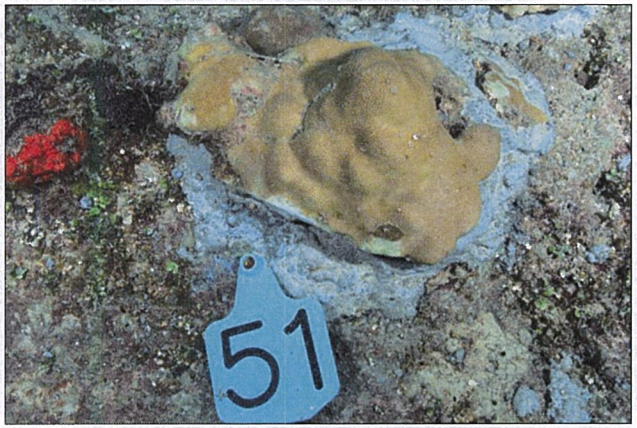


Photo B-51. *Porites solida*



Photo B-52. *Leptoseris incrustans*



Photo B-53. *Porites rus*



Photo B-54. *Favia matthaii*

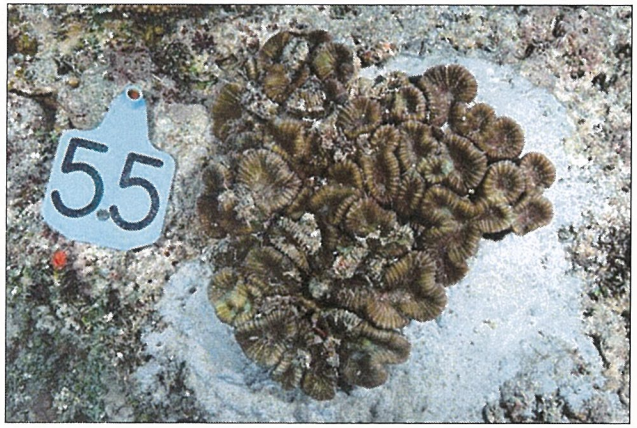


Photo B-55. *Lobophyllia hemprichii*

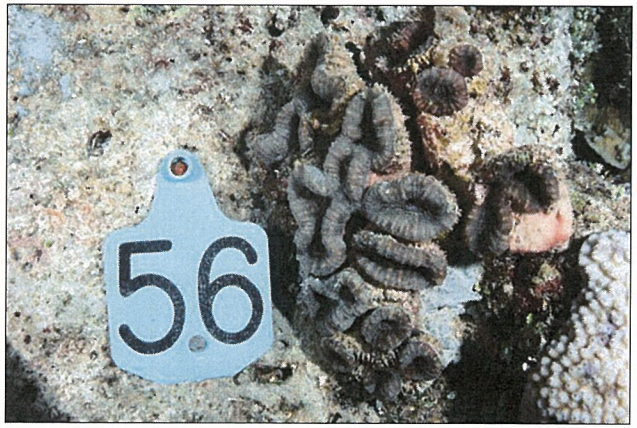


Photo B-56. *Lobophyllia hemprichii*

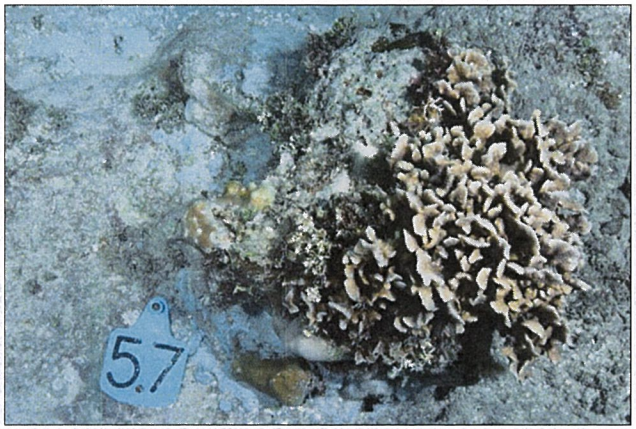


Photo B-57. *Pavona decussata*

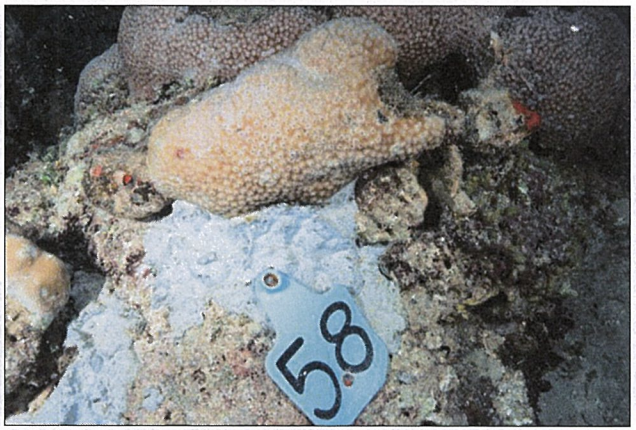


Photo B-58. *Astreopora cucullata*

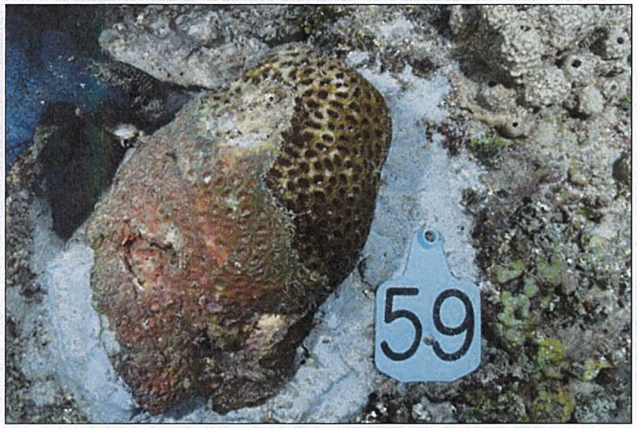


Photo B-59. *Favia matthaii*



Photo B-60. *Favia matthaii*



Photo B-61. *Astreopora cucullata*

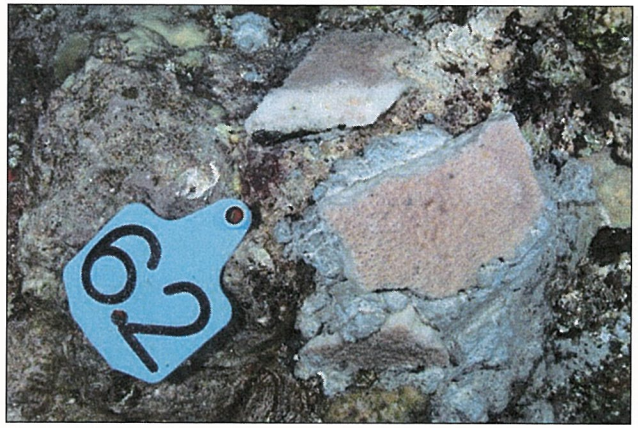


Photo B-62. *Astreopora listeri*

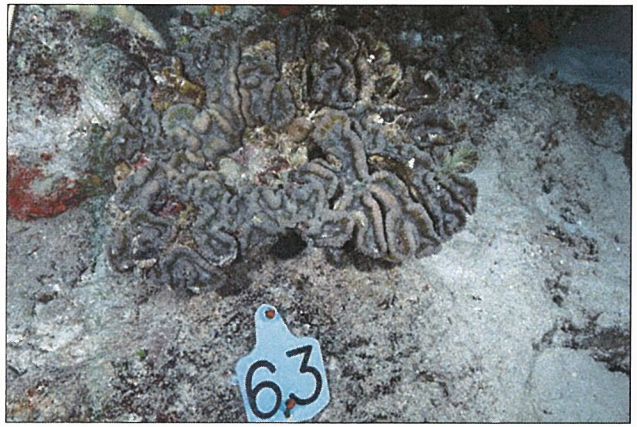


Photo B-63. *Lobophyllia hemprichii*



Photo B-64. *Lobophyllia hemprichii*

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Photo B-65. *Leptastrea* cf. *purpurea*

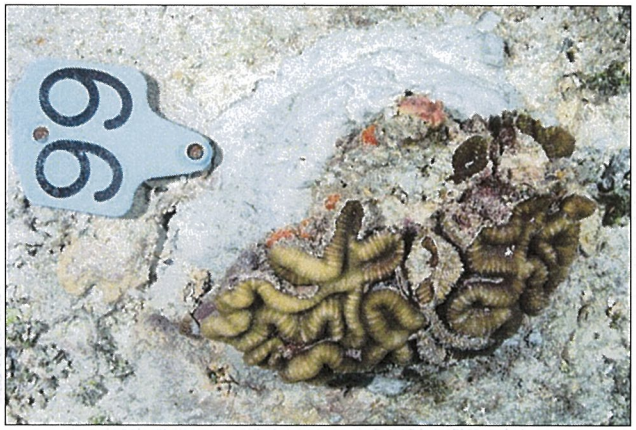


Photo B-66. *Lobophyllia hemprichii*



Photo B-67. *Porites horizontalata*

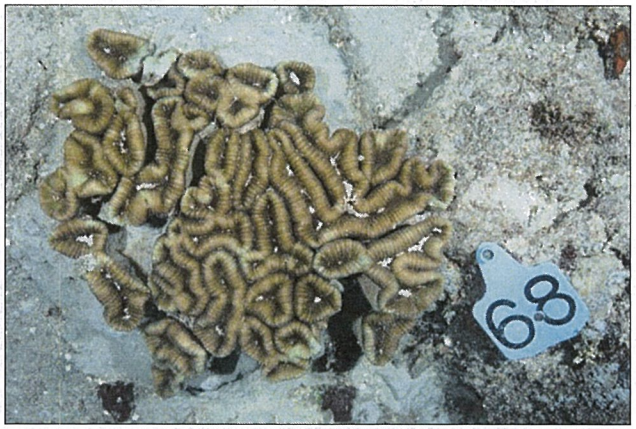


Photo B-68. *Lobophyllia hemprichii*



Photo B-69. *Favia matthaii*

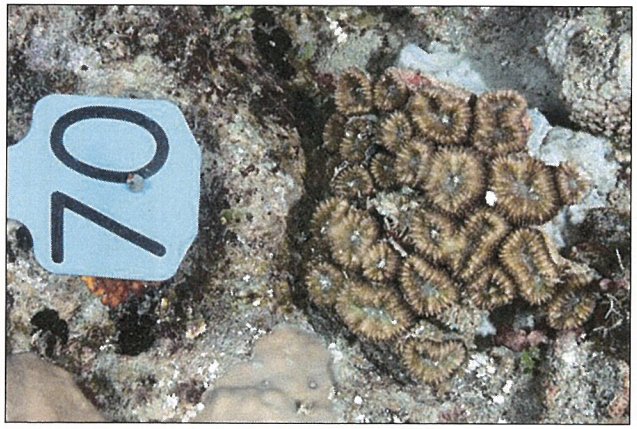


Photo B-70. *Lobophyllia corymbosa*

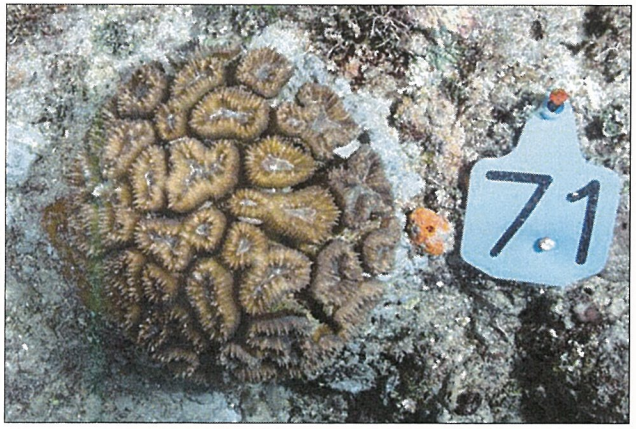


Photo B-71. *Lobophyllia hemprichii*

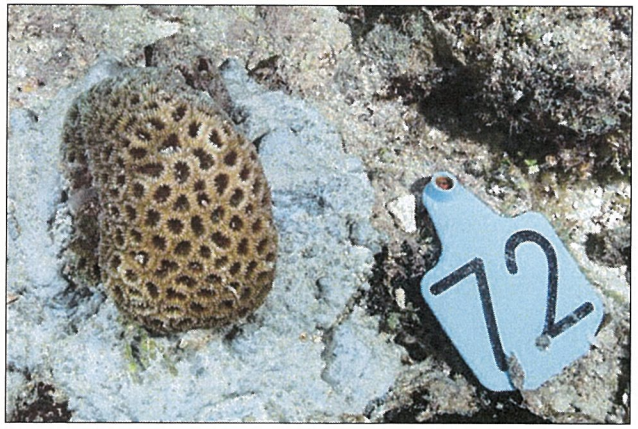


Photo B-72. *Favia matthaii*

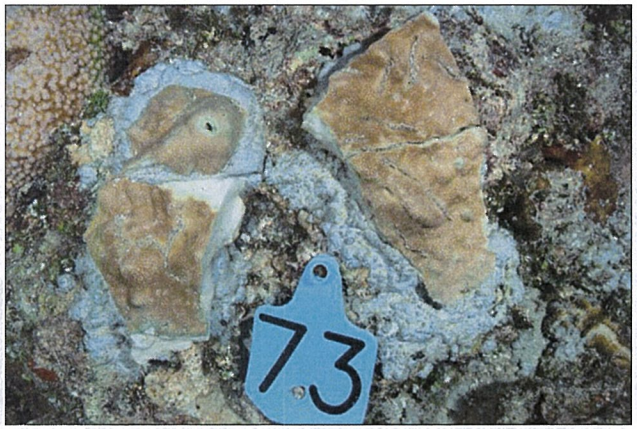


Photo B-73. *Porites ~lichen*



Photo B-74. *Herpolitha limax*

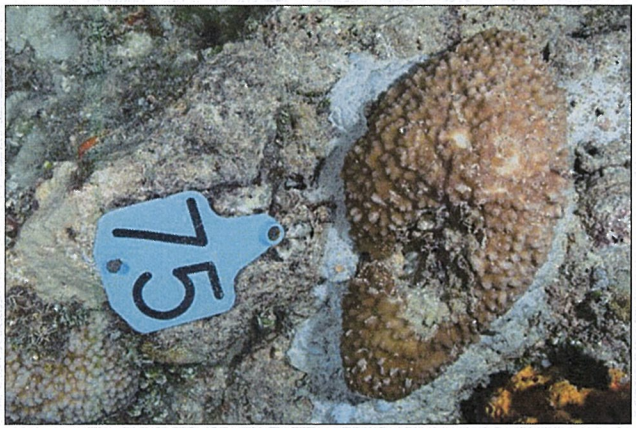


Photo B-75. *Astreopora gracilis*



Photo B-76. *Lobophyllia hemprichii*



Photo B-77. *Lobophyllia corymbosa*



Photo B-78. *Astreopora cucullata*



Photo B-79. *Lobophyllia hataii*



Photo B-80. *Lobophyllia corymbosa*



Photo B-81. *Porites lobata*

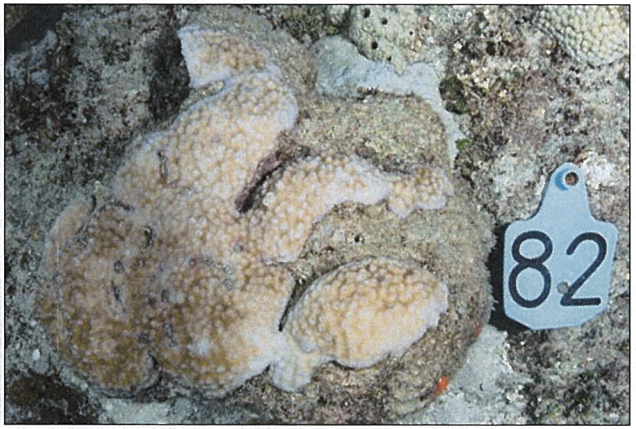


Photo B-82. *Astreopora gracilis*

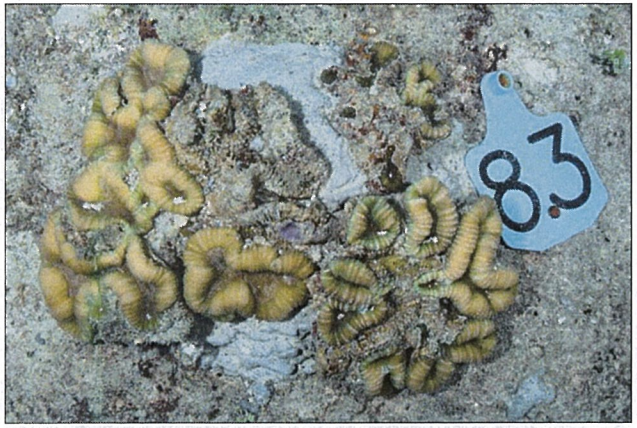


Photo B-83. *Lobophyllia hemprichii*

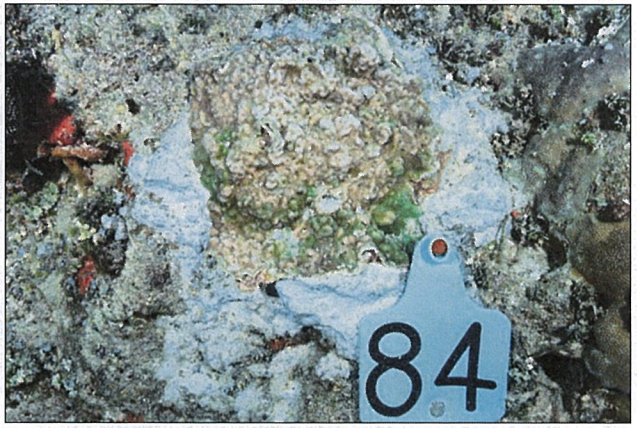


Photo B-84. *Leptoseris incrustans*

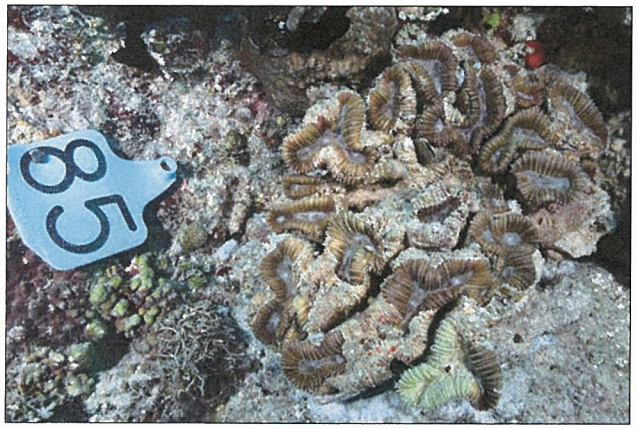


Photo B-85. *Lobophyllia hemprichii*



Photo B-86. *Astreopora myriophthalma*

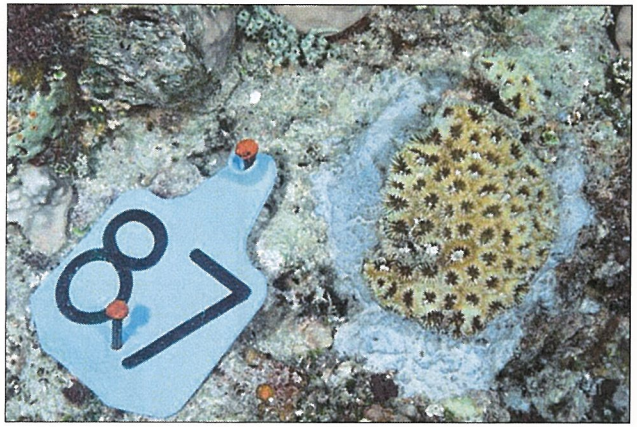


Photo B-87. *Favia matthaii*

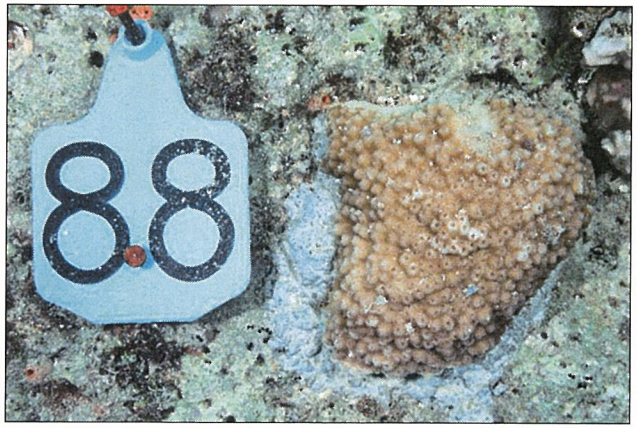


Photo B-88. *Astreopora cucullata*



Photo B-89. *Lobophyllia corymbosa*

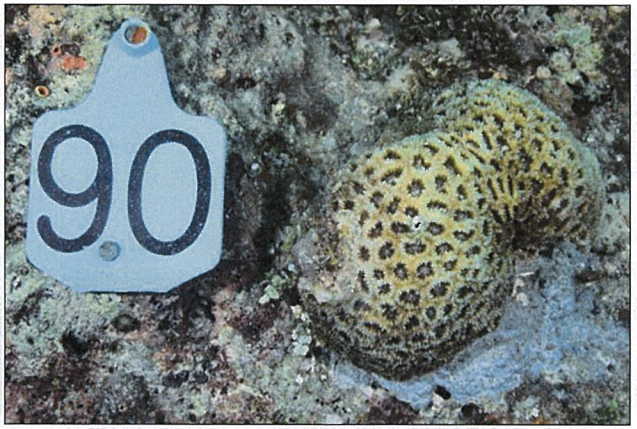


Photo B-90. *Favia matthaii*

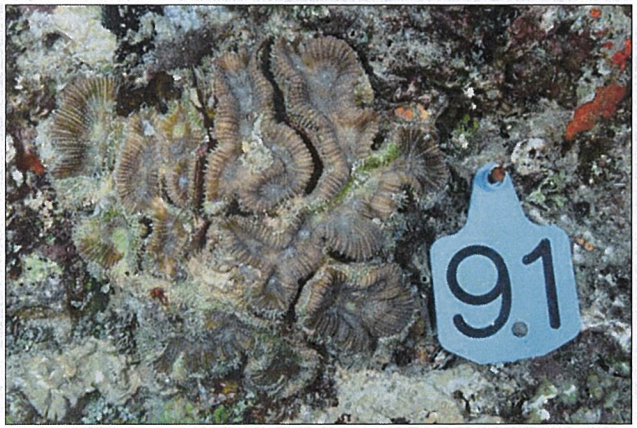


Photo B-91. *Lobophyllia hemprichii*

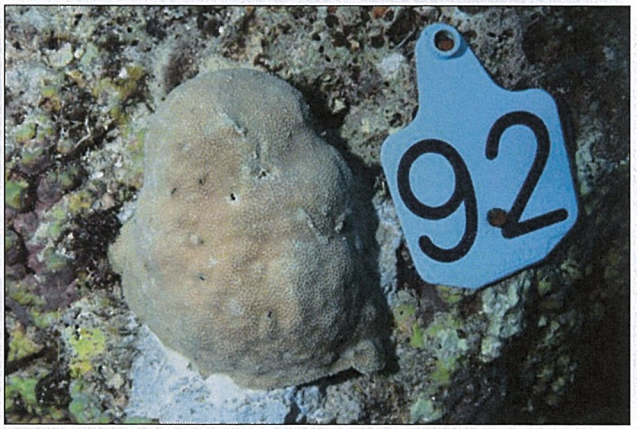


Photo B-92. *Porites lobata*



Photo B-93. *Cyphastrea chalcidicum*

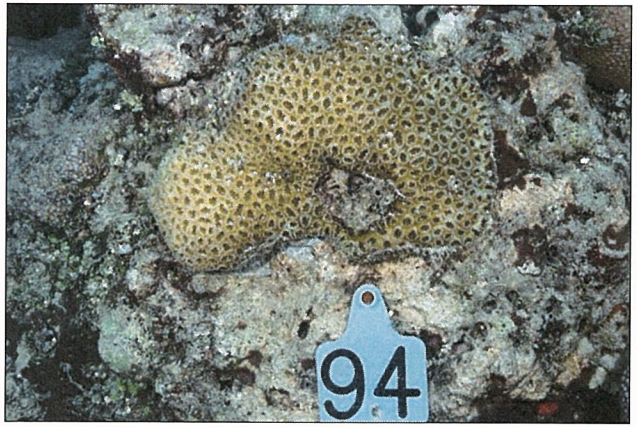


Photo B-94. *Favia matthaii*



Photo B-95 *Astreopora gracilis*

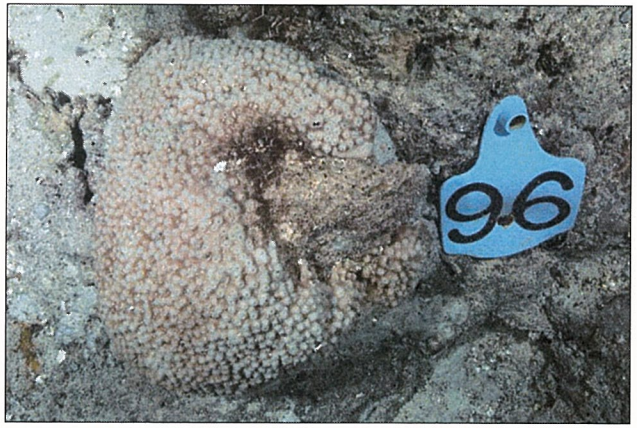


Photo B-96 *Astreopora cucullata*



Photo B-97. *Astreopora cucullata*



Photo B-98. *Lobophyllia hemprichii*

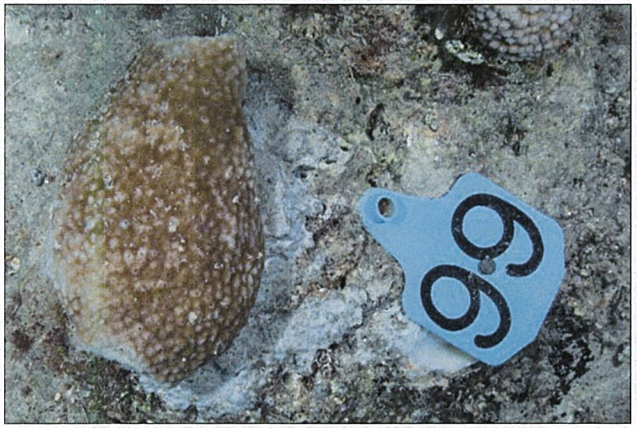


Photo B-99. *Astreopora cucullata*

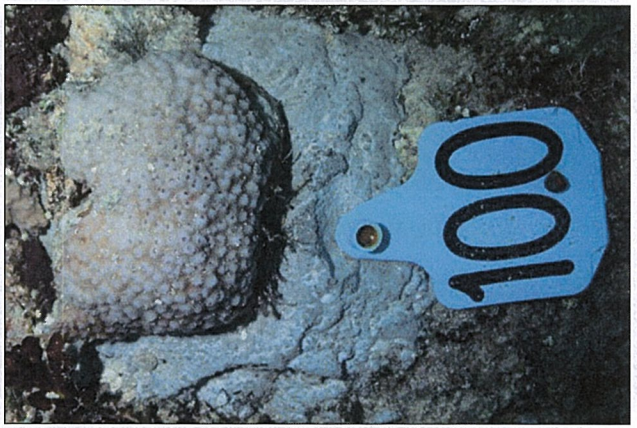


Photo B-100. *Astreopora cucullata*



Photo B-101. *Phymastrea valenciennesi*



Photo B-102. *Lobophyllia hataii*



Photo B-103. *Astreopora elliptica*

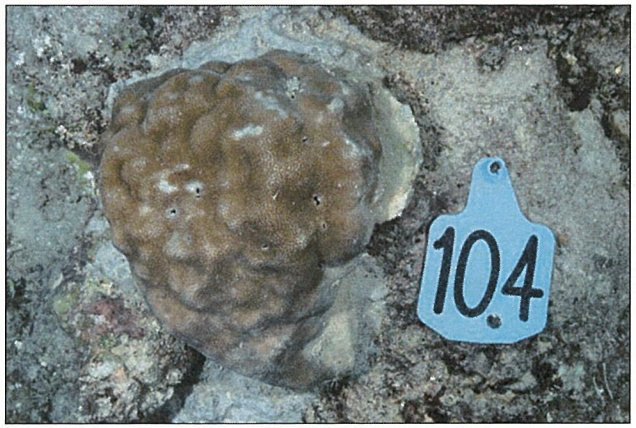


Photo B-104. *Porites lobata*

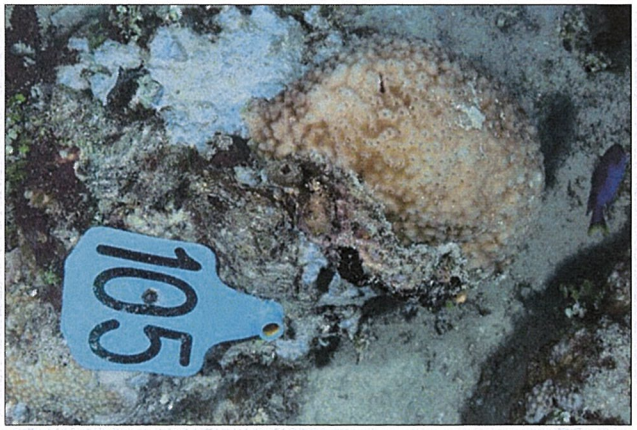


Photo B-105. *Astreopora cucullata*



Photo B-106. *Astreopora gracilis*



Photo B-107. *Astreopora elliptica*



Photo B-108. *Astreopora gracilis*

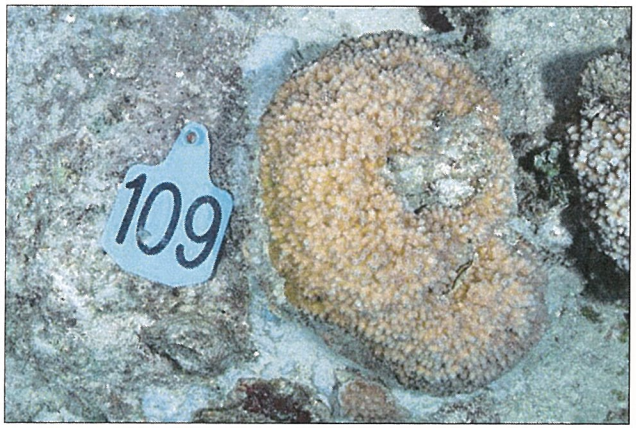


Photo B-109. *Astreopora gracilis*

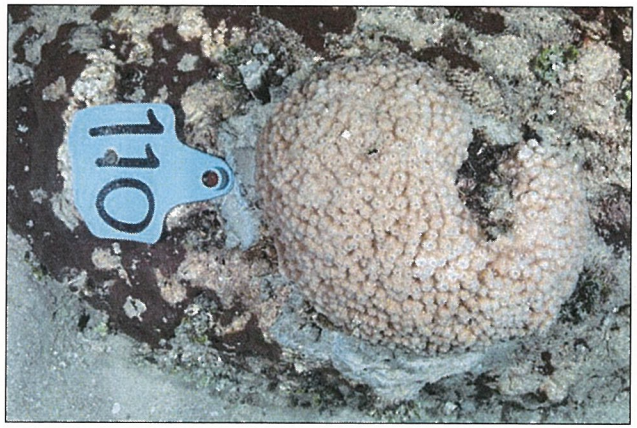


Photo B-110. *Astreopora cucullata*

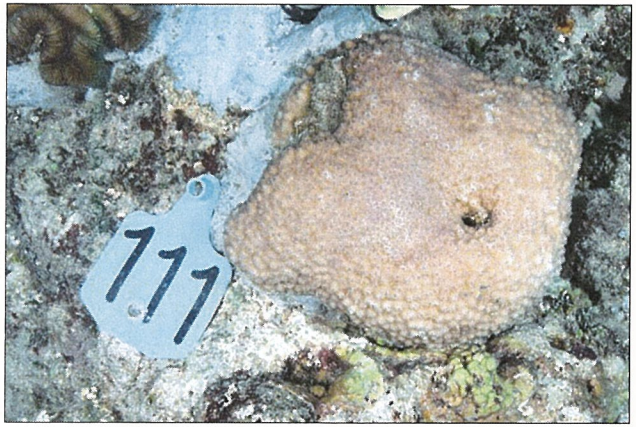


Photo B-111. *Astreopora cucullata*

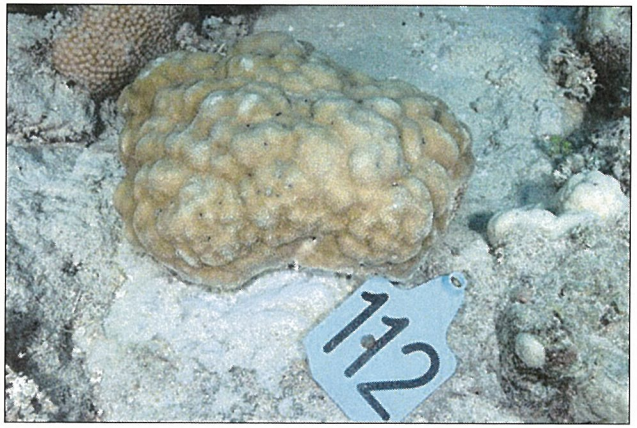


Photo B-112. *Porites lobata*



Photo B-113. *Lobophyllia corymbosa*

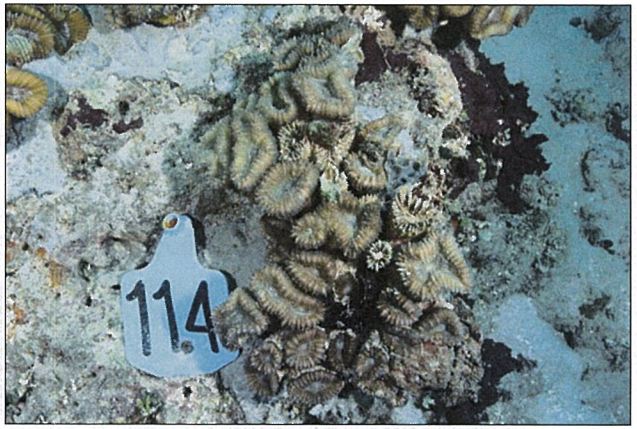


Photo B-114. *Lobophyllia corymbosa*



Photo B-115. *Lobophyllia corymbosa*



Photo B-116. *Porites horizontalata*

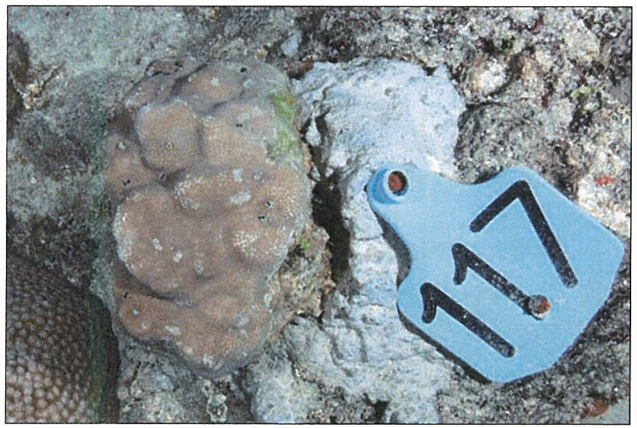


Photo B-117. *Porites lobata*

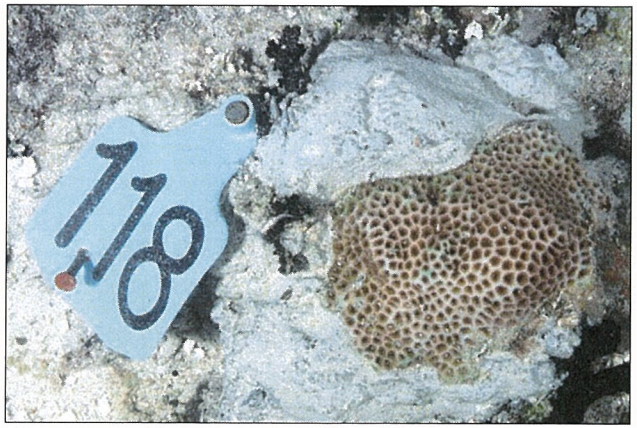


Photo B-118. *Leptastrea purpurea*



Photo B-119. *Porites lobata*

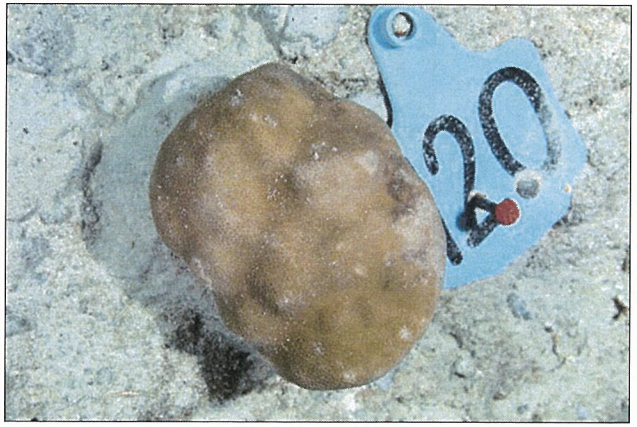


Photo B-120. *Porites lobata*



Photo B-121. *Lobophyllia hataii*

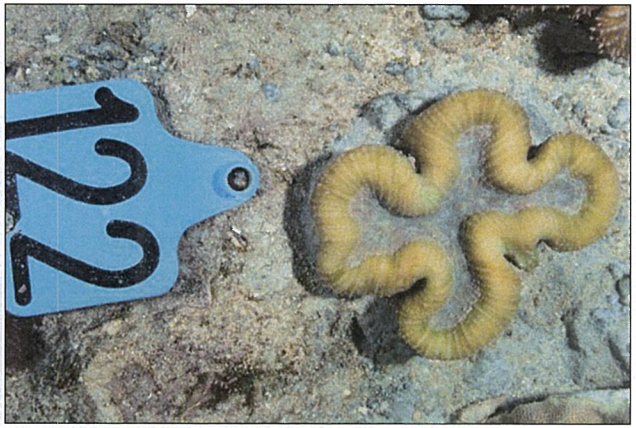


Photo B-122. *Lobophyllia hataii*



Photo B123. *Porites* aff. *lichen*



Photo B-124. *Porites rus*



Photo B-125. *Psammocora profundicella*



Photo B-126. *Leptastrea purpurea*

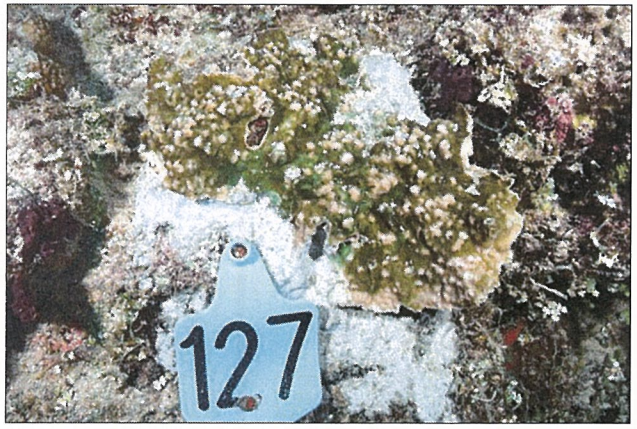


Photo B-127. Leptoseris incrustans



Photo B-128. Lobophyllia hataii



Photo B-129. *Lobophyllia hataii*

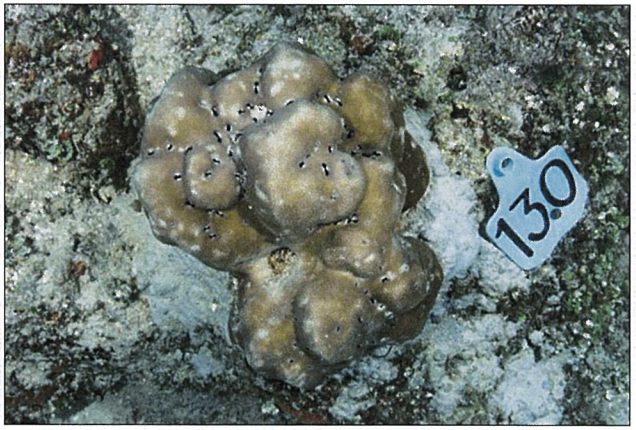


Photo B-130. *Porites lobata*

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Appendix C

Photographs of Tagged Reference Corals

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Photo C-200. *Pocillopora damicornis*



Photo C-201. *Pocillopora damicornis*



Photo C-202. *Pocillopora damicornis*



Photo C-203. *Pocillopora damicornis*



Photo C-204. *Pocillopora damicornis*

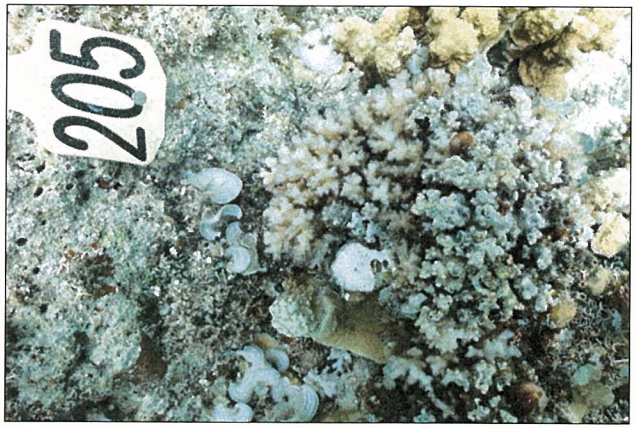


Photo C-205. *Pocillopora damicornis*

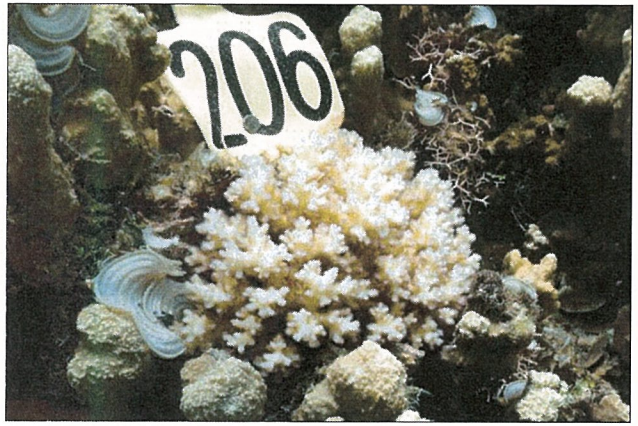


Photo C-206. *Pocillopora damicornis*



Photo C-207. *Pocillopora damicornis*



Photo C-208. *Pocillopora damicornis*



Photo C-209. *Pocillopora damicornis*



Photo C-210. *Pocillopora damicornis*



Photo C-211. *Pocillopora damicornis*

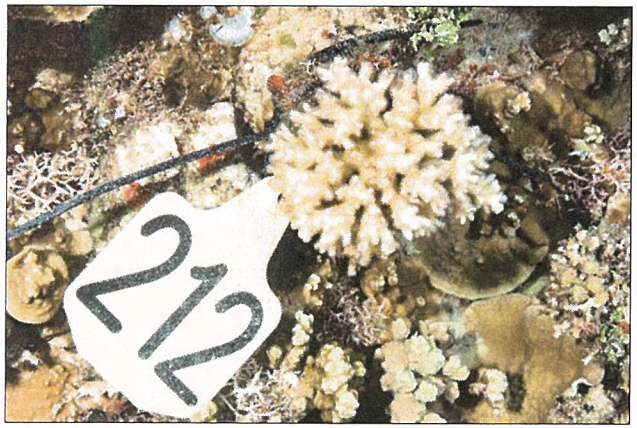


Photo C-212. *Pocillopora damicornis*

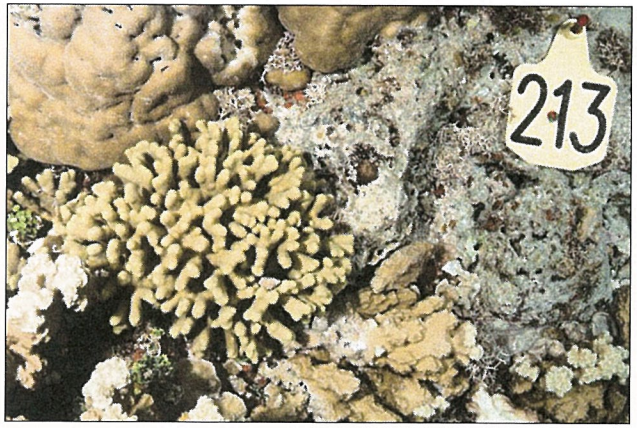


Photo C-213. *Porites cylindrica*



Photo C-214. *Porites cylindrica*

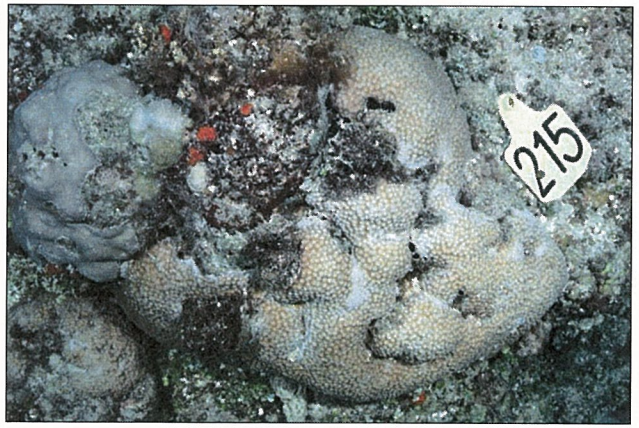


Photo C-215. *Astreopora cucullata*

Doc. No. 35GL-20-2139.*

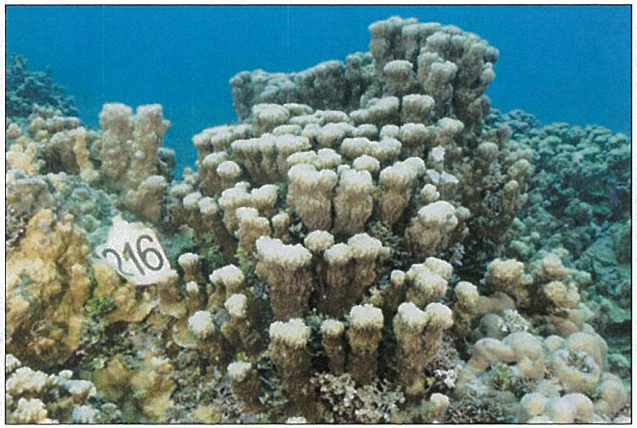


Photo C-216. *Porites monticulosa*

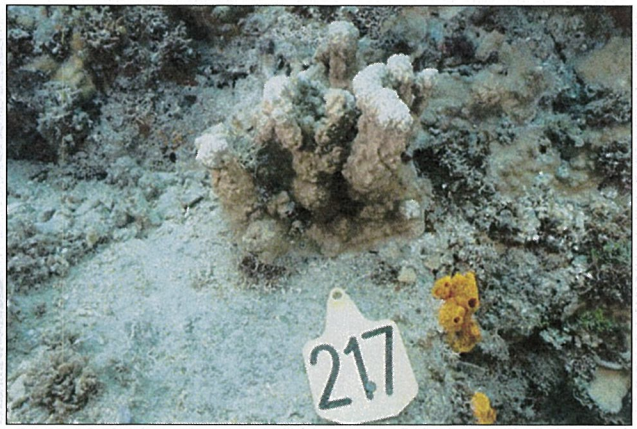


Photo C-217. *Porites monticulosa*



Photo C-218. *Porites rus*



Photo C-219. *Porites rus*



Photo C-220. *Psammocora neirstrazi*

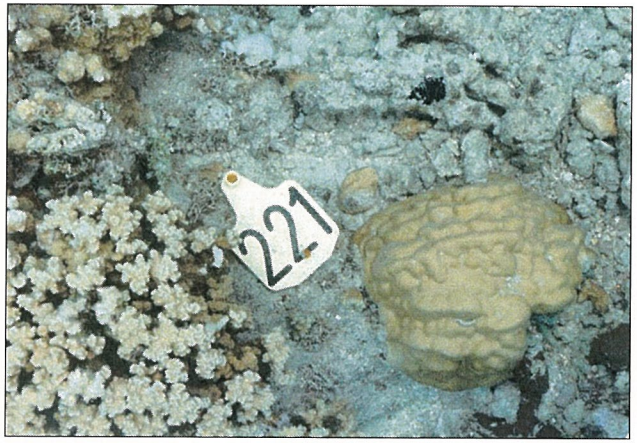


Photo C-221. *Porites lutea*

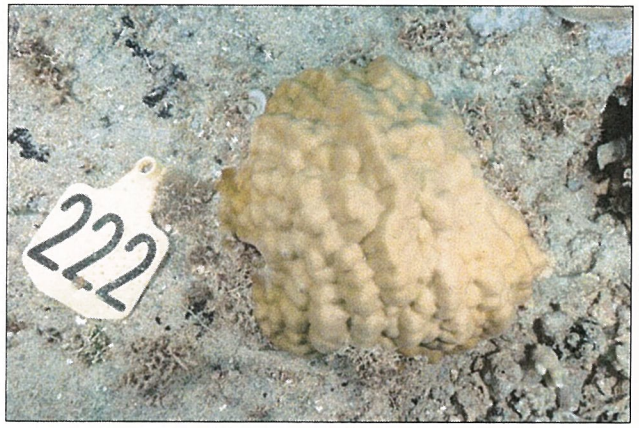


Photo C-222. *Porites lutea*



Photo C-223. *Porites lutea*



Photo C-224. *Porites lutea*



Photo C-225. *Porites lutea*

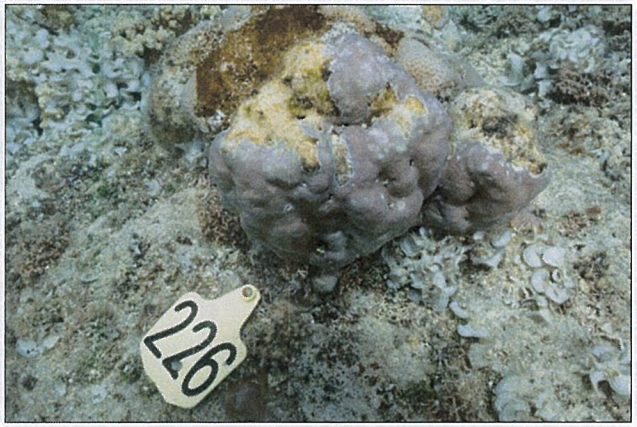


Photo C-226. *Porites murrayensis*



Photo C-227. *Porites murrayensis*



Photo C-228. *Porites solida*



Photo C-229. *Porites solida*

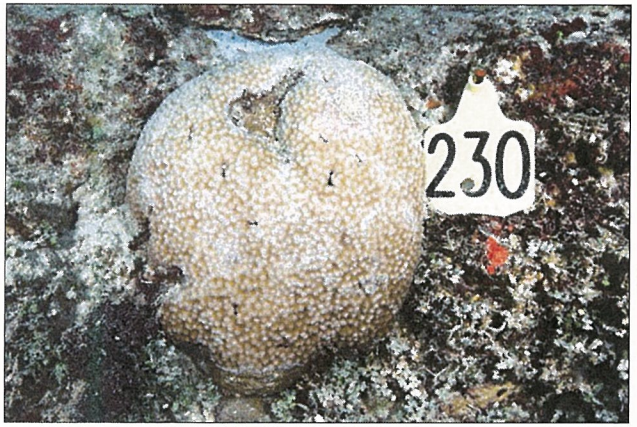


Photo C-230. *Astreopora cucullata*



Photo C-231. *Astreopora gracilis*

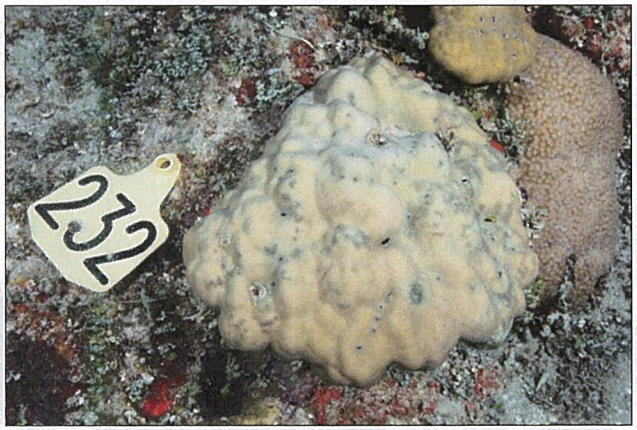


Photo C-232. *Porites lutea*



Photo C-233. Leptastrea purpurea



Photo C-234. *Astreopora gracilis*



Photo C-235. *Astreopora cucullata*



Photo C-236. *Astreopora cucullata*

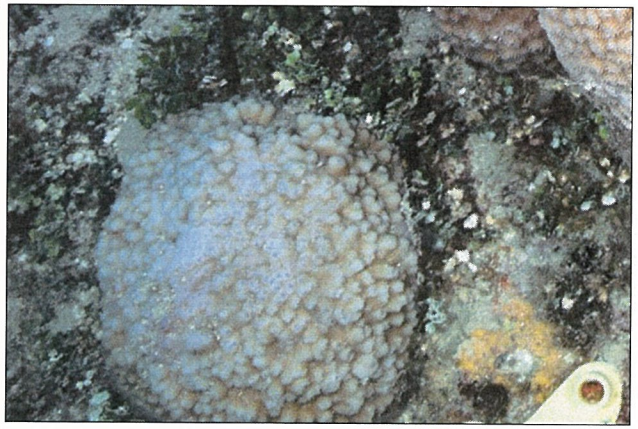


Photo C-237. *Astreopora gracilis*

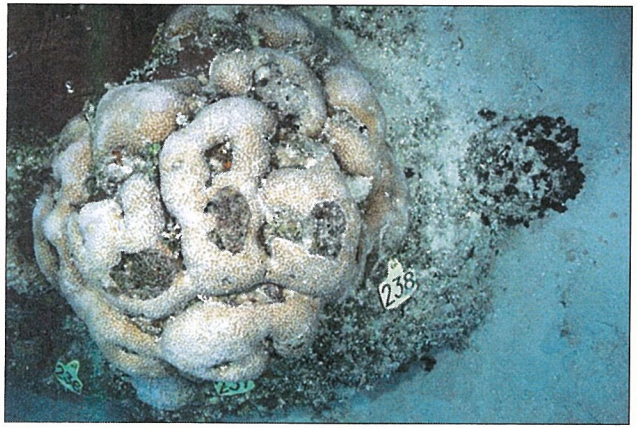


Photo C-238. *Astreopora myriophthalma*

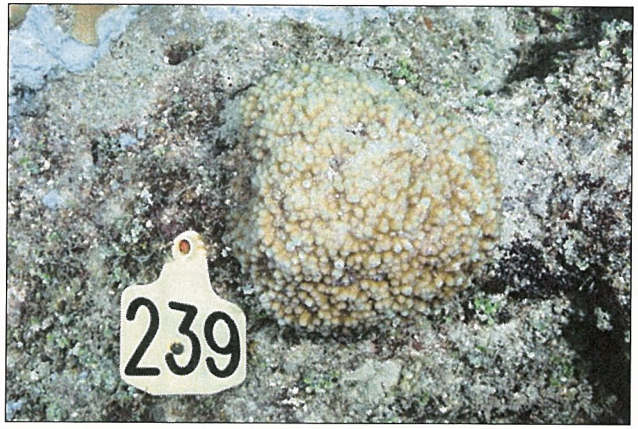


Photo C-239. *Astreopora gracilis*



Photo C-240. *Porites rus*



Photo C-241. *Astreopora cucullata*



Photo C-242. *Porites horizontalata*



Photo C-243. *Porites lutea*

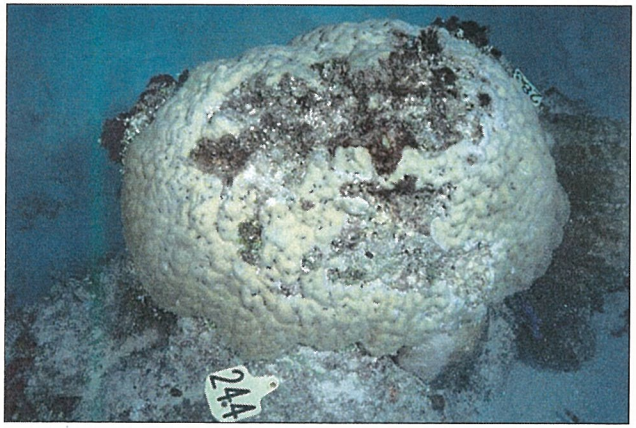


Photo C-244. *Porites lobata*



Photo C-245. *Leptoseris incrustans*



Photo C-246. *Astreopora cucullata*

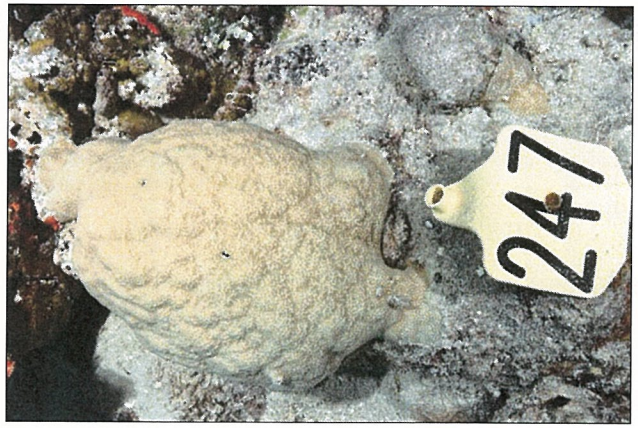


Photo C-247. *Porites* aff. *lichen*



Photo C-248. *Porites* aff. *lichen*



Photo C-249. *Porites horizontalata*



Photo C-250. *Psammocora profundicella*



Photo C-251. *Phymastrea valenciennesi*



Photo C-252. *Astreopora cucullata*

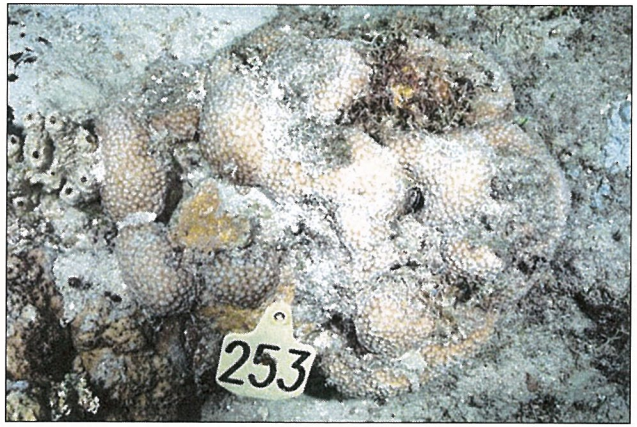


Photo C-253. *Astreopora cucullata*

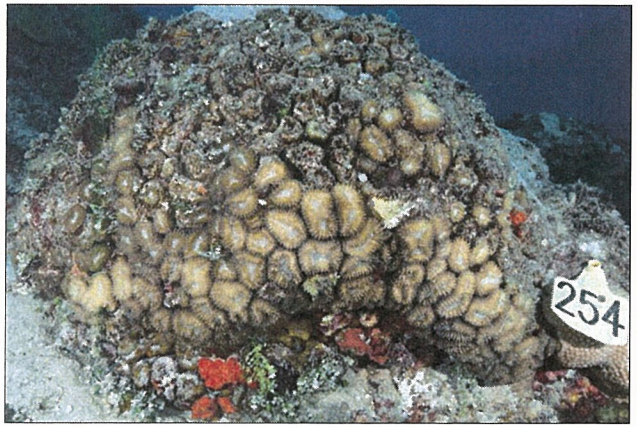


Photo C-254. *Lobophyllia corymbosa*

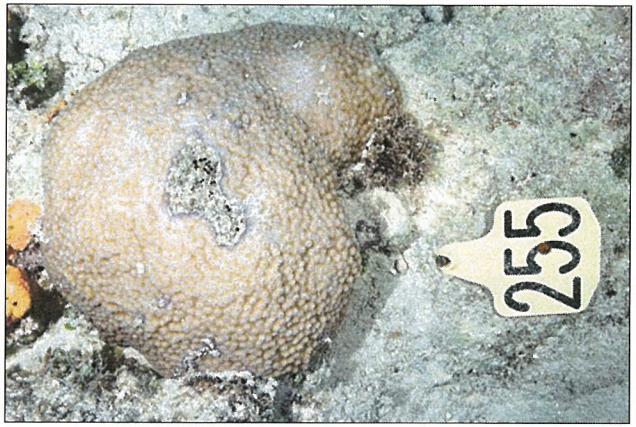


Photo C-255. *Astreopora cucullata*

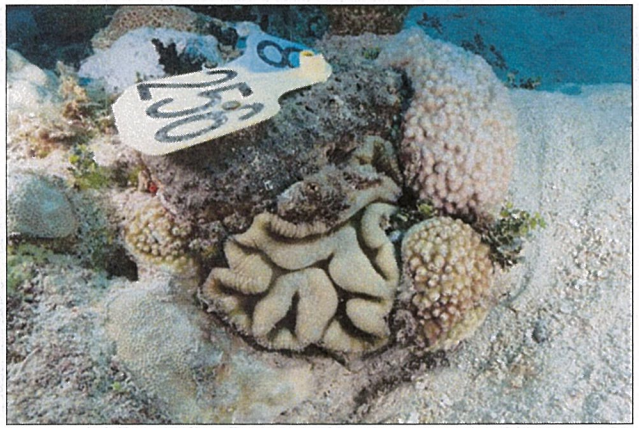


Photo C-256. *Lobophyllia hemprichii*



Photo C-257. *Lobophyllia hemprichii*



Photo C-258. *Lobophyllia corymbosa*



Photo C-259. *Leptastrea transversa*

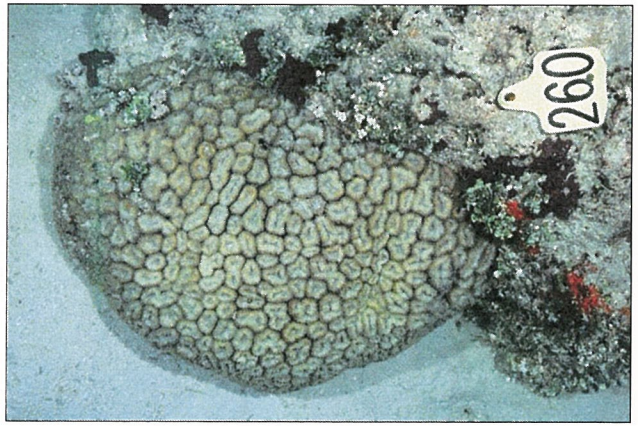


Photo C-260. *Lobophyllia corymbosa*



Photo C-261. *Herpolitha limax*



Photo C-262. *Favia favus*



Photo C-263. *Porites lutea*



Photo C-264. *Porites lobata*



Photo C-265. *Porites lobata*



Photo C-266. *Porites lutea*



Photo C-267. *Porites lobata*

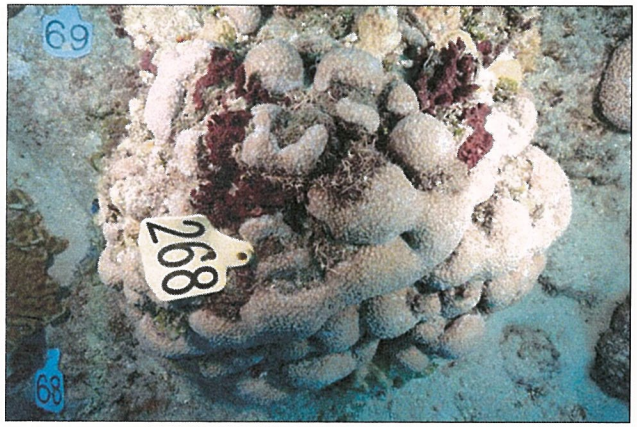


Photo C-268. *Astreopora listeri*

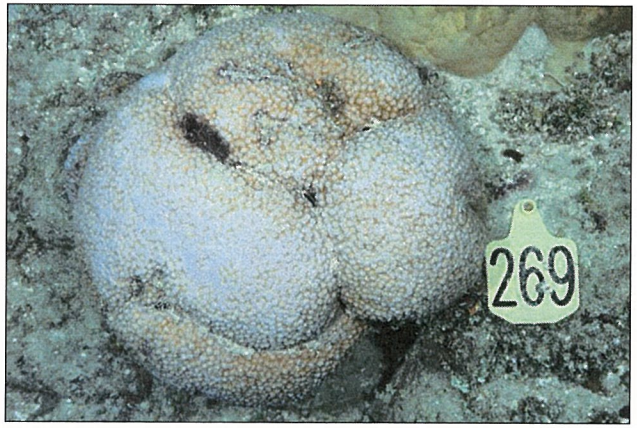


Photo C-269. *Astreopora cucullata*



Photo C-270. *Porites solida*

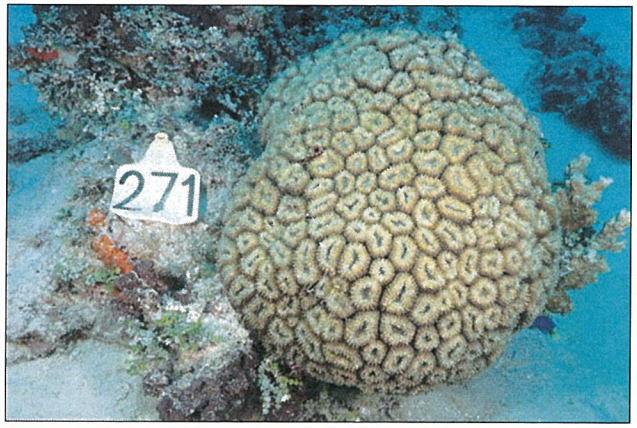


Photo C-271. *Lobophyllia corymbosa*

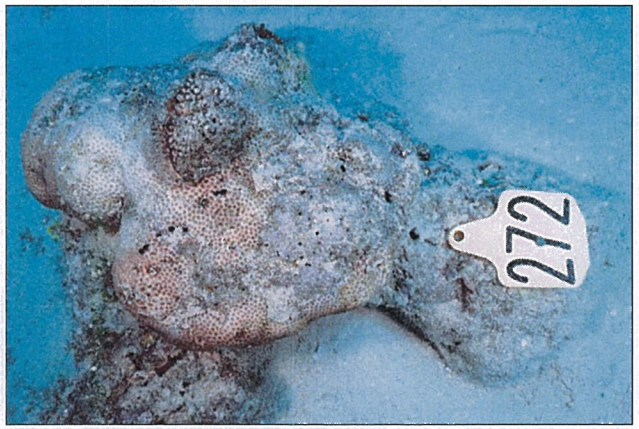


Photo C-272. *Leptastrea purpurea*

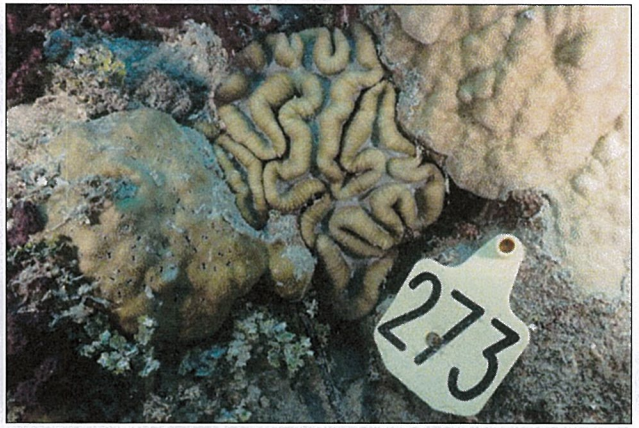


Photo C-273. *Lobophyllia hemprichii*

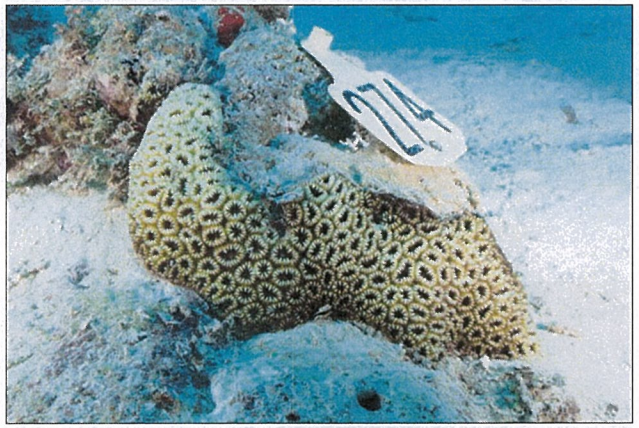


Photo C-274. *Favia favus*



Photo C-275. *Favia matthaii*

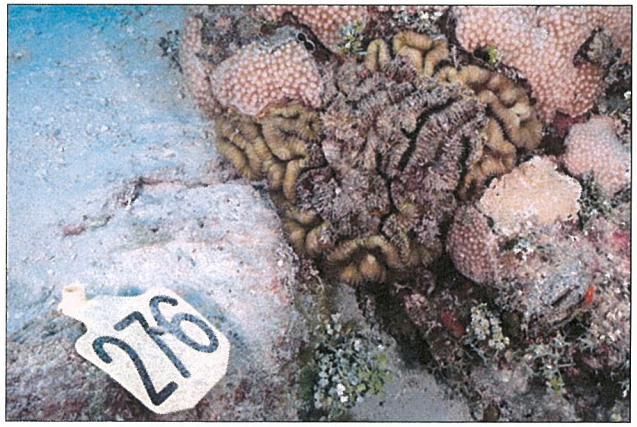


Photo C-276. *Lobophyllia hemprichii*

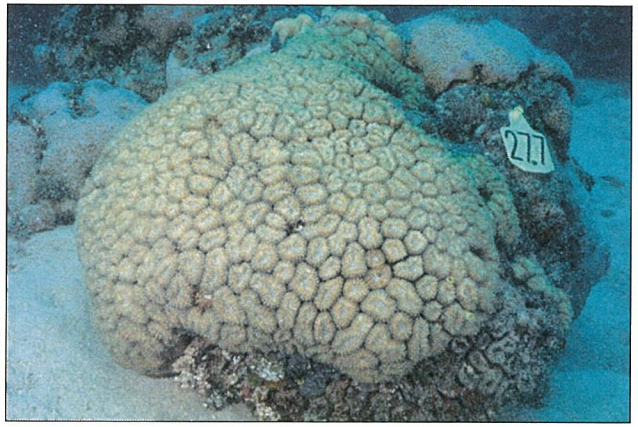


Photo C-277. *Lobophyllia corymbosa*



Photo C-278. *Astreopora gracilis*



Photo C-279. *Lobophyllia hemprichii*



Photo C-280. *Astreopora cucullata*

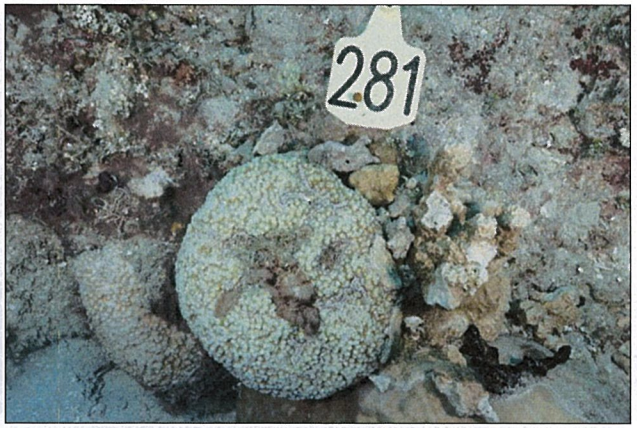


Photo C-281. *Astreopora gracilis*



Photo C-282. *Favia* cf. *matthaii*

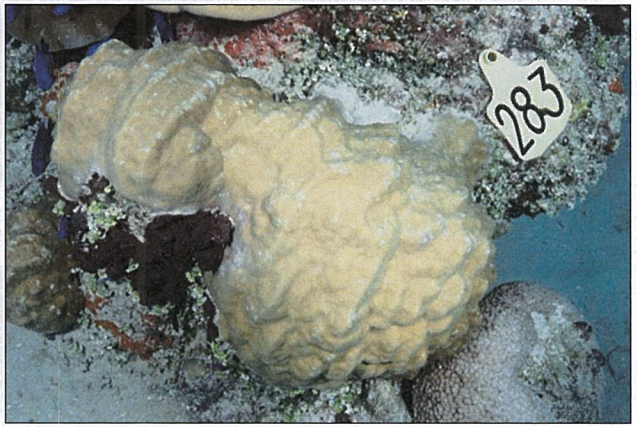


Photo C-283. *Porites lobata*

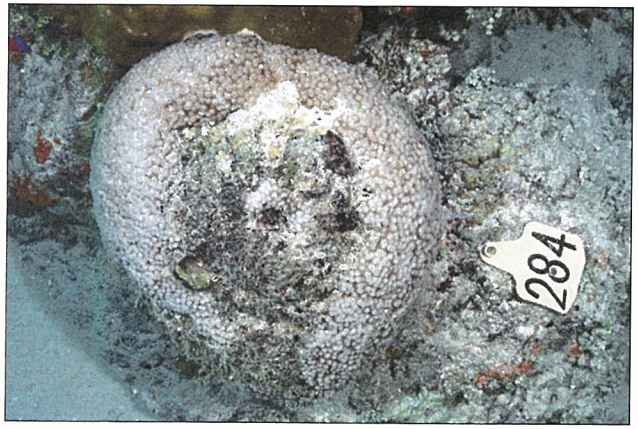


Photo C-284. *Astreopora cucullata*



Photo C-285. *Astreopora gracilis*



Photo C-286. *Astreopora cucullata*

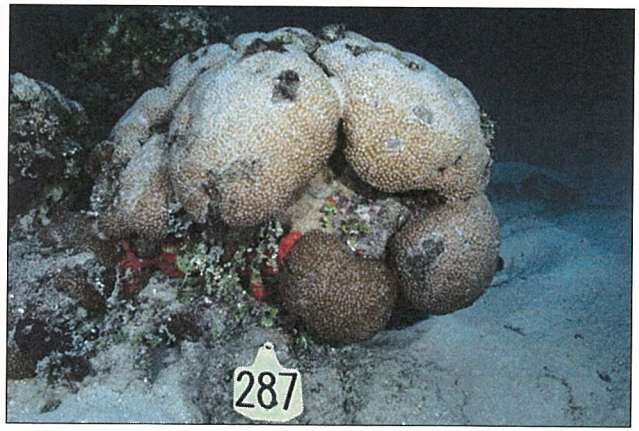


Photo C-287. *Astreopora cucullata*



Photo C-288. *Porites lobata*



Photo C-289. *Astreopora cucullata*

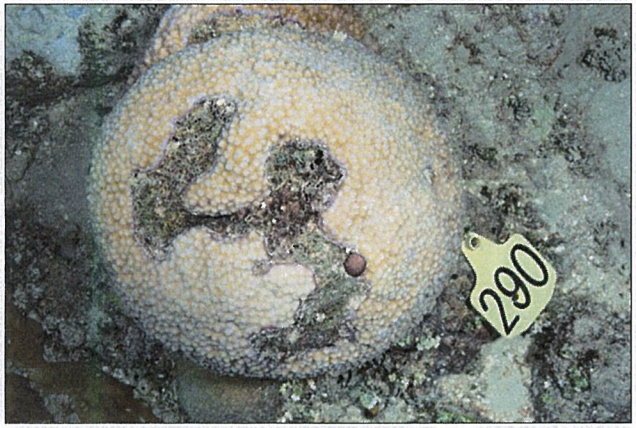


Photo C-290. *Astreopora cucullata*

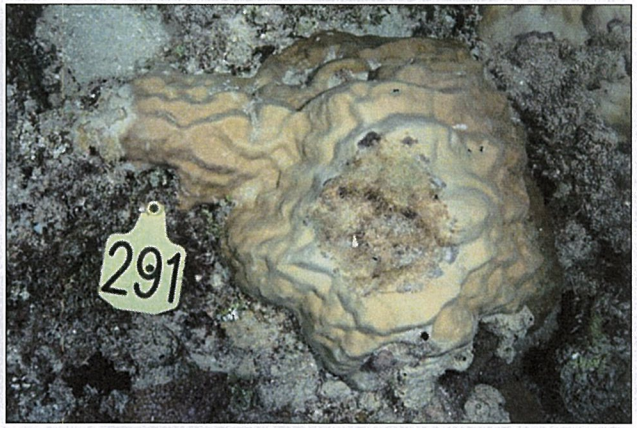


Photo C-291. *Porites lutea*

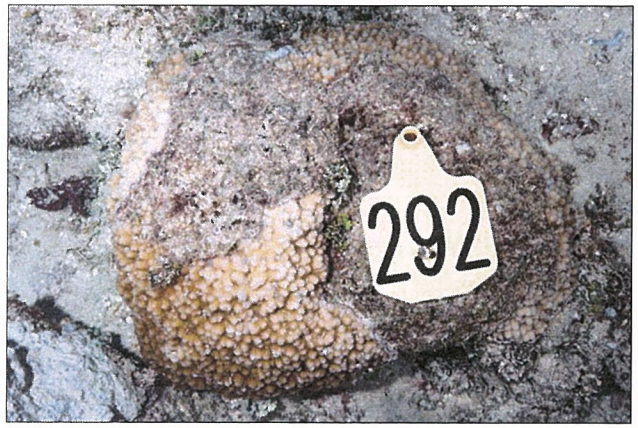


Photo C-292. *Astreopora gracilis*



Photo C-293. *Astreopora cucullata*

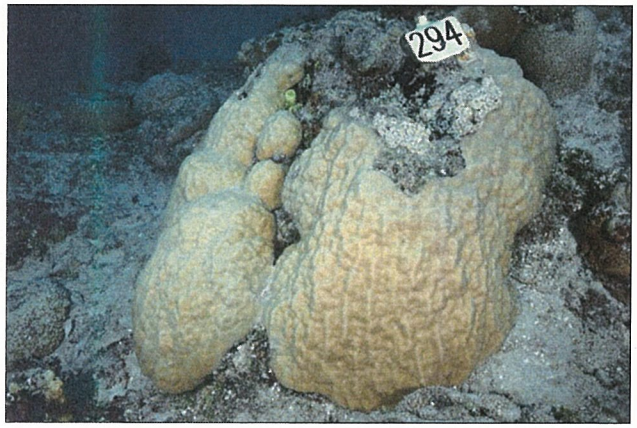


Photo C-294. *Porites lutea*



Photo C-295. *Porites lobata*



Photo C-296. *Astreopora cucullata*

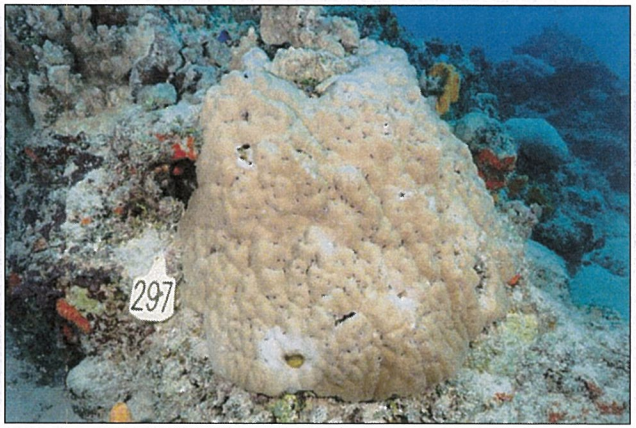


Photo C-297. *Porites lobata*

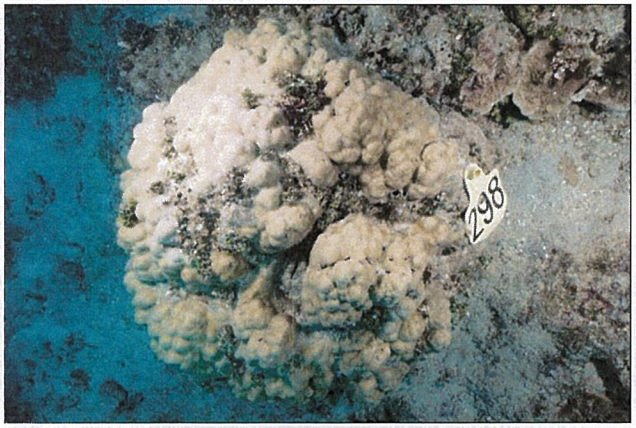


Photo C-298. *Porites lobata*



Photo C-299. *Porites lutea*

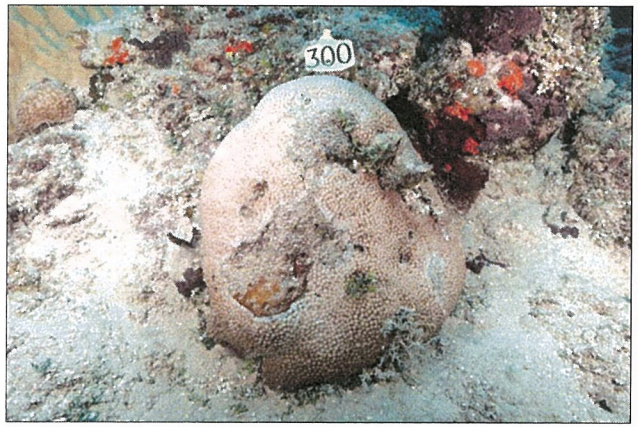


Photo C-300. *Astreopora cucullata*

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Lt. Governor

Chelsa Muña-Brecht
Director
Adrian Cruz
Deputy Director

SPECIAL PERMIT FOR SCIENTIFIC CORAL RELOCATION

LICENSE NO.: SC-20-003 **DATE REQUESTED:** 2/24/2020 **EXPIRATION DATE:** 06/30/2020

In accordance with Section 63207 of Title 5, Guam Code Annotated (GCA) relative to a special license to take fish for scientific purposes, permission is hereby granted to:

LICENSEE: Port of Guam (PAG) ADDRESS: 1026 Cabras Highway, Suite 201, Piti Guam 96925

REPRESENTATIVE: Keith Spring, Continental Shelf Associates (CSA)

WORK: 477-7991 RESIDENCE:

TO COLLECT THE FOLLOWING:
NOTE: License must be made available to Department staff upon request

CONDITIONS:

Pieces	Species (*Scientific Name*)	Relocation	Scientific
900	*Astreopora* spp., *Favia* spp., *Lobophyllia* spp., *Pavona* spp., *Pocillopora* spp., *Porites* spp., *Psammocora* spp.	From Hotel Wharf to Dog Leg Pier	XXX
**********	********** LAST ENTRY **********	**********	**********

- Permit for relocation expires on June 30, 2020.
- The corals are to be relocated using the methodology from the Coral Relocation Permit Application and Hotel Wharf Final Compensatory Mitigation Plan.
- For all coral species with 50 or more individuals relocated, 20% of the individuals will be monitored.
- For all coral species with more than 10 individuals but less than 50 individuals relocated, 10% of the individuals will be monitored.
- For all coral species with less than 10 individuals relocated, 100% of the individuals will be monitored.
- Permit activity is limited to PAG and CSA Ocean Sciences Inc.
- Officials from the Department shall be allowed at any time to visit research sites to ensure compliance with permissible activities under this permit.
- A copy of this permit must be carried at all times while conducting the permitted activity. The permit shall be produced for inspection if requested by an employee of DAWR or a DAWR conservation officer.
- Coral monitoring will be conducted at 6 months post-relocation, 18 months post-relocation, and 36 months post-relocation and within 3 weeks submit a brief report to DOAG DAWR to document if performance criteria have or have not been met. The coral relocation will be considered a success if 75% of the corals survive to 6 months, and 65% survive to 18 months and successfully remain affixed to the substrate. If standards are not met then contingency mitigation will be negotiated with regulatory agencies.
- The signatory takes full responsibility for administering the conditions and responsibility for administering the conditions and responsibilities set forth in this permit. Permit must be in possession of applicant while conducting the permitted activities.
- This permit is revocable at any time upon failure of the permittee to comply with any of the permissible activities or conditions listed above.
- This permit does not exempt the permittee from complying with other federal or local restrictions.

I have read and understand the above conditions and agree to abide by them. I understand that this license is revocable and that failure to abide by this license and its conditions will result in revocation. I further understand that violation of this license and its conditions is a misdemeanor and will subject me to penalty in accordance with 5 GCA Sections 63207.

LICENSEE:
Rory J. Respicio
General Manager Port Authority of Guam
Duenas, Camacho, and Associates Inc.
Date: 3/4/2020

Keith Spring
~~Continental Shelf Associates~~ CSA Ocean Sciences Inc
Date: 3/16/20

APPPROVED BY:
Chelsa Muna-Brecht
Director
Department of Agriculture
Date Issued: 03.03.2020

3/3/20
CSA 3/3/20

CORAL REEFS 2020

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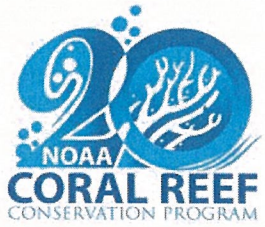
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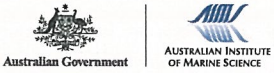






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EDITOR'S WELCOME



A Tale of Two Cities

By Kira Coley, Senior Editor

Each year, thousands of us flock to the bright lights of the city, lured by a thriving community and all the benefits urban life offers. According to a 2018 United Nations report[1], 68 percent of the world's population will be living in metropolitan areas by 2050, and megacities – those with more than 10 million inhabitants – could become increasingly common in developing countries.

While land-based cities are predicted to flourish and expand, our ocean counterparts wither and wane. Coral reefs are facing rising pressures from both natural and anthropogenic stressors. And while these ocean cities are home to more than 25 percent of all known marine fish species, over 80 percent of shallow reefs are severely overfished[2], 25 – 50 percent have already been destroyed, and around 60 percent are under threat[3].

But this is more than a tale of two cities.

What happens below the waves also impacts those living above. According to the United Nations Environment Programme, more than 850 million people live within 100 kilometers of coral reefs, with the majority directly and indirectly benefiting from the food, income, and coastal protection they provide. And then there is the tourism industry to consider. "Every year, two million people visit the Great Barrier Reef. Reef tourism contributes about 6.4 billion euros annually to Australia's economic power. About 70,000 people owe their jobs to the Great Barrier Reef," writes Professor Christian Wild from the University of Bremen and conference chairman of the **14th International Coral Reef Symposium (ICRS 2021).**

Because of the importance of coral reefs and the significant challenges they face, ECO Magazine has partnered with the organizers of ICRS 2021 to bring you our first digital edition of 2020: **Coral Reefs.** Little did we know we would end up producing a 160-page issue. Still, the number of stories we share with you here offers a glimpse into the breadth of exciting and vital research that is taking place around the world today. From case studies demonstrating successful coral restoration, selective breeding, and management approaches to novel applications for mass spectrometers and modeling techniques, this issue has it all.

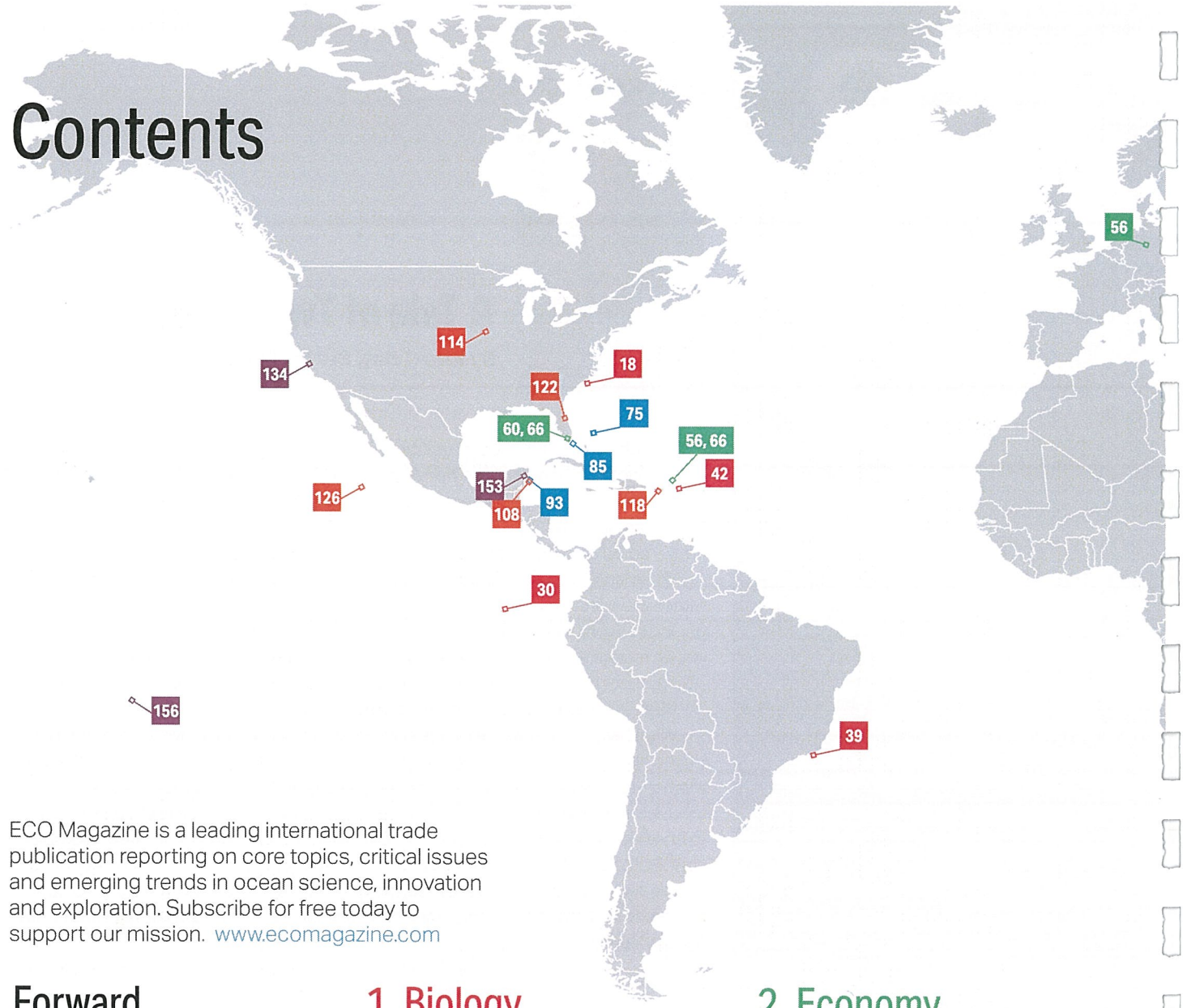
For cities above and below the water, the ability to innovate, adapt, and be resilient will be critical if both are to prosper in a future of climate change and growing demands for resources. And one thing is clear; we will need coral reefs to succeed if we are to thrive.

Thank you to our sponsors of this special edition for helping us spread awareness about the challenges coral reefs face and for supporting academics, industry members, and governments in the fight to save our ocean's cities.

I invite you all to enjoy your free subscription to ECO Magazine via www.ecomagazine.com/subscribe

1. United Nations Department of economic and Social Affairs www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html
2. World Wildlife Foundation wwf.panda.org/our_work/oceans/coasts/coral_reefs/coral_facts.cfm
3. United Nations Environment Programme www.unenvironment.org/explore-topics/oceans-seas/what-we-do/working-regional-seas/coral-reefs

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The 14th International Coral Reef Symposium (ICRS 2021)

By Prof. Dr. Christian Wild, University of Bremen, Conference Chairman ICRS 2021

Just before the worldwide shutdown to contain the COVID-19 pandemic, dramatic news came from Australia. The Great Barrier Reef off the northeast coast of Australia experienced its third heavy coral bleaching in just five years, and the fifth since 1998. The damage to the 2,300-kilometer-long reef, the world's largest living structure, is devastating. The extent and severity of bleaching are highlighted by recent aerial surveys in March 2020 of more than 1000 individual reefs taken by researchers of the ARC Center of Excellence for Coral Reef Studies at James Cook University and the Great Barrier Reef Marine Park Authority. The worst thing about it: This time, the coral bleaching also affects the south of the Great Barrier Reef, which has so far been largely spared. And another fact is remarkable: This time it was not El Niño that caused the high water temperatures that triggered coral bleaching, but Australia's new record-breaking high summer temperatures. Since recordings began, water temperatures in the Great Barrier Reef have never been higher than in February 2020.

At present, however, this unprecedented coral reef bleaching event has been somewhat overshadowed by the COVID-19 pandemic. It will, though, be an central topic at the 14th International Coral Reef Symposium (ICRS 2021), to be held in Bremen, Germany, from 18-23 July 2021. Terry Hughes, Director of the ARC Center of Excellence for Coral Reef Studies and lead scientist of the study mentioned above, will most likely present the key findings at the ICRS 2021. After all, the International Coral Reef Symposium is the only professional forum dedicated exclusively to research on coral reefs..

The International Coral Reef Symposium has a history stretching back more than 50 years. The first event took place in India in 1969 and then the second in in Australia, in 1974, when the delegate party was able to congregate on the M.V. *Marco Polo* and, between lectures, were able to dive in Australian waters. Today, the International Coral Reef Symposium regularly brings together more than 2,500 of the world's leading coral reef scientists, early career researchers, conservationists, policy makers and reef managers to present the latest research findings and exchange current knowledge fundamental in advising international and national policies in the conservation and sustainable use of coral reefs. The Symposium is sanctioned every four years by the International Coral Reef Society (ICRS), whose current president is Andréa Grottoli. Despite the long history of the International Coral Reef Symposium, the ICRS 2021, hosted by the University of Bremen, will be the first of its kind in Europe.

The growth of the International Coral Reef Symposium reflects the global importance of this ecosystem. Coastal protection from erosion in more than 100 countries is only one of the many ecosystem services we owe to intact coral reefs. Intact coral reefs reduce 97 percent of wave energy and 84 percent of wave height, and they are by far the most economically significant ecosystems on earth. A good example is the tourism industry. Every year, two million

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people visit the Great Barrier Reef. Reef tourism contributes about 6.4 billion euros annually to Australia's economic power. About 70,000 people owe their jobs to the Great Barrier Reef. In numerous developing countries, as in Egypt, the tourism industry is even more important. Coral reefs serve as an indispensable source of food for tropical coastal communities, where fish is often the only healthy protein available in sufficient quantities at affordable prices. More than 500 million people in the tropics depend on intact coral reefs. The global population is increasingly benefiting from medical agents newly discovered in coral reefs. In the ocean, coral reefs are by far the centers of biodiversity. This is where most species live and develop.

Unfortunately, coral reefs are also among the most threatened ecosystems. For decades, coral reefs worldwide have been exposed to increasing environmental stressors. Not a single reef is now unaffected by global or local threats. One major threat to coral reefs is "coral bleaching." In many cases, this event leads to a large scale die-off of reef-building coral species. A key trigger for coral bleaching is global ocean warming, which is directly attributable to climate change. In addition, there are numerous local threats due to the intensive use of coastal areas. Reef waters are polluted by close-by hotels, ports, tourist infrastructures, mining and deforestation. Agriculture and aquaculture run-offs promote strong algae growth through eutrophication and bring pesticides into the sea.

In light of their importance and uncertain future of coral reefs, the ICRS 2021 will be the key event to develop science-based solutions addressing the global coral reef crisis. The overarching topic "Tackling the Challenging Future of Coral Reefs" outlines its primary goals listed below:

- Showcase significant work, latest findings and new ideas from all disciplines
- Provide a platform for the international coral reef community to build bridges between science, conservation, politics, management and public awareness
- Review existing knowledge for a comprehensive outlook on the future distribution and function of coral reef ecosystems
- Explore new insights and technologies to develop science-based and sustainable solutions to tackle the global coral reef crisis
- Promote public and political outreach to disseminate the key symposium outcomes at the local and international level
- Create awareness by involving the public through accompanying lectures and exhibitions

Originally, these objectives were to be pursued from 5-10 July, 2020. However, like so many other major events, the ICRS 2020 had to be postponed due to the COVID-19 pandemic. Fortunately, new dates have been established. The 14th International Coral Reef will take place a little more than a year later than planned, from 18-23 July, 2021. The postponement also creates valuable opportunities and new perspectives for the scientific program. All previous contributions may now be updated, and new abstracts can be submitted.

No changes were made to the venue and the ecological "green strategy" of the Symposium. The organization and execution of the Symposium are planned with the confident goal to minimize and compensate all local and global environmental impacts. A climate-neutral ICRS 2021 in Bremen is a signal that Europe is taking responsibility for contributing to the worldwide degradation of coral reefs via the emission of greenhouse gases.

Our hosts, the University of Bremen, also celebrates its 50th anniversary in 2021. The administration of the Free Hanseatic City of Bremen and the International Coral Reef Society support ICRS 2021 in all aspects.

Bremen is ideally suited for hosting the International Coral Reef Symposium. Its scientific environment is outstanding and diverse. Bremen University's campus, with its strong marine science focus, includes the Center for Marine Environmental Sciences (MARUM) and Bremen Marine Ecology (BreMarE) clusters. Together with several world-class marine research institutions, such as the Max Planck Institute for Marine Microbiology, the Alfred Wegener Institute for Polar and Marine Research and the Leibniz Centre for Tropical Marine Research, this creates a multi-disciplinary research hub. Many scientists in Bremen are actively involved in coral reef related work and also act as members of the ICRS 2021 organizational committee. Interested participants of the symposium can book science tours to the different institutions on the ICRS 2021 website.

Additionally, you can book several social tours, field trips and excursions to interesting destinations near to and within Bremen. These trips are organized by the ICRS 2021 committee and/or external partners.

One important aim leading up to, during and after the ICRS 2021 is to inform, educate and inspire interested publics in Bremen and Germany with information about our extensive outreach program on coral reefs, their threats and their protection. Our Bremen partners, the Haus der Wissenschaften, the Übersee-Museum Bremen, are supporting our efforts with exhibitions and by hosting several public lectures. The exhibition "Coral reefs - diverse. vulnerable. lost?" will be shown at the Übersee-Museum for three summer months in 2021. During ICRS 2021, we will be invited to participate in a workshop lasting several days under the direction of the Australian marine biologist Nathan Cook, to which pupils from Bremen are also cordially invited. In the Haus der Wissenschaften, we will be showing the best photographic works from our successfully launched photo competition entitled "Colourful diversity, white death - what colours tell us about coral reefs," accompanied by a series of lectures on coral reefs.

I look forward to welcoming all national and international participants to the 14th International Coral Reef Symposium in Bremen in 2021, and helping to tackle the challenging future faced by our coral reefs.

More information at: www.icrs2021.de

ICRS 2021 BREMEN 14TH INTERNATIONAL CORAL REEF SYMPOSIUM 18-23 JULY 2021



Expert Interview with Professor Andréa Grottoli

Professor Andréa Grottoli received her B.Sc. degree from McGill University in 1992, her PhD from the University of Houston in 1998 and completed postdoctoral training at the University of California –Irvine in 2000. Her research focuses on three areas: 1) determining what drives resilience in corals in the face of climate change, 2) reconstructing oceanographic conditions in the past based on coral skeletal isotope and trace metal records, and 3) the impact of land-use on the delivery of carbon to small tropical and temperate rivers.

In 2004, she established the Stable Isotope Biogeochemistry Laboratory in the School of Earth Sciences at the Ohio State University where she is a full Professor and Chair of the Promotion and Tenure Committee.

Grottoli has also won several awards including the F.W. Clarke Award in Geochemistry, the Mid-Career and the Best Paper Awards from the International Society for Reef Studies, and the Voyager Award from the American Geophysical Union's Ocean Sciences Section. She is a Fellow of the International Society for Reef Studies, an AAAS Fellow, President of the International Coral Reef Society, and the Director of the NSF-funded Coral Bleaching Research Coordination Network.

ECO: You are an award-winning marine biologist, engaged in the exploration of coral reefs. Since the end of 2018 you have also been President of the International Coral Reef Society (ICRS). Where does your enthusiasm for this tropical ecosystem come from?

Grottoli: I love the outdoors and am curious about the natural world. As a kid growing up in Canada, I spent my summers outdoors doing things like camping, canoeing, and swimming. I have always known that I wanted a life deeply connected to nature and to the well-being of natural systems.

As a first-year graduate student I had the opportunity to take a field course on coral bleaching in Hawaii led by the late Dr. Paul Jokiel. It was amazing and inspirational. The reefs were beautiful, the problem (coral bleaching and climate change) was compelling and in need of research and solutions, and the people involved in coral research were (and still are) incredible. The more I learned about coral reefs and the impact of climate change on reef ecosystems, the more I realized that I wanted to study corals and how we might save and protect coral reefs. That summer in Hawaii changed my career path and led me here.

ECO: Many marine biologists assume that the coral reefs will have disappeared by the end of 2100. Now you are leading the ICRS as President through these difficult times. What do you think are the greatest threats?

Grottoli: Climate change, particularly elevated temperature and ocean acidification, is the greatest threat to coral reefs on a global scale. And of the two, elevated temperature is the largest threat with devastating effects on coral reefs right now. Marine heat waves leading to mass coral bleaching events are causing extreme levels of coral mortality in some cases. The effects of ocean acidification are not severe now but will be later this century. At the local and regional level, climate change stress can be further exasperated by coastal inputs such as nutrients, pollutants and over-fishing. Failure to address both rising carbon dioxide levels – which cause rising temperatures and ocean acidification - and coastal inputs will ensure the continued decline of corals and coral reefs.

ECO: Finding solutions to these serious threats requires a lot of knowledge, commitment and a strong voice. The ICRS, formerly the International Society for Reef Studies (ISRS), is ideally equipped for this task. Founded in 1980, the ICRS grew to become the world's leading non-profit organization for coral reef research. Today, the ICRS has over 1260 members from around the world. What is the secret of this success?

Grottoli: As the plight of corals reefs becomes increasingly clear, more people are gravitating towards studying and protecting coral reefs. Our members are genuinely committed to understanding coral reefs and leveraging that scientifi-

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cally acquired knowledge to protect and conserve reefs for future generations.

ECO: What are the goals of the ICRS?

Grottoli: Our mission is to promote the acquisition and dissemination of scientific knowledge to secure coral reefs for future generations. We implement our mission by leading in coral reef scientific discovery, contributing to the education of future coral reef scientists, and by being a strong voice for science informing policies that protect reefs. We are also in the final stages of our ICRS Action Plan, which we hope to launch later this summer.

ECO: Women in management positions are still the exception but the ICRS has broken with this tradition. Your predecessor, Prof. Dr. Ruth Gates, was the first and you are now the second woman at the head of the ICRS. What has changed since then and what are your personal goals for your time as President?

Grottoli: ICRS has been growing and maturing over time. The diversity of our membership and of our elected Officers and Councilors increases every year, enhancing the creativity and productivity of the Society.

Under my leadership as ICRS President, ICRS has redefined itself over the past year. We have developed a mission and vision statement, and are weeks away from launching our ICRS Action Plan. We have also expanded our support for student research and completely revamped the website and membership registration process.

Next year, we will hold our quadrennial symposium in Germany. Going forward, my goal is to forge stronger ties with other science-based coral reef organizations to form a larger collective voice to promote science-based decision making for coral reef protection. I also am working toward transitioning our large international conference (held every 4 years) to have 50 percent or more virtual content and provide greater access globally by 2024. Finally, I am looking to diversify our revenue stream so that we can provide financial stability to the student research and travel scholarships, cash awards, and chapter sponsorships that we offer. Luckily, I have an incredible group of officers and council members that are dedicated to coral reefs and the Society. None of these initiatives would be possible without their commitment and selfless contributions.

ECO: What measures does the ICRS recommend to protect coral reefs?

Grottoli: Protecting coral reefs requires tackling global climate change as well as regional stressors. Addressing these issues requires both global and local actions. At the global level, ICRS is actively contributing sound science-based information in the development and implementation of relevant international agreements with our partner the International Coral Reef Initiative. At the regional level, ICRS has members all over the world doing their part to study the effects of local and regional stressors on coral reefs, implementing conservation efforts to protect coral reefs, and developing tools and strategies for maximizing coral persistence over the coming century. The Society supports some of this work through fellowships and support for our chapter's local meetings and workshops.

But we can all individually play a role in protecting coral reefs as well. ICRS has developed a Pledge for Coral Reefs (#pledge4reefs) to be launched this summer, that outlines a series of actions individuals can take to protect coral reefs by reducing their carbon footprint (thereby reducing climate change inducing greenhouse gases), promoting education and awareness of coral reefs, and supporting policies that sustain healthy reefs.

ICRS also plays a large role in sharing and disseminating knowledge and awareness of coral reefs through our quadrennial symposium. The 14th International Coral Reef Symposium, originally scheduled for July 2020, will now be hosted in July 2021. Coral scientists from all over the world will be in Bremen, Germany for a week to share the most recent findings and discoveries in coral reef research. We will also be hosting a policy side event, featuring a position paper by the ICRS2021 outlining a blueprint for coral reef protection. The ICRS Action Plan will be one component of this blueprint. The 14th ICRS symposium is more important than ever with coral reefs in decline globally. Sharing the most up-to-date scientific findings is critical for moving coral reef science forward, and for supporting evidence-based policy development and implementation.

ECO: Wikipedia defines the ICRS as a scientific organization. With the "Pledge for Coral Reefs", the ICRS also specifically addresses interested individuals to commit themselves to coral reefs. Could they support their work through membership, or do you have to be a scientist to join the Society?

Grottoli: You do not need to be a scientist. We welcome anyone interested in coral reefs to become an ICRS member. The more diverse the interests and expertise of our membership, the better we can be as a Society

More information can be found at: coralreefs.org.



Top 15 Coral Reef Research Contributors

As nominated by the coral community, here is ECO Magazine's shortlist of top people and projects in 2020

PROJECTS

Category: Economy

Project: Allen Coral Atlas

The Allen Coral Atlas is the first 3.7-meter resolution global map of the world's coral reefs. The Atlas is one piece of Vulcan Inc.'s broader coral program, which takes on the daunting task of saving the world's coral reefs. The project uses a ground-breaking new method for mapping coral reefs from outer space using nanosatellites, cloud computing, and machine learning, creating a mosaic view of the current state of the world's coral reefs. As a result, and for the first time in human history, we can attempt to map every single coral reef habitat on Earth in detail. Currently, the Allen Coral Atlas includes maps of Fiji, the central Great Barrier Reef, Heron Island, Karimunjawa, Kayankerni Reef, Lighthouse Reef, Mo'orea and West Hawai'i.

Website: www.allencoralatlas.org

Category: Threats

Project: Updating Global Policy with the Extinction Status of Reef-Building Corals

The Red List of Threatened Corals is arguably one of the most important biodiversity indicators in global policy circles, highlighting the imminence of massive and irreversible climate impacts to nature. By mid-202, this project will update the Red List of Threatened Corals and the coral Red List Index, last calculated in 2008, using a crowd-sourcing online approach, fortuitously immune to the current Covid crisis preventing travel and meetings. The project's goal is to influence the key global policy events, such as the biodiversity and climate conventions now delayed to 2021, that will respond to updated information on the extinction risk of reef-building corals worldwide. The Coral Specialist Group is recruiting 100 scientists with experience in coral reef ecology and coral species, to participate remotely in groups of 10-20, each dealing with subsets of species.

Website: www.coralspecialistgroup.org/updating-global-policy-with-the-extinction-status-of-reef-building-corals

Category: Biology

Project: CoralTrace - A new approach to understanding climate-induced reef crises

CoralTrace is an innovative project led by Professor Wolfgang Kießling and Nussaibah Raja Schoob that uses fossil records to inform us about the current and future status of coral reefs. Using the Paleobiology Database and the Erlangen PaleoReefs Database together with a new fossil trait database on extinct reef builders, CoralTrace aims to reveal the interplay of individualistic evolutionary fate and whole ecosystem changes in reefs over time. This new study broadens our view of the future of coral reefs in the context of climate change.

Website: www.cris.fau.de/converis/portal/project/229379311

Project: SymPortal

SymPortal is a novel analytical framework and platform for genetically resolving the algal symbionts of reef corals using next-generation sequencing (NGS) data of the ITS2 rDNA. This unique database and service builds a thriving resource that improves the resolution of algal-symbiont information as more samples are submitted by the community. The creators are continually improving symportal.org to better serve the coral reef research community. Recently, the *Journal of Molecular Ecology Resources* named symportal.org as a computer program "to watch" in 2020.

Website: www.symportal.org

www.ecomagazine.com/subscribe

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PAPERS

Category: Protection

Project: Fragments of Hope

Fragments of Hope is an excellent example of community-supported coral restoration, in Belize. The project has completed over 10 years of monitoring, documenting successes, supporting local livelihoods, and providing a convergence space for international researchers to co-create knowledge. The Fragments of Hope's focus is the restoration of coral reef habitats and advocacy for the sustainable management of associated habitats. Coral restoration efforts are conducted by trained fishers and tour guides, and the team works closely with regulatory agencies, including the Belize Fisheries Department.

Website: www.fragmentsofhope.org

Paper: Considerations for Maximizing the Adaptive Potential of Restored Coral Populations in The Western Atlantic

This study provides concrete guidelines on how to establish self-sustaining, sexually reproducing coral populations, which contain enough genetic and phenotypic variation to adapt to changing environments when applying coral restoration. This includes practical directions, choosing which parental colonies to sample, the effect of nursery on coral phenotypes, gene flows and more.

Authors: Iliana B. Baums, Andrew C. Baker, Sarah W. Davies, Andréa G. Grottoli, Carly D. Kenkel, Sheila A. Kitchen, Ilsa B. Kuffner, Todd C. LaJeunesse, Mikhail V. Matz, Margaret W. Miller, John E. Parkinson and Andrew A. Shantz

Weblink: https://doi.org/10.1002/eap.1978

Paper: Bacterial Community Dynamics are Linked to Patterns of Coral Heat Tolerance

Important research on the adaptability of grip-forming corals with the help of their symbiotes. In this paper, the authors show that the microbiome of reef corals is different across thermally variable habitats and changes over time when corals are reciprocally transplanted. Exposing these corals to thermal bleaching conditions changes the microbiome for heat-sensitive corals, but not for heat-tolerant corals growing in habitats with natural high heat extremes. Importantly, particular bacterial taxa predict the coral host response in a short-term heat stress experiment. Such associations could result from parallel responses of the coral and the microbial community to living at high natural temperatures. A competing hypothesis is that the microbial community and coral heat tolerance are causally linked.

Authors: Maren Ziegler, Francois O. Seneca, Lauren K. Yum, Stephen R. Palumbi & Christian R. Voolstra

Weblink: www.nature.com/articles/ncomms14213

Category: Biology



Dr. Katharina Fabricius, Senior Principal Research Scientist, Australian Institute of Marine Science (AIMS)

Dr. Katharina Fabricius has published extensively on ocean acidification, water quality, and on the cumulative impacts of climate change and water quality on coral reefs. Today, she is leading a project investigating organism and ecosystem responses to long-term exposure to ocean acidification at natural CO_2 seeps in Papua New Guinea. This project has grown into a collaboration involving scientists from 20 organizations. The findings from these CO_2 seeps are now being tested along environmental gradients in the GBR. She has published over 100 peer-reviewed articles, reports and books, including contributions to the Scientific Consensus Statement on water quality in the Great Barrier Reef. In 2016, Fabricius received the Eminence in Research Award from the ICRS.

Category: Economy



Sherya Yadav, Ph.D. Candidate, University of Hawaii at Mānoa

Shreya Yadav has been described by colleagues as a "shining beacon of enthusiastic passion for coral reefs, natural history, and storytelling through incredible visuals." Yadav's research seeks to understand how corals resist and recover from climate change, related disturbances, and the effects of frequent temperature stress on a reef's structural and functional integrity. In 2019, she received a National Geographic Early Career Grant that will enable her to use photogrammetry to map remote and lesser-studied reefs in the Maldives. For this project, Yadav works with local communities to investigate the effects of the Tuna fisheries and reef fishes on coral health, as well as the community's preferences.

Category: Threats



Dr. Tom Shlesinger, PostDoc, Florida Institute of Technology

Dr. Tom Shlesinger has been nominated for uncovering a hidden threat to coral persistence: the breakdown in spawning synchrony. Our changing climate is a threat to corals, causing disfiguring bleaching and mortality to reefs that once teemed with life. In a paper published in September 2019 in *Science* (DOI: 10.1126/science.aax0110), Shlesinger and Professor Yossi Loya highlighted an equally dangerous yet nearly invisible hazard to coral: the loss of breeding synchrony. They found that environmental changes have resulted in shifts in the timing of gamete release in several species of broadcast-spawning corals in the Red Sea. Similar changes are likely occurring globally. Such a loss of spawning synchrony could result in reproductive failure, a much less obvious but no less insidious threat to coral reefs.

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Category: Protection



Professor David Smith, Director of the Coral Reef Research Unit, University of Essex

Professor David Smith has focused on coral reef ecology and conservation for 20 years. He is the Associate Editor for the journal *Global Change Biology* and advises governments and organizations on research strategies and conservation solutions. Smith is the Chief Marine Scientist for Mars Inc. He pioneered the project aiming to restore degraded reefs in Indonesia and helped locals create the 'spiders' that aid the reefs restoration. During his extensive career, he has been part of all four categories and has been described as an inspiration to the next generation of marine scientists.



Dr. Christopher Doropoulos, Research Scientist, CSIRO

Dr. Christopher Doropoulos's research focuses on enhancing the resilience of coastal marine environments by adapting to global change through large-scale restoration. He recently played a leading role in a study that tests industrial-scale strategies in the largest harvest and cultivation of coral spawn slicks for reef restoration. Doropoulos is dedicated to translating research into useful applications, using his expertise in recruitment ecology and reef recovery trajectories to develop the best strategies for optimizing large-scale restoration. As a young researcher, he has an impressive publication list of some 45 journal articles, including seven in Coral Reefs, and was recently awarded the Julius Career Award for outstanding early-mid career researchers.



Dr. Anne Cohen, Associate Scientist W/Tenure, Woods Hole Oceanographic Institution

Dr. Anne Cohen has been nominated for her "Super Reefs" initiative, a science-based program that aims to find and protect coral reefs with demonstrated potential to survive 21st-century climate change. Cohen takes an inclusive approach to identify Super Reefs within all coral reef systems and advocates for Super Reefs to be included in international conservation and protection efforts. Her work has inspired coral reef island nations, CEOs of major companies, leading conservation organizations, philanthropists and members of the public to support the protection of Super Reefs within Marine Protected Areas (MPAs). Cohen's speeches at the United Nations and The Our Ocean Conference have inspired the production of a 3-D Super Reefs 'Science on a Sphere', viewed in 145 countries and translated into several languages, as well as a *Super Reefs-Future of Coral* documentary, a National Geographic expedition to document the Super Reefs of the South Pacific, and a nomination to the JMK Innovation Prize.



Dr. Nyawira Muthiga, Kenya Program Director, The Wildlife Conservation Society (WCS)

Dr. Nyawira Muthiga has over 30 years' experience working in coastal Kenya and coral reefs around the world. She has contributed immensely to the development of MPAs and the conservation of marine ecosystems in the region. Muthiga helped develop MPA management plans as well as awareness and training programs at the Kenya Wildlife Service. She also contributed to a regional *Manual for MPA Managers* and a *Guide for MPA Management in the Western Indian Ocean* produced by Western Indian Ocean Marine Science Association (WIOMSA). As Chair of the Coral Reef Task Force of the Nairobi Convention, Muthiga oversaw the development of a regional strategy for the management of coral reefs focusing on climate change mitigation. She also coordinated a regional workshop that culminated in the establishment of the Marine Turtle Task Force of the Western Indian Ocean, under the umbrella of the Nairobi Convention and the Indian Ocean South East Asian MOU for marine turtle conservation. In 2018, Dr. Nyawira Muthiga and Dr. Tim McClanahan were given the Award for Conservation Excellence (ACE).



Dr. Nancy Knowlton, Sant Chair for Marine Science, Smithsonian National Museum of Natural History

Dr. Nancy Knowlton is the Sant Chair for Marine Science at the Smithsonian's National Museum of Natural History and a scientific leader of the Census of Marine Life. She authored *Citizens of the Sea* to celebrate the ten-year anniversary of the Census. Knowlton founded the Center for Marine Biodiversity and Conservation at the Scripps Institution of Oceanography, University of California, San Diego. She has devoted her life to studying, celebrating, and striving to protect the multitude of life-forms that call the sea home. In 2020, Knowlton was awarded the Darwin Medal from the ICRS.



New Frontiers in Marine Science

A spotlight on the latest coral reef research

Coral reefs only occupy 0.1 percent of the ocean, but they support 25 percent of all marine species. Because of the diversity of life found in the habitats created by corals, reefs are often called the "rainforests of the sea." Fishes and other organisms' shelter, find food, reproduce, and rear their young in the many nooks and crannies formed by corals. They are also a source of new medicines.

About half the world's shallow water coral reefs are already gone, and without urgent action to address climate change, pollution, overfishing and destructive coastal development, these life-sustaining natural wonders could all but disappear.

The following articles, published in *Frontiers in Marine Science*, provide deeper insights into the latest research on the impact of heat waves on coral reefs as well as ongoing efforts to restore and protect reefs in a changing world.

www.frontiersin.org/journals/marine-science

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frontiers in Marine Science

RESEARCH TOPIC: Coral Reefs in the Anthropocene

This Topic has won the 2019 Frontiers Spotlight Award, an annual prize awarded to the most active, collaborative and impactful Research Topic across Frontiers' full editorial program: life sciences, health, physical sciences and engineering, humanities and social sciences, and sustainability.

A global team of Editors invited research that exposes the damage to reefs, and dives deep into the science of coral reef management.

Based on the cutting-edge research presented at the European Coral Reef Symposium 2017, the collection has attracted more than 460,000 views to date and drawn the support of Greenpeace and the confidence of the IUCN.

https://www.frontiersin.org/research-topics/6185/coral-reefs-in-the-anthropocene

RESEARCH TOPIC: Coral Reef Restoration in a Changing World: Science-based Solutions

Human activities are impacting coral reef ecosystems worldwide. To date, the rehabilitation of these important ecosystems has created major challenges for local communities, resource managers and researchers alike. However, recent developments in coral propagation techniques and other technological advancements that facilitate discovery and innovation in science afford an unprecedented opportunity to promote coral reef restoration efforts as we move forward in the 21st Century.

This Research Topic compiles articles that provide details on innovative techniques and ecological engineering approaches to carry out coral reef restoration programs worldwide, taking into account contemporary and anticipated challenges to coral reef ecosystems.

https://www.frontiersin.org/research-topics/12642/coral-reef-restoration-in-a-changing-world-science-based-solutions

RESEARCH TOPIC: Remote Sensing for Applied Coral Reef Science and Management

Field studies provide crucial information about coral reef structure and function from molecule to community scales, but there is far less understanding of reefs and their processes across landscapes, ecosystems, regions, and ocean basins. Airborne and satellite remote sensing techniques are currently the only means to observe and monitor reefs at these scales.

Associated technologies continue to advance, bringing applications to small, lightweight sensor systems deployable on commonly available drones, effectively placing advanced remote sensing capabilities in the hands of individual researchers and managers.

This Research Topic presents state-of-the-art and novel applications of remote sensing for coral reef environments, from fundamental reef science to management support.

https://www.frontiersin.org/research-topics/13811/remote-sensing-for-applied-coral-reef-science-and-management

Science, Diplomacy, and the Red Sea's Unique Coral Reef: It's Time for Action

Rapid ocean warming poses a serious risk to the survival of coral reefs. The Red Sea's reef ecosystem seems to be more resilient to rising sea temperatures than most others. It is one of the longest continuous living reefs in the world, and its northernmost portion extends into the Gulf of Aqaba. The corals in the Gulf have an unusually high tolerance for the rapidly warming seawater in the region, making it potentially one of the planet's largest marine refuges from climate change. However, this unique portion of the Red Sea's reef will only survive if serious regional environmental challenges are addressed.

https://www.frontiersin.org/articles/10.3389/fmars.2020.00090/full

Heat Waves Are a Major Threat to Coral Reefs in Brazil

Coral reefs are threatened by climate change on a global scale with warming waters leading to mass coral bleaching events. South Atlantic reefs, however, appeared to be a refuge, as they have escaped multiple marine heat-wave events which have plagued the Indo-Pacific and Caribbean. Despite massive coral loss seen throughout the world, coral reefs in the South Atlantic have remained relatively stable. This has recently changed.

The authors document the first mass die-off recorded in South Atlantic reefs during a record-breaking heat wave event in 2019. The mass die-off in 2019 is unprecedented in the South Atlantic reefs and coincides with increased heating events.

https://www.frontiersin.org/articles/10.3389/fmars.2020.00179/full

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Occupying less than one quarter of 1% of the marine environment, coral reefs are home to more than 25% of all known marine fish species

32 of the 34 recognized animal Phyla are found on coral reefs compared to 9 Phyla in tropical rainforests

Source: WWF

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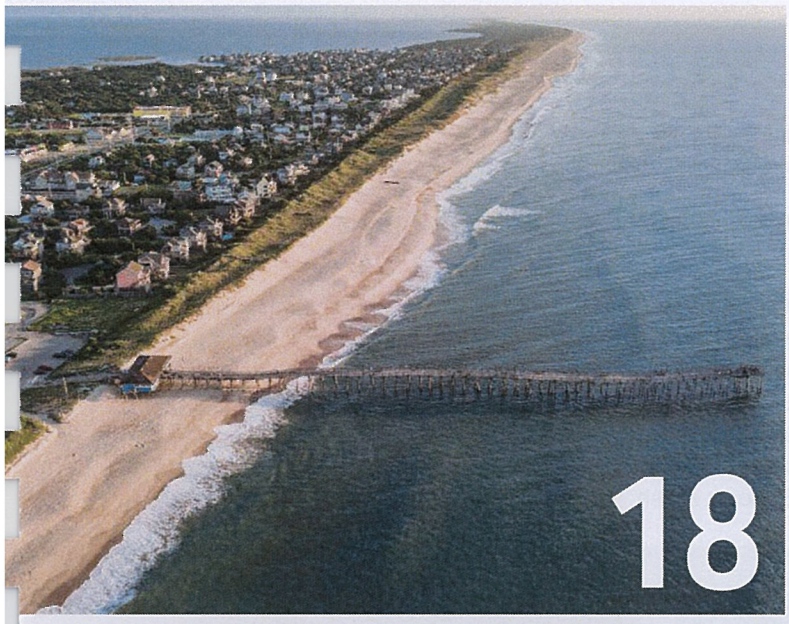
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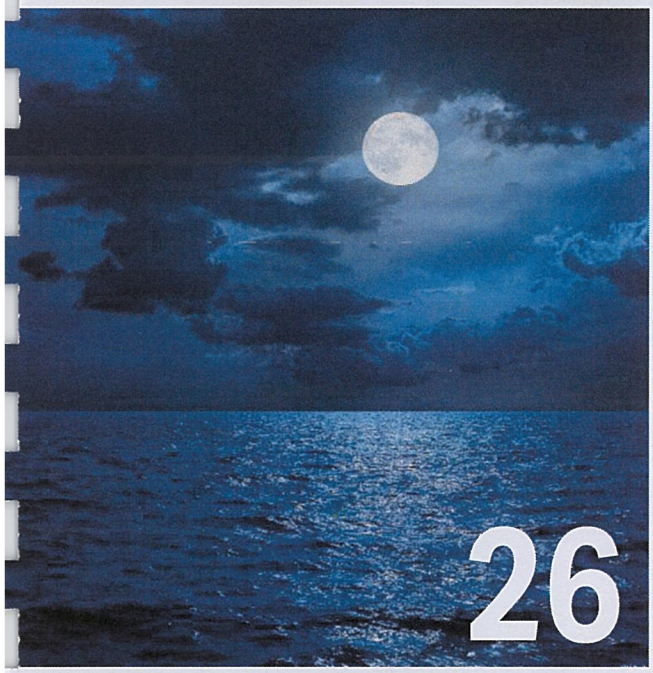
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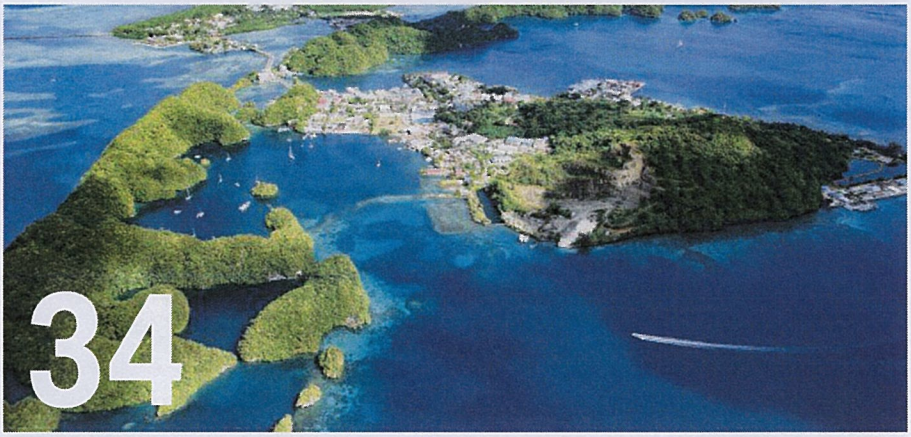
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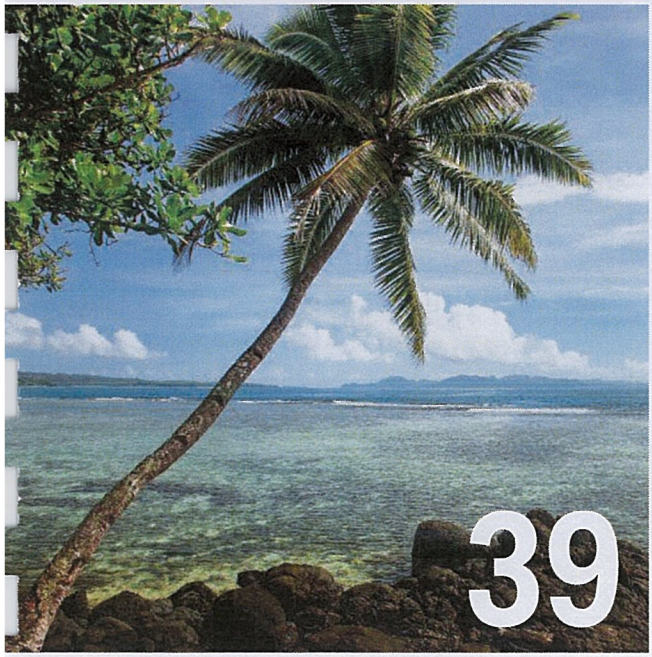

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Deep SEARCHing for Science

By Sara B. McPherson, Bureau of Ocean Energy Management (BOEM) Office of Public Affairs

In April 2019, the Remotely Operated Vehicle (ROV) *Jason* traveled deep into the waters off the U.S. southeastern coast on multiple exploration dives. Throughout the month, *Jason* traversed multiple deep-sea habitats, diligently collecting reams of data. It ventured into Pamlico Canyon, approximately 35 miles off the North Carolina coast – diving 2,600 meters (8,530 feet) below the surface – passing brisingid starfish, stony corals and octocorals carpeting the canyon's steep outcroppings and overhangs. Schools of fish tailed the ROV as it explored multiple methane seeps, capturing footage of a deep-sea coral community thriving on the carbonate hard substrate. These and other observations revealed the area to be a much more complex and vibrant ecosystem than was previously known.



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Pamlico Canyon walls covered in brinsingid starfish, cup corals, and a diversity of other corals including both octocorals and stony corals. Image courtesy of Ivan Hurzeler and Deep SEARCH 2019 - BOEM, USGS, NOAA, ROV Jason, ©Woods Hole Oceanographic Institution

Aerial view of Outer Banks North Carolina



Participating in these and many other dives were scientists from multiple federal agencies and U.S. and international academic institutions, all partnering on the Deep Sea Exploration to Advance Research on Coral/Canyon/Cold seep Habitats, or Deep SEARCH.

Research from Deep SEARCH

Deep SEARCH is a multi-agency, multi-year interdisciplinary study designed to shed light on little-known deep-sea ecosystems of the U.S. Mid- and South Atlantic. It is a collaborative project between the Bureau of Ocean Energy Management (BOEM), the U.S. Geological Survey (USGS) and the National Oceanic and Atmospheric Administration (NOAA), sponsored by the National Oceanographic Partnership Program (NOPP). BOEM developed the study concept, funded the competitive contract with TDI-Brooks International, Inc. as the prime contractor and brought together scientific personnel, ships and equipment from USGS and NOAA's Office of Ocean Exploration and Research (OER).

"This study brought together experts who will collaborate to improve our understanding of the distribution, ecology and underlying geological foundation of sensitive deep-sea environments within this region," explains Dr. Amanda Demopoulos, USGS chief scientist for the multi-year study.

Since 2017, the Deep SEARCH team has spent 65 days at sea on five different research vessels. The team completed three Autonomous Underwater Vehicle (AUV) *Sentry* dives, 11 Human-Occupied Vehicle (HOV) *Alvin* dives, and 11 ROV *Jason* dives, spending 259 hours of total time on the ocean floor. Team members have also participated in five additional cruises through partnerships with the BOEM Atlantic Deepwater Ecosystem Observatory Network project and with NOAA OER and the NOAA Ship *Okeanos Explorer*. Scientists have collected and processed more than 2,800 biological and geological samples from the seafloor and water column. The study findings are intended to inform various agency needs. BOEM plans to use the new scientific data to inform

its environmental reviews and offshore energy decisions; USGS and NOAA will gain new scientific understanding of the region's physical and biological resources and geologic foundation to better fulfill their agency missions.

The early Deep SEARCH results demonstrate that the waters off the U.S. southeastern coast contain diverse habitats – submarine canyons, cold-water coral mounds and gardens, methane seeps and soft sediments – all teeming with life.

"One of the primary goals of the Deep SEARCH project is to gain a better understanding of largely unexplored habitats of the deep sea in waters of the southeastern United States" said Dr. Michael Rasser, a marine ecologist with BOEM who oversees multiple scientific research projects, including Deep SEARCH.

While these areas support marine biodiversity and sensitive biological communities, there is still much the scientific community doesn't know about them. Scientists do know that maintaining the area's biodiversity is critical to the sustainability of these deep-sea ecosystems. Loss of this biodiversity could have significant impacts to the deep sea, the water column, and even to human health.

This area of the Atlantic Ocean also has the potential for future U.S. offshore energy and marine mineral development. That's why Deep SEARCH's primary goal is to help BOEM better understand and predict the location of various seafloor communities off the U.S. southeastern coast that may be vulnerable to disturbance from activities associated with resource development.

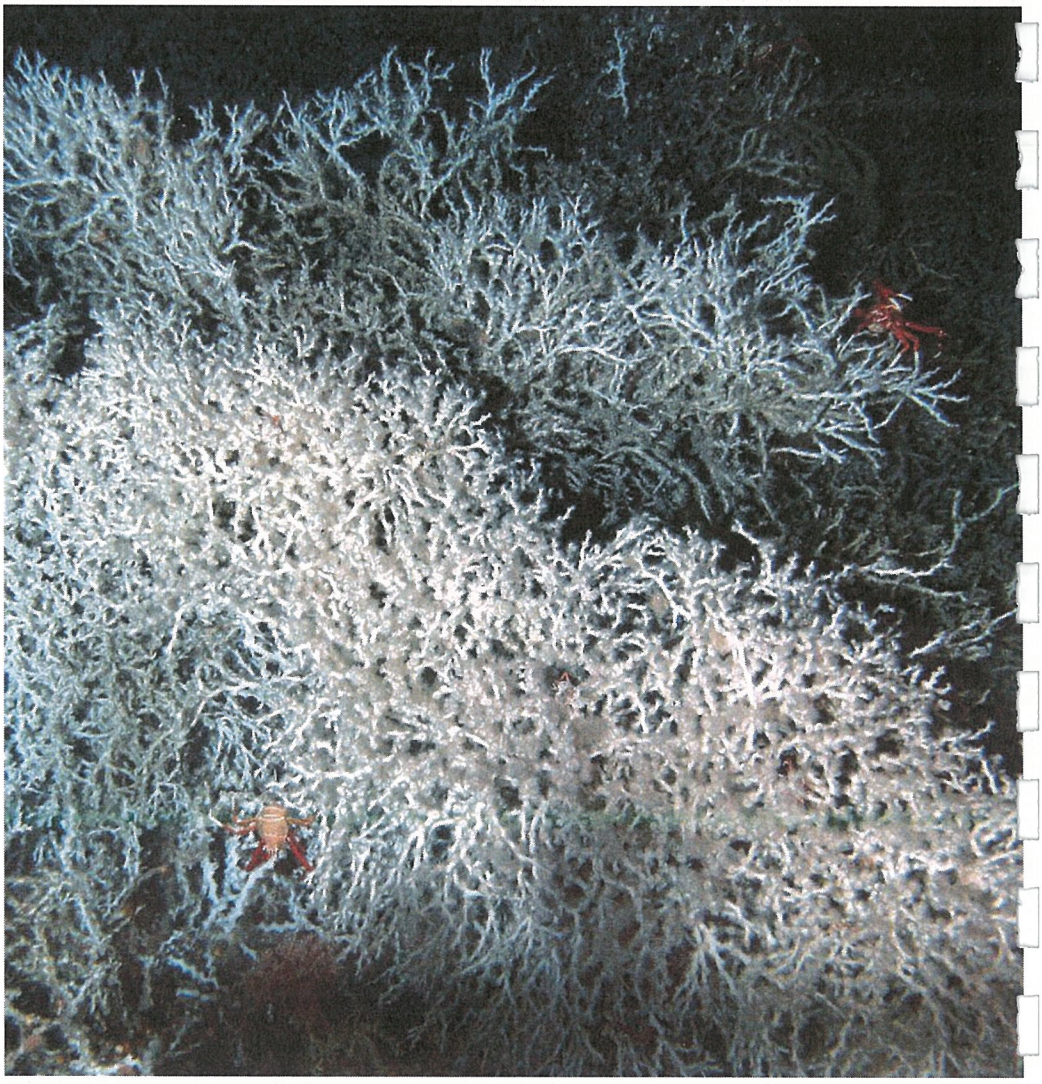
Changing Perspectives, Improving Scientific Models

BOEM is the bureau within the Department of the Interior tasked with overseeing the management of offshore energy and marine mineral resources in an economically and environmentally responsible manner. To properly manage these resources, BOEM's Environmental Studies Program develops, funds and manages rigorous scientific research to help inform policy decisions on OCS energy and mineral resources. The program also manages the Environmental Studies Program Information System (ESPIS), an online search tool that allows text and map-based queries to find relevant study information.

"The deep sea is the largest habitat on earth. There's no way we can explore it all," says Dr. Erik Cordes, Deep SEARCH program manager and vice chair of the Department of Biology at Temple University. "So we collect data to better understand species distributions in an area and use these data to predict the locations of potential sensitive habitat." The team incorporates this information into scientific modeling – conceptual representations of ecosystems based on observations and other data – to predict where environmental resources are located.

"Since we can't possibly explore the entirety of the deep sea, we rely on models to predict what we might see in unexplored areas. Sometimes, we collect data that changes our predictions about what life looks like in the deep sea," explains Rasser.

Deep SEARCH has done just that. In August 2018, the Deep SEARCH science team observed extensive reefs of *Lophelia pertusa*, a deep-sea stony coral in an area approximately 160 miles southeast of Charleston, South Carolina, at depths between 700 and 900 meters (2,300 to 3,000 feet). The team also found more than 3,000 mound structures in the area, some growing in waters deeper and further offshore than expected. Combined, these newly mapped reef tracts added up to almost 100 linear miles of reef habitat.



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Lophelia is a stony coral that forms complex habitats and provides shelter for diverse communities of fish and invertebrates. The reef communities sequester carbon and produce nutrients that fuel the region's productivity, making them biodiversity hotspots in the deep sea. The species is commonly found in the North Atlantic, but Deep SEARCH scientists were surprised to observe it in some of the locations surveyed.

"This was a significant scientific finding," says Rasser. "It changed our perspective of where we find these corals in the ocean. The first step in protecting these sensitive habitats is finding them." Once sensitive habitats are identified in U.S. waters, BOEM and other federal agencies are better able to work together to make sure they are protected.

Work with a Real Impact

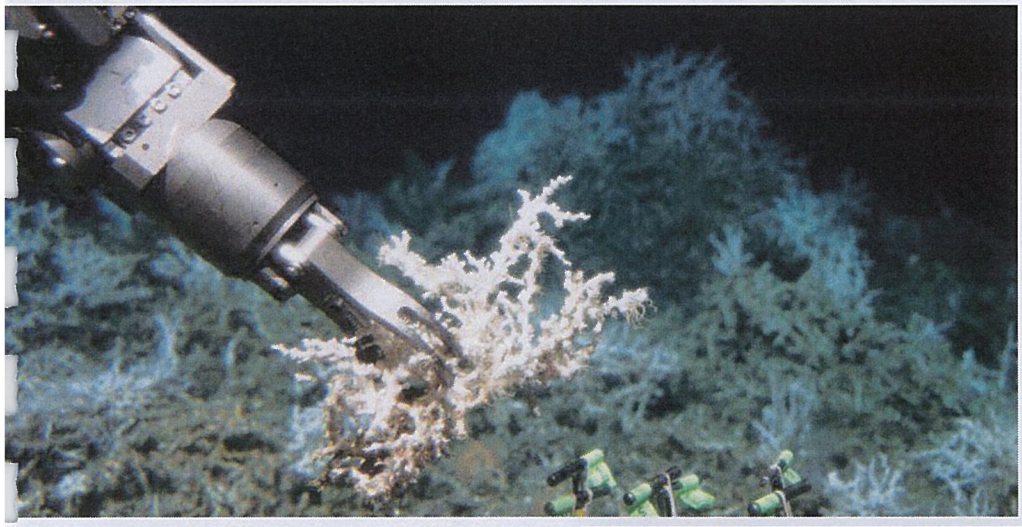
The research team is using the Deep SEARCH findings to create baseline information for the Mid- and South Atlantic, which will help BOEM create more accurate scientific models. This can also help inform BOEM's future offshore energy development decisions, especially those that could affect sensitive habitat like the deep-sea coral.

According to Cordes, that's what makes being a part of this project so exciting. "This is a case where science is directly feeding into management decisions," he explains. "The work we're doing here will have a real impact."

The Deep SEARCH team wrapped up three years of field work in late 2019. Researchers from each participating agency and organization are now undertaking the less glamorous – but no less vital – task of analyzing thousands of samples and corresponding data. According to Cordes, the team will synthesize the various datasets together to create a holistic picture of this little-known deep-sea ecosystem. A final report detailing the study's findings and conclusions is expected in 2022.

For BOEM, the data will improve scientists' understanding of the interconnectedness of this important underwater habitat and ensure that the bureau has the best available science to help inform its offshore energy and marine mineral policy decisions.

"There is still so much we don't know about the ocean, especially the deep sea," says Rasser. "Projects like Deep SEARCH help us expand our knowledge base. The more we know about life in the ocean, the better decisions we're able to make."



Using the ROV *Jason*, the Deep SEARCH team also discovered vestimentiferan tubeworms growing on carbonate rock at the Kitty Hawk and Pea Island methane seeps off the North Carolina coast. This is the first known instance of tubeworms in this part of the Atlantic and further proof of the important information that can be gained from exploratory studies like Deep SEARCH.

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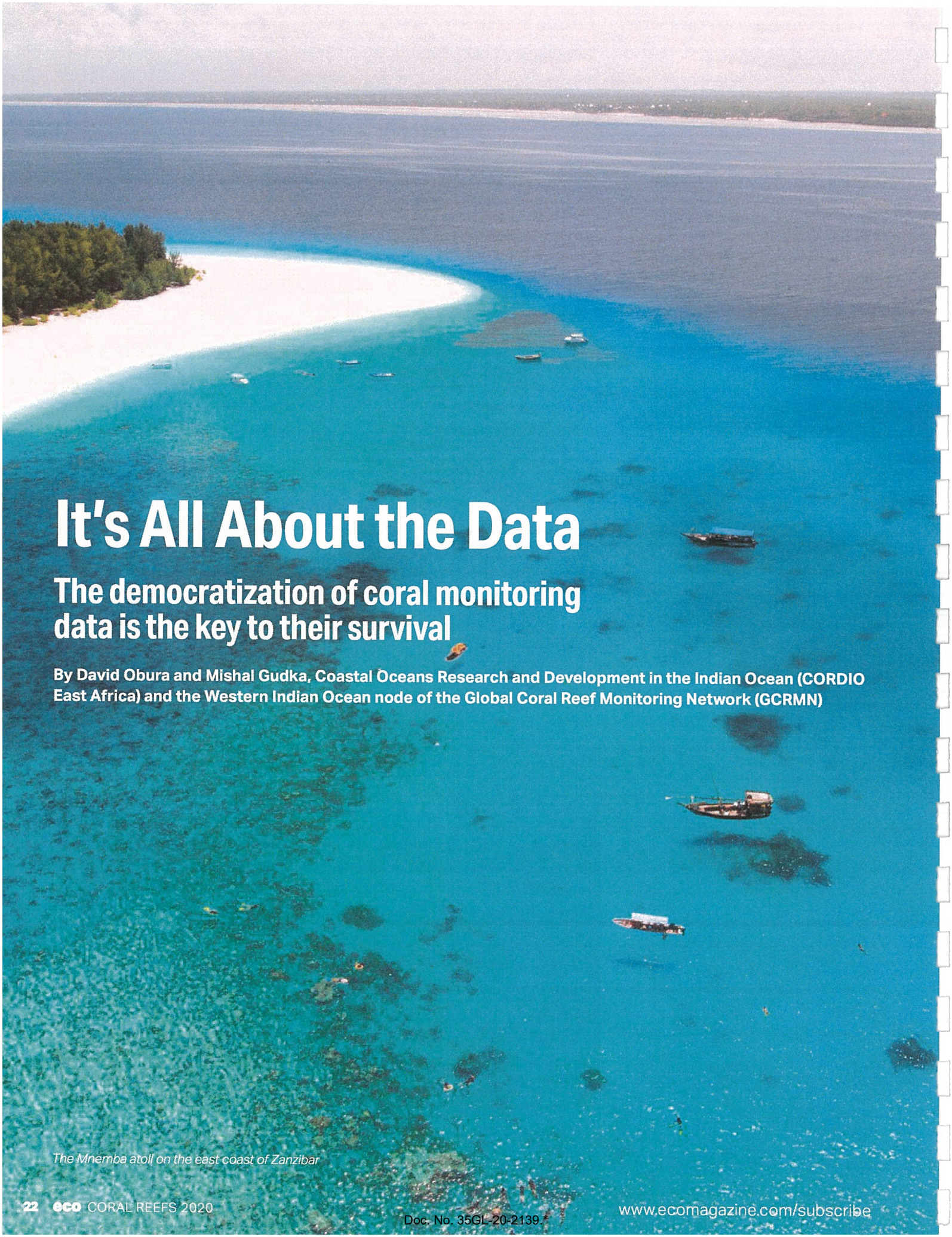
Lophelia colony. Image courtesy of Brooke et al. 2005, NOAA-OER Florida Deep Corals.

Human occupied vehicle (HOV) Alvin collecting a sample of live Lophelia pertusa on the Deep SEARCH 2018 mission. Image courtesy of Deep SEARCH 2018 - BOEM, USGS, NOAA, HOV Alvin. Copyright Woods Hole Oceanographic Institution.

A tubeworm growing from under a carbonate outcrop surrounded by anemones and fish (to accompany sidebar). Image courtesy of DEEP SEARCH 2019 - BOEM, USGS, NOAA, ROV Jason, ©Woods Hole Oceanographic Institution.



BOEM's Environmental Studies Program www.boem.gov/environmental-studies
Environmental Studies Program Information System (ESPIS) https://marinecadastre.gov/espis/#/



It's All About the Data

The democratization of coral monitoring data is the key to their survival

By David Obura and Mishal Gudka, Coastal Oceans Research and Development in the Indian Ocean (CORDIO East Africa) and the Western Indian Ocean node of the Global Coral Reef Monitoring Network (GCRMN)

The Mnemba atoll on the east coast of Zanzibar

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A little over twenty years ago, the first global bleaching event wreaked havoc across the world's reefs, nowhere more than in the Western Indian Ocean (WIO). At the time, the Swedish government was supporting the launch of the Western Indian Ocean Marine Science Association (WIOMSA) and it soon became clear that there were little data and coherence in coral reef monitoring across this major reef region. In response, CORDIO was formed in 1999 to support the various teams and partners monitoring the impact of the 1998 mass bleaching event across their countries. At the same time, the Global Coral Reef Monitoring Network (GCRMN) was also established. The GCRMN formed nodes in East Africa, the Southwest Indian Ocean Islands, and South Asia to collect and compile data from local contributors. The data collection rendered a chilling conclusion that catapulted coral reefs onto the global climate and conservation agendas: In just 9 months, 16 percent of reefs on the planet were destroyed by this single event. This statistic highlights the value, and indeed the challenges, of collecting data and aggregating it to a single, digestible point.

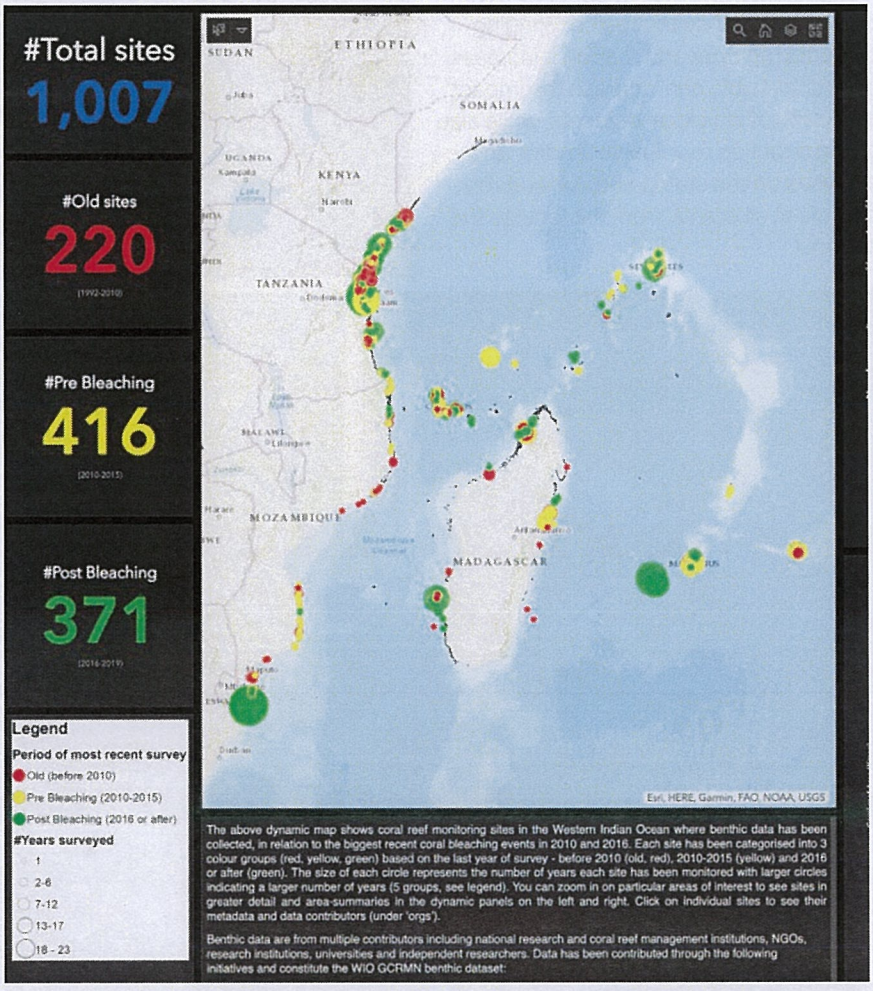
Coral cover is the leading variable used to describe the state of coral reefs. However, greater nuances are needed to inform management and, set policy such as the status of algae that compete with corals, fish that control reef processes and provide protein to people, and many other reef functions. But reliably measuring and then simplifying the complexity, richness, and variety of biodiversity and services sustained by the reefs can be problematic. It is this diversity that provides an income for reef users, researchers, and managers working at the local scale. Therefore, monitoring programs need to address this richness to provide information that supports their work.

For biodiversity observing networks of all types, the grand challenge is to reconcile the local need to address diversity with the constraints required to combine data at higher levels. This challenge is particularly strong where local communities and reef management areas—with their own and varied cultures and priorities—conduct monitoring to manage their local reefs. Monitoring variables and protocols need to be customized to their needs. They may focus on locally important species and resources, use local names that differ to scientific taxonomy, and use variants of monitoring techniques to suit their capacity and context.

An early WIO example was seen in 1999, when local fishers, park rangers, project staff, and scientists—led by Kenya Wildlife Service, WWF Kenya, and CORDIO—began monitoring in the Kiunga Marine Reserve. For the first global GCRMN reports (up to 2008), aggregating this data with that from other researchers and institutions was done manually, summarized from projects. Then the summaries were aggregated through national tables and reports to the regional, then global, level. However, this approach requires herculean efforts to summarize and aggregate data, and each biannual GCRMN report is an entirely new endeavor.

Now, advancements in technology and applications have changed the game, allowing seamless aggregation of data from multiple sources into big datasets with multiple uses. At last, there is real potential to move beyond just coral cover to a richer set of variables for describing reef health, on a global scale.

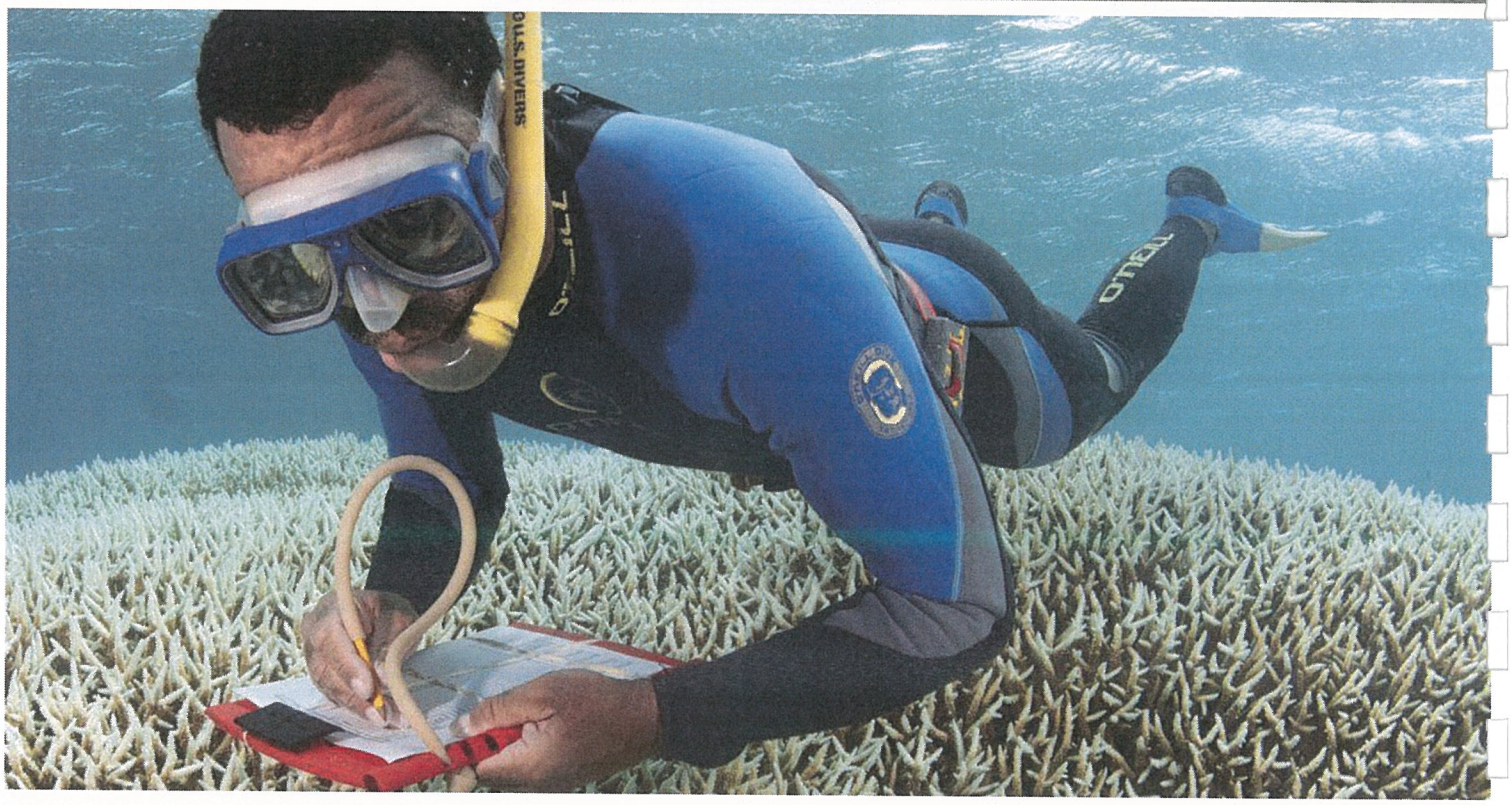
The WIO region is an excellent example of where this local to regional, and even global data-uptake has transformed over the last five years. This transformation has been facilitated by regional cooperation frameworks such as the Indian Ocean Commission and Nairobi Convention, through the Nairobi Convention Coral Reef Task Force (CRTF), established in 2001. The CRTF provides a regional framework for monitoring and reporting on the status of coral reefs. It also combines two nodes of the GCRMN, East Africa and the Southwest Indian Ocean Islands.



Monitoring effort at coral reef monitoring sites (benthic) in the Western Indian Ocean

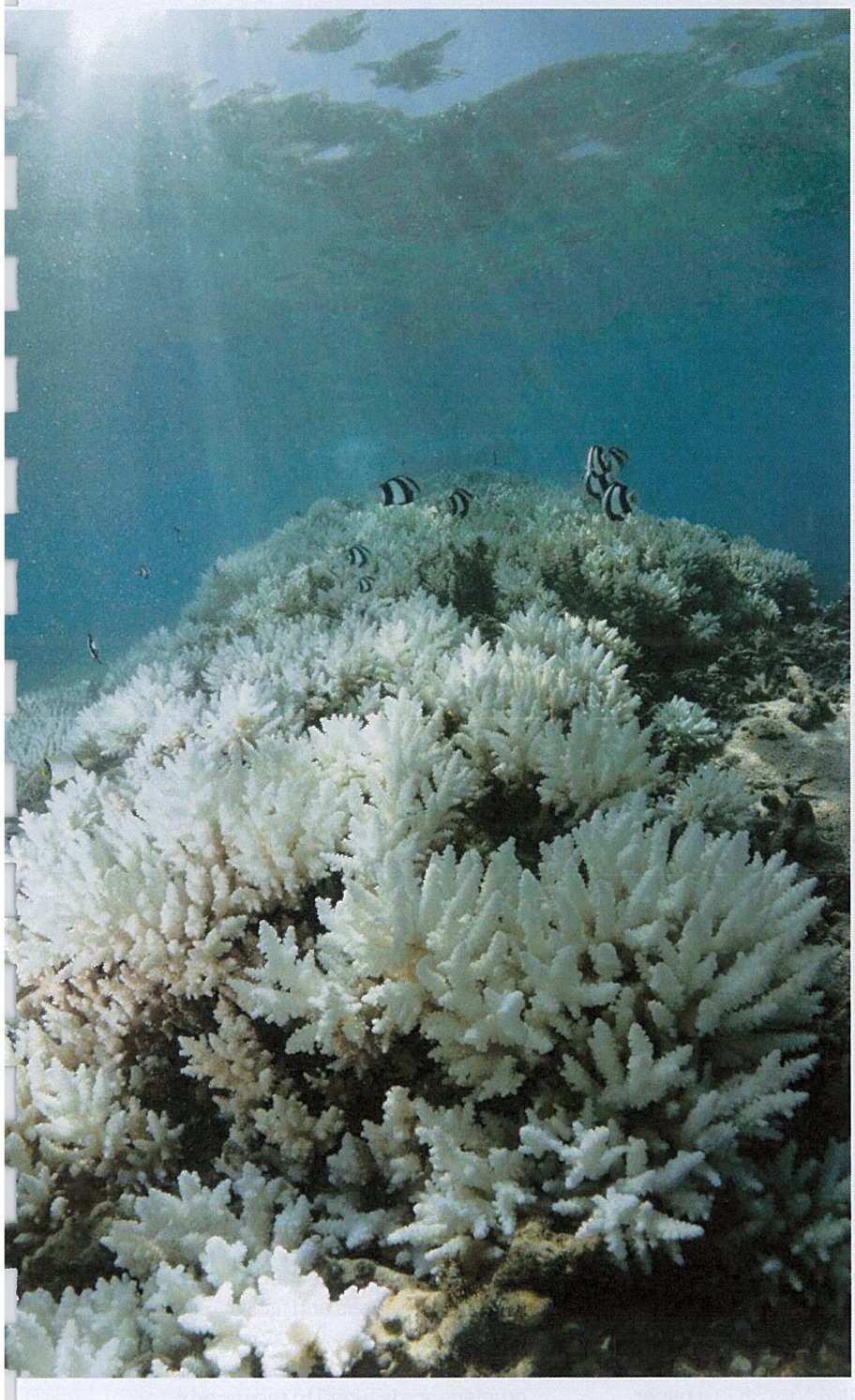
The Indian Ocean Commission's Biodiversity Programme, funded by the European Union, supported the implementation of two key projects: i) the first quantitative assessment of data on coral reef health by the regional monitoring networks in the WIO, producing a regional coral reef status report in 2017; and ii) an assessment to determine the impact of the third global coral bleaching event on the WIO in 2016. This led to the collation of the first regional dataset of the CRTF monitoring network, including benthic and fish data from researchers, NGOs, national research institutes, universities, and coral reef management agencies. In 2019, a third update of the dataset was completed and contributed to two processes: the first regional coral reef Red List of Ecosystems, and the Global GCRMN coral reef status and trends report 2020 (the first global report since 2008). To date, this collaborative effort has gathered data from over 1000 monitoring sites across the region. Bringing this data together and making it increasingly accessible can increase the impact and utility of individual datasets, while also giving direction to valuable studies and analyses on the status and vulnerability of reefs at all scales, from the local to the regional.





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Sailors on a traditional dhow sailing boat against sand dunes off Lamu Island on the north coast of Kenya.

Monitoring coral bleaching with snorkel c.Keith Ellenbogen

Bleached corals - Mayotte c.Julien Wickel

Over the next few years, the regional Red List of Ecosystems for coral reefs will be used as the basis for more detailed national scale coral reef assessments in Kenya, Tanzania, and Mozambique. This will merge the network data collection mechanisms into national policy processes, providing more nuanced and contextual information to guide local action, national strategy and policy setting, and data-driven reporting on coral reef health.

David Obura, founding director of CORDIO East Africa, said, "This process is demonstrating the value of structured data-sharing in the region. We have a highly collaborative environment and culture, but it needs a formal system to facilitate the process. We are trying to build on these foundations. With support from the motivated reef network, we should be able to achieve our objectives of expanding the scope of coral reef research and management in the region."

Now in 2020, potentially still a pivotal year for biodiversity, climate, and the ocean, global conventions will be looking for an update to the GCRMN 1998 "16 percent" finding. The GCRMN is targeting this with its new report to be published later this year. It builds on the regional data aggregation process from the WIO and other GCRMN regions that cover all the world's coral reefs. Once compiled, the global and regional datasets can serve multiple purposes, helping countries scale up efforts nationally as well as focus on more local initiatives.

Some countries struggle to report against several conventions and agreements, such as the Convention on Biological Diversity and the Sustainable Development Goals, and many have obligations under regional conventions and fora. In the Western Indian Ocean, the coral reef dataset compiled under the Nairobi Convention's Coral Reef Task Force could provide a consistent base of information supporting coral reef action within and among the region's countries.

Reporting in 2020 will be a crucial milestone for this process, but it takes time to build the systems and relationships needed. The next decade will prove critical. But thankfully we see fresh opportunity to make this happen. The two upcoming United Nations 'Decades' on ocean science and ecosystem restoration are highly relevant to coral reefs and can support the process. These Decades, along with the renewal of global biodiversity goals 2021-2030 and Sustainable Development Goals, should provide us with the tools and connections needed to effectively monitor and protect the world's reefs. Never has the need been greater.

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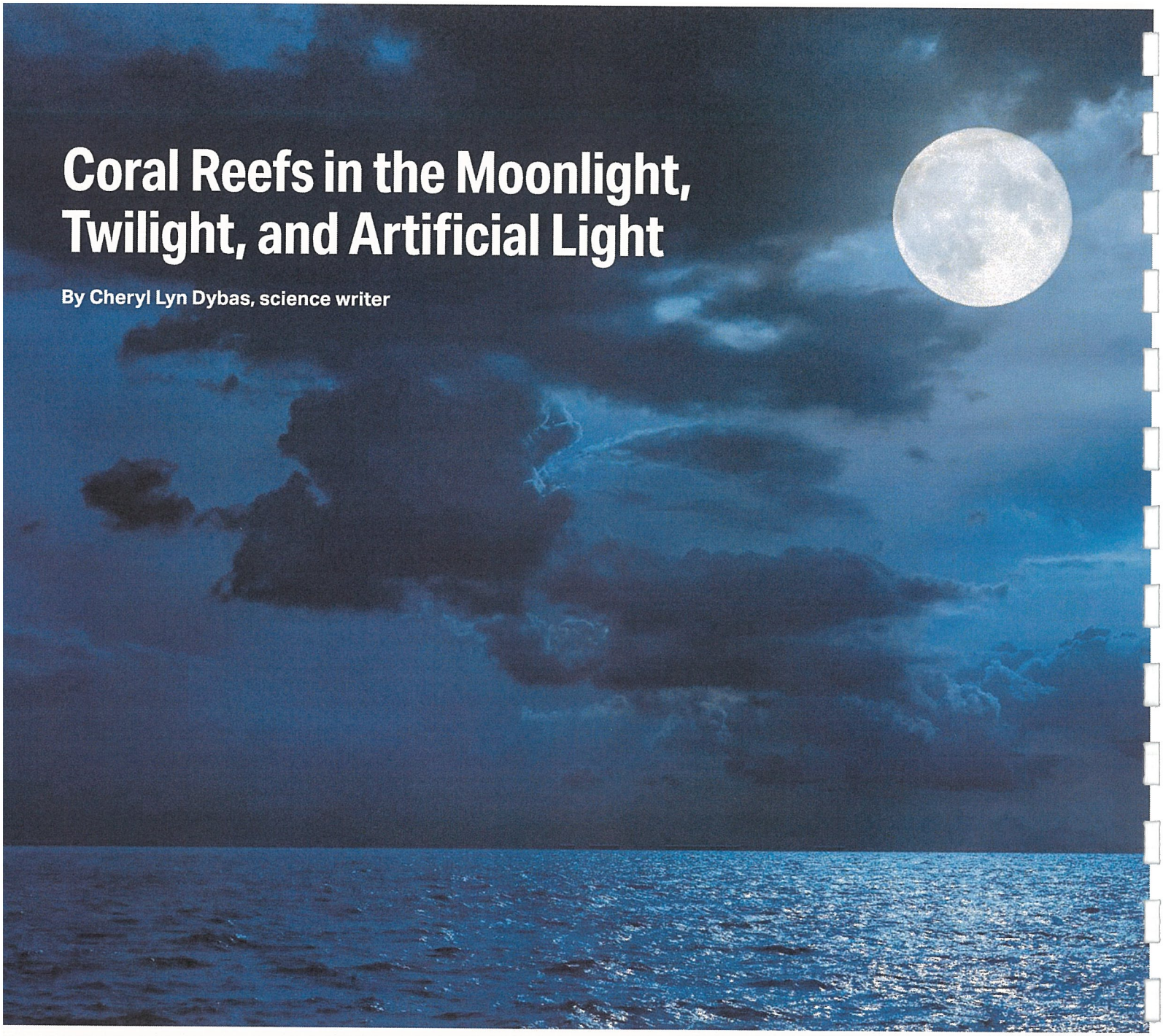
2016 third global coral bleaching event impact assessment: www.cordioea.net/coral-bleaching/wio-post-bleaching-assessment-2017/

2017 Regional Coral Reef Status report: www.cordioea.net/wio-monitoring/gcrmnwio2017/

2019 Red List of Ecosystems of Coral Reefs of the Western Indian Ocean update: https://cordioea.net/research-assessment/norad/rle/

Coral Reefs in the Moonlight, Twilight, and Artificial Light

By Cheryl Lyn Dybas, science writer



Moon phases: Visible in the deep-sea?

The moon's phase drives tides on the Earth's surface, but could it also affect processes far, far below, in the depths of the sea?

Marine scientist Annie Mercier of Memorial University in St. John's, Canada, and her colleagues say the answer is yes. They found evidence of lunar periodicity in the reproduction of six deep-sea species, including corals. Release of gametes in free-spawning species, and of larvae in brooding species, peaked around the new and full moons respectively, says Mercier.

But how? Can a life form in the abyss "see" the moon?

"The nature of the lunar period and its significance in the deep-sea remain elusive," states Mercier in a paper published in the *Journal of Biological Rhythms*. Possible explanations, she says, include fluxes in particulate matter floating from the sea's surface to its depths, or cyclic currents—or the ability of deep-sea species to directly perceive the moon's light.

In near-surface environments bathed in moonlight or exposed to the tides (and hence the moon), biological rhythms synchronized with lunar phases are common. Lunar reproduction cycles are found in reef corals and fishes. Spawning in many shallow-water tropical and subtropical echinoderms, mollusks and crustaceans is tuned to the moon's phases.

Deep-sea environments, however, which make up more than 66 percent of the Earth's surface, "are virtually overlooked," says Mercier, "given the difficulties of studying deep-sea organisms *in situ* and in the laboratory."

With The Deep's dim light and weak tides, "the existence of lunar periodicity hadn't been thought about," she says.

Nonetheless, in the sea urchin

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Phormosoma placenta, spawning in both sexes coincides with the new moon. The deep-sea coral *Gersemia fruticosa* releases its peak number of planulae, or free-swimming larvae, at the full moon. Another deep-sea coral, *Drifa*, concentrates its efforts at the waning moon phase. *Flabellum angulare*, a third deep-sea coral, is a new-moon spawner, while the deep-sea anemone *Allantactis parasitica* spawns at the time of the full moon.

There's a scattering of other reports on deep-sea synchronicities with the moon. Peak deposition rates of planktonic foraminifera at 2,700 meters down, for example, happen 12.5 days after each full moon. Changes in melatonin release in deep-sea fishes follow tidal oscillations. And growth bands in deep-sea gorgonians linked with lunar periods may result from an influx of sediments that's timed with moon phases.

How widespread lunar reproductive cycles are in the ocean's depths, says Mercier, "is a big question. Moon-related cycles may offer a means of coordinating breeding activities, critical for species that cue to spawning going on around them." Since breeding often coincides with the brightest or darkest nights of the lunar cycle, she says, "timing it to conceal one's offspring may be what's really going on."

In her study, internally brooding corals released larvae at the full moon or during the waning phase; free-spawning species timed gamete release with the new moon. "While these patterns apparently contradict the full-moon mass events in broadcast-spawning shallow-water corals," says Mercier, "they need to be looked at in light of the environmental and predatory pressures of coastal versus deep-sea habitats."

For now, however, what happens in The Deep stays in The Deep.

Sunset sonata: Corals, the moon and 'the blue pulse'

Shallow-dwelling corals also spawn on cue; they, too, may be timing the event to the phase of the moon. Coral reefs release eggs and sperm all at once for one, or at most a few, consecutive summer nights right after sunset on the evenings after a full moon.

What's the signal that says "go"?

Scientist Alison Sweeney of Yale University wondered whether corals' spawning events might happen not only on a certain day, but at a certain time. Could they be synchronized with fluctuations in the light spectrum at twilight?

"There are dramatic--and physiologically relevant--changes in both skylight color and intensity during evening twilight," says Sweeney. "The path length of direct sunlight through the atmosphere increases, and skylight becomes increasingly blue-shifted."

The twilight spectrum is deep blue before the moon rises, but after moonrise becomes more red. During the first half of the lunar month, the moon is already in the sky at sunset and the twilight spectrum is therefore red-shifted. But at full moon, when the moon is just below the horizon at sunset, there's a brief period before moonrise when the spectrum of skylight is a deep twilight blue.

Sweeney thought that corals and other reef species could be using this "pure twilight" to synchronize spawning, but only if the spectrum of light in the ocean followed the same pattern as that of skylight.

By measuring the light spectrum in the sea near a tropical coral reef over a six-day period around the full moon, she found that the twilight spectrum shifted depending on whether the moon had risen. A team of researchers measured twilight irradiance on August 3, 4, 6, 7 8 and 9, and observed a "significant effect of lunar elevation on underwater irradiance on the evenings around the full moon," says Sweeney. "The twilight spectrum was deep blue just after sunset, but gained red wavelengths as soon as the moon rose. The length of the blue twilight period increased each evening as the moon rose later and later."

She calls it "the blue pulse."

The scientists also monitored elkhorn coral spawning. The corals spawned simultaneously between 21:30 and 21:50 on the third and fourth nights after a full moon. The researchers published their results in *The Journal of Experimental Biology*.

"Somewhat counterintuitively," they wrote, "no eyes are required to detect these spectral changes. In fact, eyes probably reduce the ability of an organism to perceive low-intensity changes such as these. A broad, unobstructed sheet of photoreceptive tissue like that present in corals and sea urchins would actually be the optimal detector design for observing this spectrum."

What happens on nights when the moon hides behind clouds? Sweeney says that corals are capable of detecting changes in light even on overcast evenings.

Artificial light may also affect corals. It's red-shifted compared with both moonlight and sunlight, "and may therefore alter twilight spectral dynam-

ics," says Sweeney. "With many of the world's coral reefs located in attractive travel destinations and densely-populated coastal cities, it's important to investigate the effects of artificial light on corals' spawning."

What's next on the horizon? Sweeney is testing the effects of skylight spectra on spawning to find out for sure: are corals-in-love moonstruck?

The answer may lie in corals' light-sensitive proteins called extraocular (outside the eye) opsins, close evolutionary variants of the visual opsins in our eyes' retinas. The biological role of corals' extraocular opsins, says Sweeney, "isn't yet clear and is being actively investigated. Tissues expressing these opsins could use twilight to extract significant information about lunar phase and time of day."

Corals in the twilight zone: Who eats what on a deep Red Sea reef

Many coral reefs are found below scuba diving depths. Because of the difficulty in visiting these parts of the ocean, the biology of mesophotic (twilight zone) reefs is little understood. The reefs are abundant, however, and scientists believe there is an urgent need to develop a better understanding of these unique ecosystems.

Now Monaco Explorations is providing support for the study of mesophotic coral reefs in the Gulf of Aqaba in collaboration with the Inter-University Institute in Israel and the Monaco Scientific Centre (CSM). Christine Ferrier-Pages, head of the CSM coral ecophysiology team, is leading a mission to understand how photosynthetic corals can survive in such deep and low-light environments.

The Gulf of Aqaba, or Gulf of Eilat, is a large waterbody at the northern tip of the Red Sea, east of the Sinai Peninsula and west of the Arabian mainland. Its coastline is divided among four countries: Egypt, Israel, Jordan and Saudi Arabia.

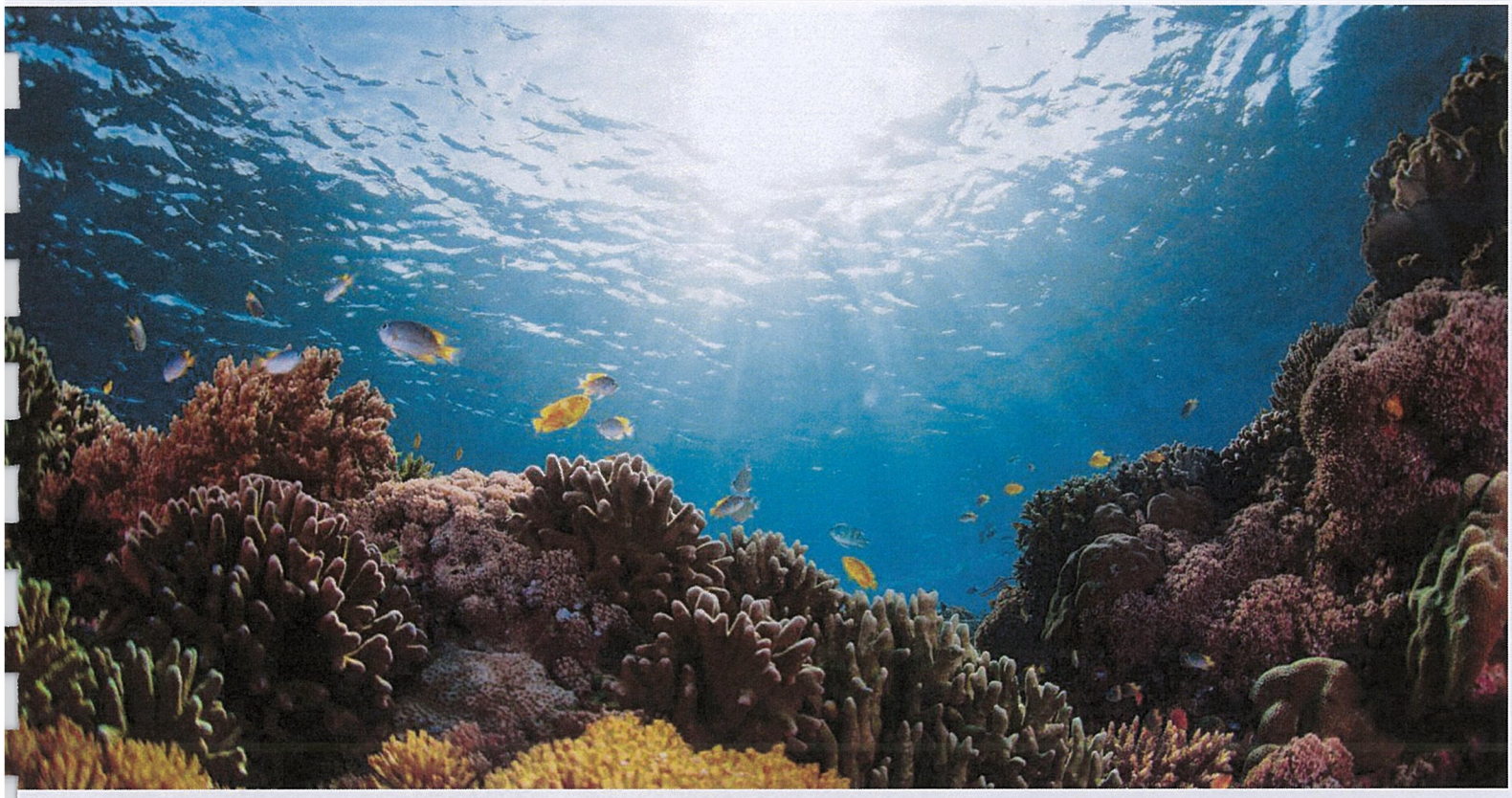
"We know very little about the deep-water reef systems there, but they may be important when it comes to the survival of coral reefs in global climate change," says Ferrier-Pages. "Being able to access these unique places using technical diving and remotely operated underwater vehicles [ROVs] is a crucial part of our current mission."

The Gulf of Aqaba is unique in being relatively deep (800 meters at its center) and narrow. This brings mesophotic reefs close to shore - making them easily accessible for scientific study. Standard research techniques allow scuba diving



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from shore to reefs at depths nearing 60 meters. Deeper than that, ROVs are used.

The team is conducting its study aboard the research vessel *Sam Rothberg*, which leaves a marina in Eilat every morning. The researchers are looking at the different characteristics of habitats where deep corals are growing. They're exploring sites between 60 and 150 meters below the surface. Several coral-dominated mesophotic regions are on the list, a unique opportunity to study corals in the Red Sea, says Ferrier-Pages.

Is increasing artificial light at night a danger to coral reefs?

The potentially damaging effect of artificial light at night on the reproduction of reef corals is becoming a widespread concern. It's the subject of new research by scientists at the University of Southampton in the UK.

Thanks to funding from a Natural Environment Research Council grant, Southampton scientists Jorg Wiedenmann and Cecilia D'Angelo of the university's Coral Reef Laboratory are tackling gaps in our understanding of how the reproduction of reef corals is affected by artificial light at night.

They're working with a team at Bangor University and other U.K. universities, the Interuniversity of Marine Science Eilat and Bar Ilan University in Israel, and the Horniman Museum London.

"Coral reefs are immensely valuable ecosystems," says Wiedenmann, "but they are in serious decline due to global warming and human impacts such as coastal construction, overfishing, pollution and nutrient enrichment. The key to coral reef survival is for the remaining individuals to produce enough offspring that can survive on damaged reefs and help them recover."

To maximize reproductive success, many corals release their eggs and sperm at the same time, sometimes in only a single night of the year in a process called mass coral spawning, scientists from Wiedenmann to Annie Mercier to Alison Sweeney have found. The timing of mass coral spawning is thought to be synchronized and triggered by the light of the moon. The scientists fear that increasing amounts of artificial light at night may override the signal of the moonlight, resulting in a less efficient synchronization of coral reproduction and reduced recruitment of juvenile corals on reefs.

Artificial "sky glow" can now be detected along 22 percent of the world's coasts every night. That figure is expected to increase dramatically as coastal human populations more than double by 2060.

Many coastlines are exposed to artificial light at night near piers, promenades, ports, harbors and dockyards, increasingly with white LED lighting, which penetrates deeper into seawater than older lighting technologies.

LED lighting is predicted to make up 69 percent of global lighting by 2020, exacerbating the impacts of artificial light at night.

The coral research at Southampton is part of a larger project led by the University of Bangor that studies the impact of artificial light at night on marine life.

"The presence of artificial light in coastal regions has the potential to interfere with natural light cycles and related biological processes, ultimately reshaping the ecology of coastal habitats," says Wiedenmann. "We know that many marine invertebrates are extremely sensitive to natural light throughout their life cycles and that gradients of light intensity and color, largely caused by variations in moonlight and sunlight, are major factors in marine ecosystems."

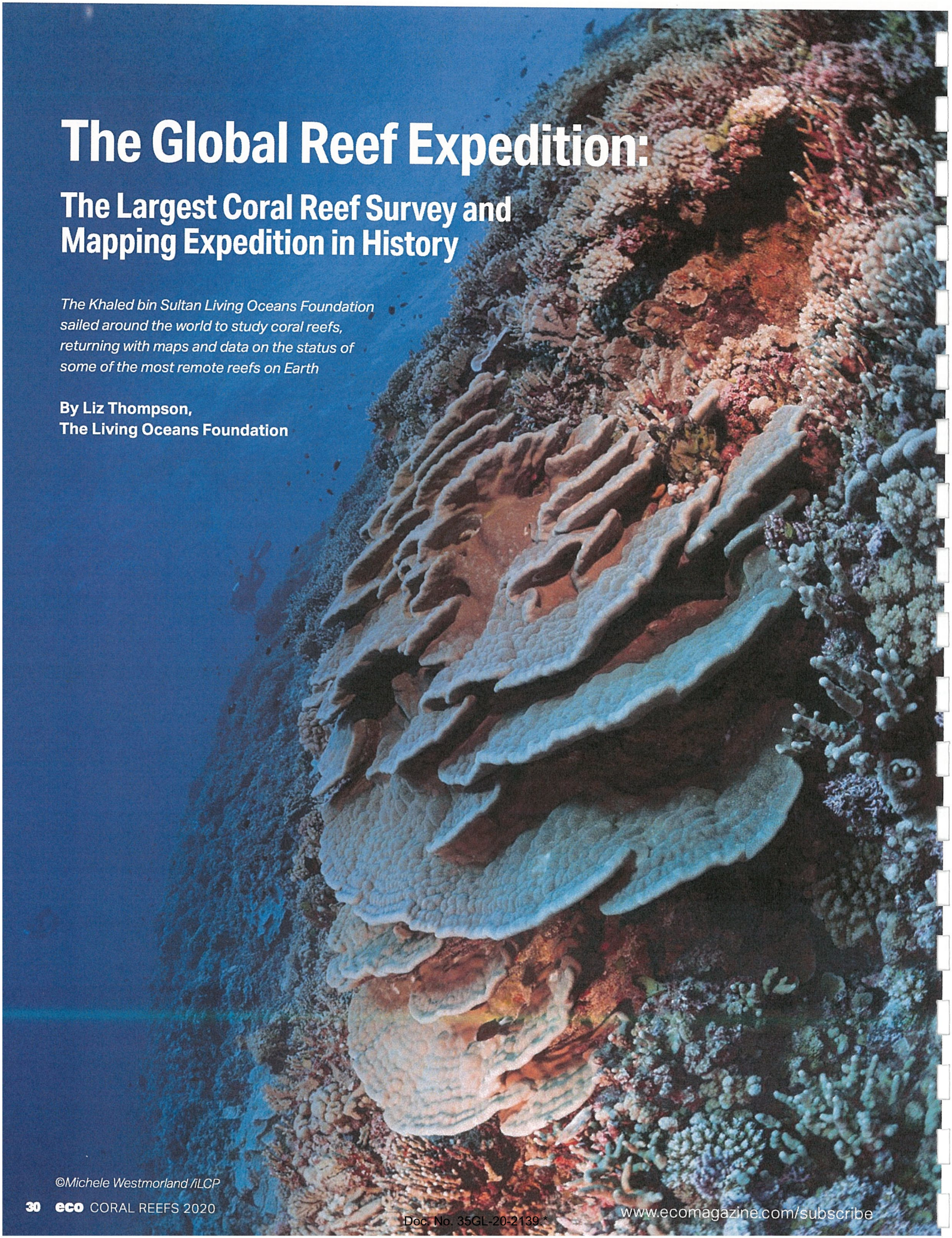
He and colleagues believe that scientists need to find out how much damage is caused by artificial light at night, and quantify the benefits of less intense forms of artificial light on corals and other marine species. "That," Wiedenmann says, "is vital to the future of coastal habitats around the world."

The Global Reef Expedition:

The Largest Coral Reef Survey and Mapping Expedition in History

The Khaled bin Sultan Living Oceans Foundation sailed around the world to study coral reefs, returning with maps and data on the status of some of the most remote reefs on Earth

By Liz Thompson, The Living Oceans Foundation



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In 2011, the Khaled bin Sultan Living Oceans Foundation embarked on the Global Reef Expedition—an ambitious research mission to study the health and resiliency of coral reefs around the world. The expedition circumnavigated the globe mapping and surveying some of the most remote coral reefs on the planet. Many of these reefs had never been studied by scientists before.

The Foundation assembled an international team of scientists, photographers, videographers, and conservationists, who worked hand-in-hand with local leaders. This team includes nearly 200 scientists from 25 countries to assess reefs across the western Atlantic, Pacific, and Indian Oceans. Together, they took a snapshot in time, recording the health of coral reefs on Earth as they are today.

The Global Reef Expedition team mapped and characterized the world's coral ecosystems, identified their current status and major threats, and examined the factors that enhance their ability to recover from major disturbance events such as bleaching and cyclone damage, or outbreaks of crown-of-thorns starfish. After five years of studying over 1,000 coral reefs in 15 countries and conducting more than 11,000 standardized surveys documenting life on the reef and the seafloor, the field research is complete. Now, scientists are releasing their findings from the largest coral reef survey and mapping expedition in history.

Scientists are still analyzing the data, but what they saw can't be ignored. There was evidence of human impacts everywhere they went: the big fish were gone, plastics and discarded fishing gear were found on the most isolated reefs on Earth, and corals were bleaching before their eyes. The problems coral reefs faced varied between sites, and each reef had its own suite of issues to address, both natural and man-made. While some areas were in surprisingly good shape, almost all countries visited on the Global Reef Expedition showed signs of coral reefs in crisis.


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Coral reefs are considered a keystone ecosystem for assessing the health of the entire ocean. Although they occupy less than one-quarter of one percent of the marine environment, more than a quarter of all known marine fish species spend at least part of their lives in these delicate habitats. They are also vital ecosystems for humans. It is thought that one in seven people worldwide depends on coral reefs for food or income, so their impact on people far outstrips their relatively small size.

The grand idea behind the Global Reef Expedition was to get a baseline assessment of coral reef health around the world and, hopefully, find places resilient to change. The expedition specifically chose to explore remote reefs far from civilization, particularly those relatively free from human influence. Yet, they also surveyed reefs that were close to ports and heavily fished. By comparing the health and ecological condition of remote and relatively pristine coral reefs with those that have been compromised by chronic stress from human use, the Foundation can create models of coral reef health and resiliency and identify high-priority sites for protection.

The Living Oceans Foundation was able to access these remote reefs using the M/Y *Golden Shadow*, a 219-foot

yacht with dedicated laboratory facilities. Also on board was a diving decompression chamber and an onboard aircraft—the Golden Eye—that was used extensively for aerial surveys of coral reefs. This modern and advanced research vessel was made available to the Foundation by Prince Khaled bin Sultan of Saudi Arabia, who donated the use of his own ship for the Global Reef Expedition.

On this epic voyage, the science team observed coral bleaching on pristine reefs in the Indian Ocean and explored the little-known cold-water coral reefs of the Galápagos Islands. They also conducted what was probably the last survey of healthy reefs in the northern reaches of the iconic Great Barrier Reef, before they were decimated by a mass bleaching event.

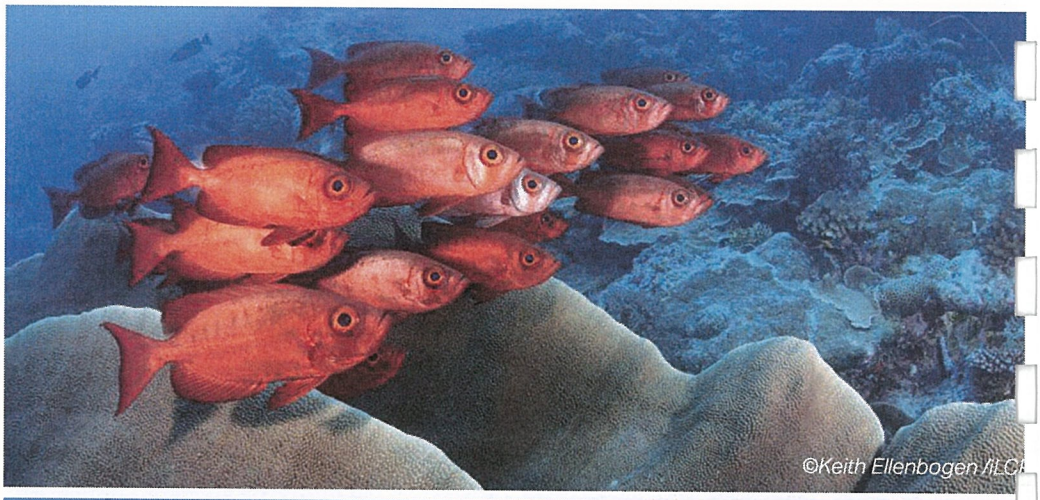
The first stop on the Global Reef Expedition was in The Bahamas. Here, scientists wanted to see how coral reefs were surviving under the triple threats of climate change, coral disease, and loss of several keystone species.

The Global Reef Expedition then traveled to Jamaica, where the Foundation teamed up with local fishers and conservation organizations to help establish a fishing sanctuary to preserve local fisheries for current and future generations. The expedition continued down through the Caribbean, and across the South Pacific, where scientists came upon many healthy and ancient coral reefs, a giant swarm of sharks, and indigenous communities who protected their reefs with rules set forth by traditional leaders centuries ago.

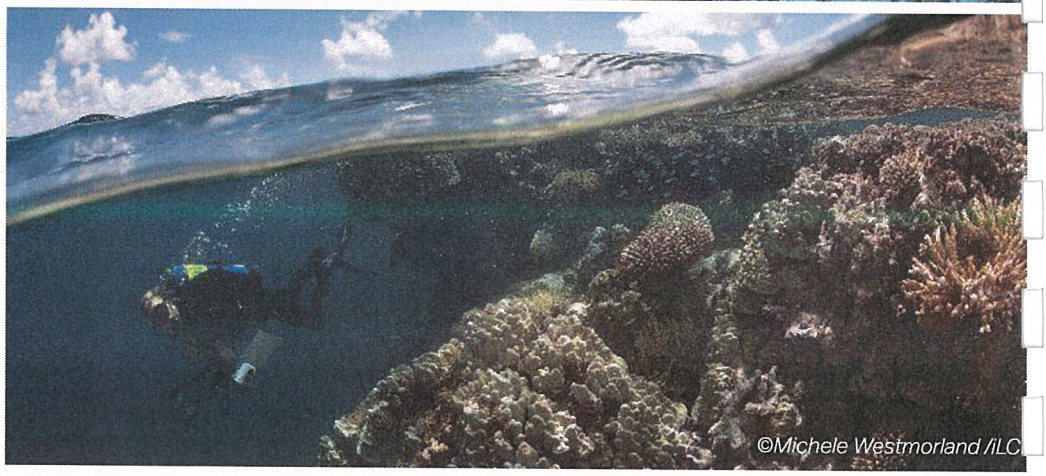
The scientists mapped and surveyed the reefs down to a one-square-meter scale to better understand their health and resiliency. In the process, they developed a new method to accurately map coral reefs using a combination of Earth-orbiting satellites and field observations. The first global coral reef atlas was published last year, combining maps collected on the expedition with the Foundation's previous research in the Red Sea. This database contains over 65,000 square kilometers of reefs and surrounding habitats—by far, the largest collection of high-resolution maps ever made of coral reefs.

The high-resolution maps contain detailed information on the location and depth of different habitats, including the size of seagrass beds and mangrove forests along the coast. All of these coastal habitats are vital components of tropical coastal ecosystems. They help filter water, protect the coast from storms, and provide a nursery habitat for commercial and subsistence fisheries. These maps and information have been shared with participating countries as well as scientific and regulatory organizations, which can be used to develop science-based management strategies to protect and restore coral reef ecosystems.

In addition to conducting scientific research, the Foundation spent time with local communities to explain the study, share preliminary results, and discover how community members use the reef and what changes they have witnessed over their lifetimes. The Global Reef Expedition also brought along educators to teach local students about coral reef habitats, and award-







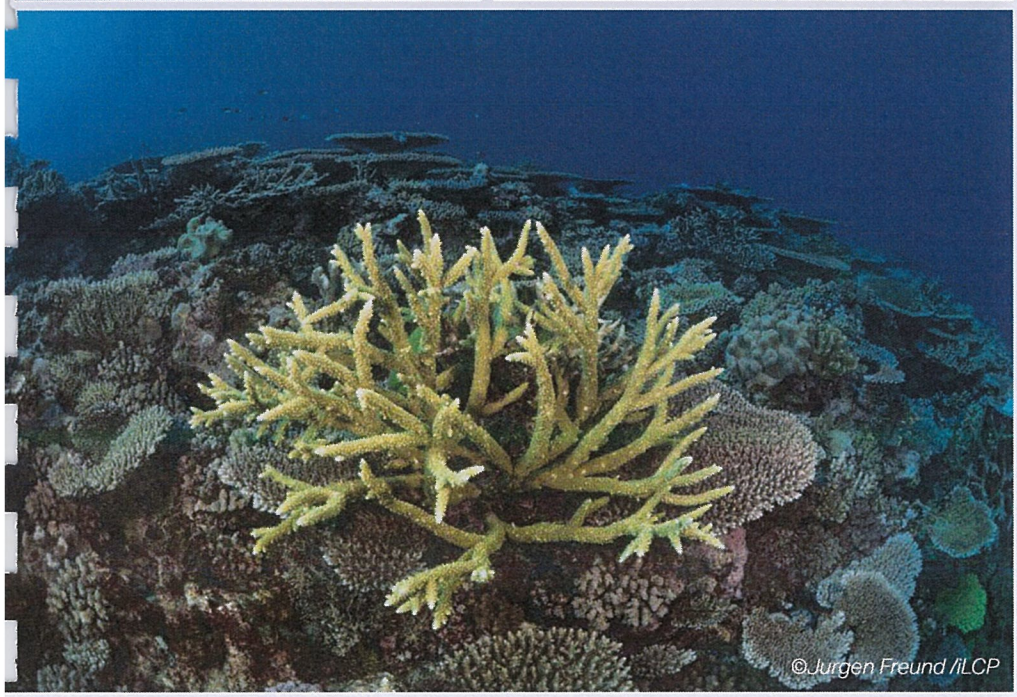
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winning filmmakers and photographers to capture the journey, documenting what the scientists saw underwater.

Now that the field research is complete, Living Ocean Foundation scientists are analyzing the data and publishing scientific reports about the status of coral reefs in each country visited on the Global Reef Expedition. The Foundation recently released reports on the state of coral reefs in French Polynesia, Tonga, the Cook Islands, and New Caledonia. It will soon publish reports from their research missions to the Solomon Islands and Palau.

So far, this research has informed the creation of a marine protected area (MPA) in Pedro Bank, Jamaica, and in Lau Province, Fiji, and is currently being used to inform marine spatial planning efforts across the South Pacific.

As more data becomes available, the Foundation will share the information with local resource managers and relevant government officials to protect and conserve reefs most likely to survive the coral reef crisis.

Using the data collected on the expedition, the Foundation hopes to identify the critical ecosystem components that promote coral reef resilience and produce practical reef management tools. The scientists are now working across vast geographic scales to see what factors are most important to maintaining the structural integrity and health of reefs.

By improving our understanding of these essential ocean ecosystems, we can better make predictions regarding the future health of coral reefs, including their capacity to adjust to climate change. The Foundation will also develop science-based tools and decision aids that can support plans to mitigate threats to these life-supporting marine ecosystems. Models are being created with the maps and data collected during the expedition that will allow us to make comparative assessments of coral reef biodiversity, oceanographic conditions, and human pressures. These models will describe the status of coral reef health, identify major threats, and determine processes and factors that control marine ecosystems' health and resilience worldwide.

To explore the maps and scientific reports from the Global Reef Expedition, visit www.livingoceansfoundation.org.

The Coralassist Project

Testing novel conservation interventions to help coral reefs survive the climate crisis

By James Guest with contributions from John Bythell, Alasdair Edwards, Achim Treumann, Adriana Humanes, Pawel Palmowski, Elizabeth Beauchamp, Liam Lachs, Eveline van der Steeg, and Helios Martinez (School of Natural and Environmental Sciences, Newcastle University), Yim Golbuu (Palau International Coral Reef Center), Julia Strahl (University of Oldenburg) and Caroline Palmer (Plymouth University)

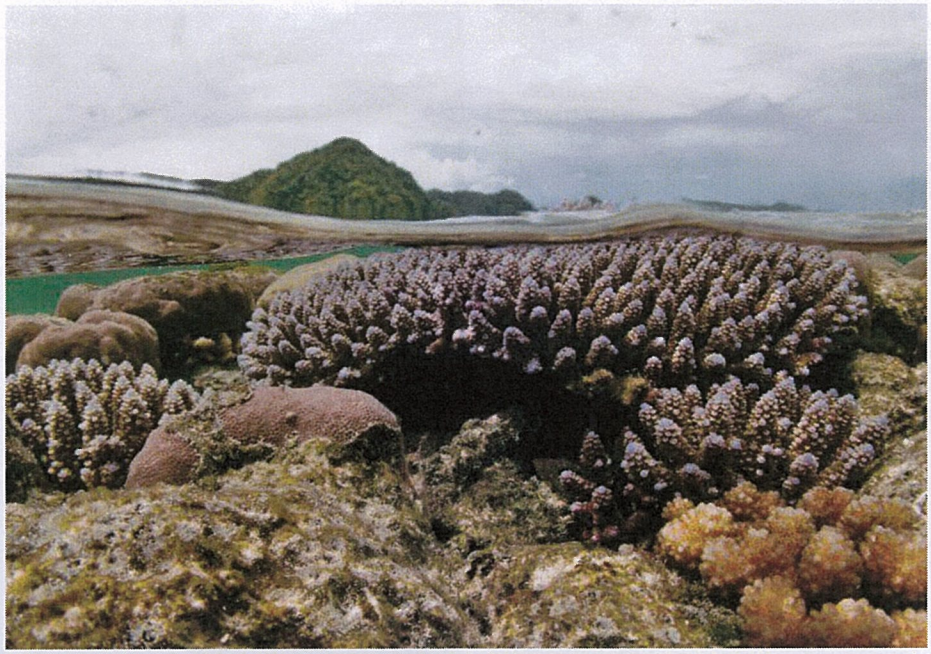


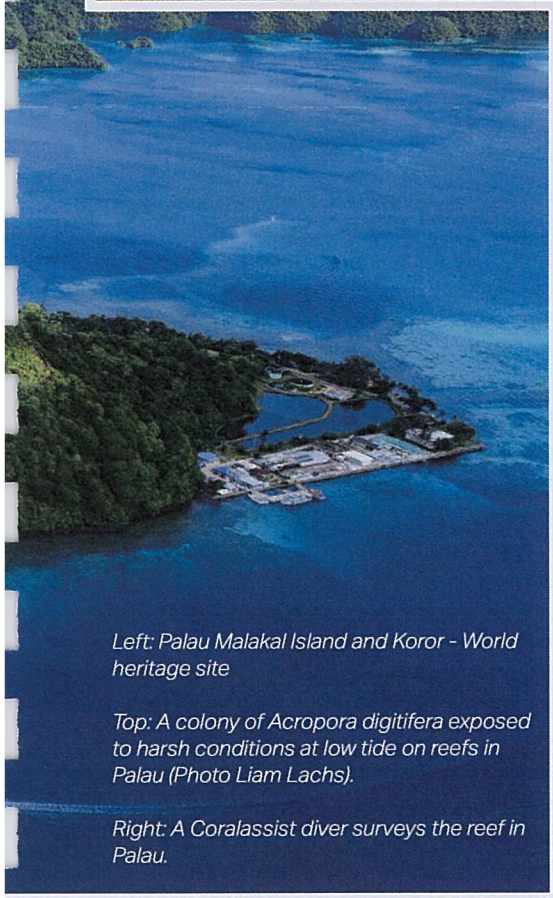
For a coral reef ecologist, Palau is one of the most remarkable places on Earth to conduct research. Consisting of a series of isolated oceanic islands, and lying just 7 degrees north of the equator in the Indo-West Pacific Ocean, Palau's reefs have escaped and resisted the impacts that have devastated many of the world's coral reefs. The relative resilience of Palau's reefs makes them the ideal research base for Coralassist, a European Research Council Horizon 2020 funded project, whose aims are to search for and breed more heat-tolerant corals.

Coral reef ecosystems are often compared to tropical rainforests because of their remarkable biodiversity. Yet, during the last few decades, we have witnessed massive losses of corals due to human activities. Declining reef health has enormous implications for society, as coral reefs are considered to be one

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Left: Palau Malakal Island and Koror - World heritage site

Top: A colony of Acropora digitifera exposed to harsh conditions at low tide on reefs in Palau (Photo Liam Lachs).

Right: A Coralassist diver surveys the reef in Palau.

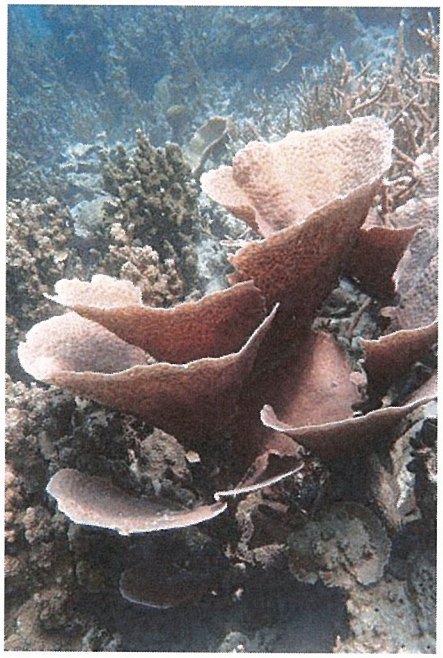
of the most valuable ecosystems on the planet, in terms of the ecological goods and services that they provide. Climate change is implicated as the biggest driver of reef decline, although coastal development, pollution, and overfishing have also taken a tremendous toll. These valuable ecosystems have become sentinels for the emerging climate crisis and will be one of the first ecosystems irreparably changed if we do not rapidly reduce greenhouse gas emissions.

Corals are highly susceptible to small increases above normal summertime average temperatures. When the water gets too hot for more than a few days, the relationship between the coral animal and its microscopic symbiotic algae breaks down, and corals become ghostly white due to the loss of algal photosynthetic pigments, a process known as coral bleaching. If prolonged, this can lead to the corals dying in large numbers in the space of just a few months. For example, evidence suggests that a staggering 50 percent of corals on Australia's iconic Great Barrier Reef died as a result of back to back heatwaves in 2016 and 2017. The primary solution to this problem is to reduce the pressure on reefs by reducing greenhouse gas emissions, but even acting now on climate change may not be enough for many. This knowledge has led us, and many fellow scientists, to explore what other options exist for 'future-proofing' against anticipated heatwaves. These do not solve the problem of declining reef health but may help buy time for some high-value reefs while dealing with the root causes of decline.

Reefs are resilient and recover naturally after a major bleaching event if given enough time.Still, it usually takes between five and ten years for a reef to return to something resembling its original state. If the intervals between bleaching events become too short (one to two years), then vital recovery processes may fail (i.e., recruitment, growth, and reproduction). Corals can also adapt to higher temperatures, either through natural selection or a process known as acclimatization, whereby the experience of non-lethal stress makes a coral more resistant to subsequent stressful events. However, we don't yet know if the rate at which corals can adapt and acclimatize is fast enough to keep up with the current pace of warming. This has led to suggestions that we may need to "assist evolution", by finding ways to produce more robust corals and use ecological restoration approaches to seed them onto vulnerable reefs. This is enormously challenging. Growing corals to adulthood is a labor-intensive and expensive process, especially in enough numbers to repopulate vast areas of the degraded reef. There are also huge unknowns about these approaches. For example, we know little about the process of heritability in most corals, and heat-tolerant



Selecting the toughest corals on the reef. Coral colonies are tagged and mapped on the reef (upper left panel), small "nubbins" are exposed to realistic heat stress in aquarium tanks over time (upper right panel), differences in health status of each nubbin are recorded over time to differentiate between more and less heat tolerant individuals (lower panel).(Photos Jamie Craggs, James Guest, Adriana Humanes).



A colony of Echinopora lamellosa in Palau.

corals may also grow slower or produce fewer offspring. Much research is still needed before assisted evolution can be implemented as an effective management and conservation strategy.

Since 2017, our international team, led by researchers from Newcastle University, has spent extended periods conducting experiments at the Palau International Coral Reef Center. The main goal of the Coralassist project is to find the hardiest corals. This is done by carrying out heat stress tests on small pieces of coral, referred to as "nubbins", clipped from tagged colonies to see which ones survive. During these experiments, we stress-test nubbins in flow through sea-water tanks by gradually increasing the water temperature to mimic a natural coral bleaching event. We assess the average health status of several nubbins from each colony (i.e., level of bleaching, partial mortality, or death) to compare the performance of each coral colony over time.

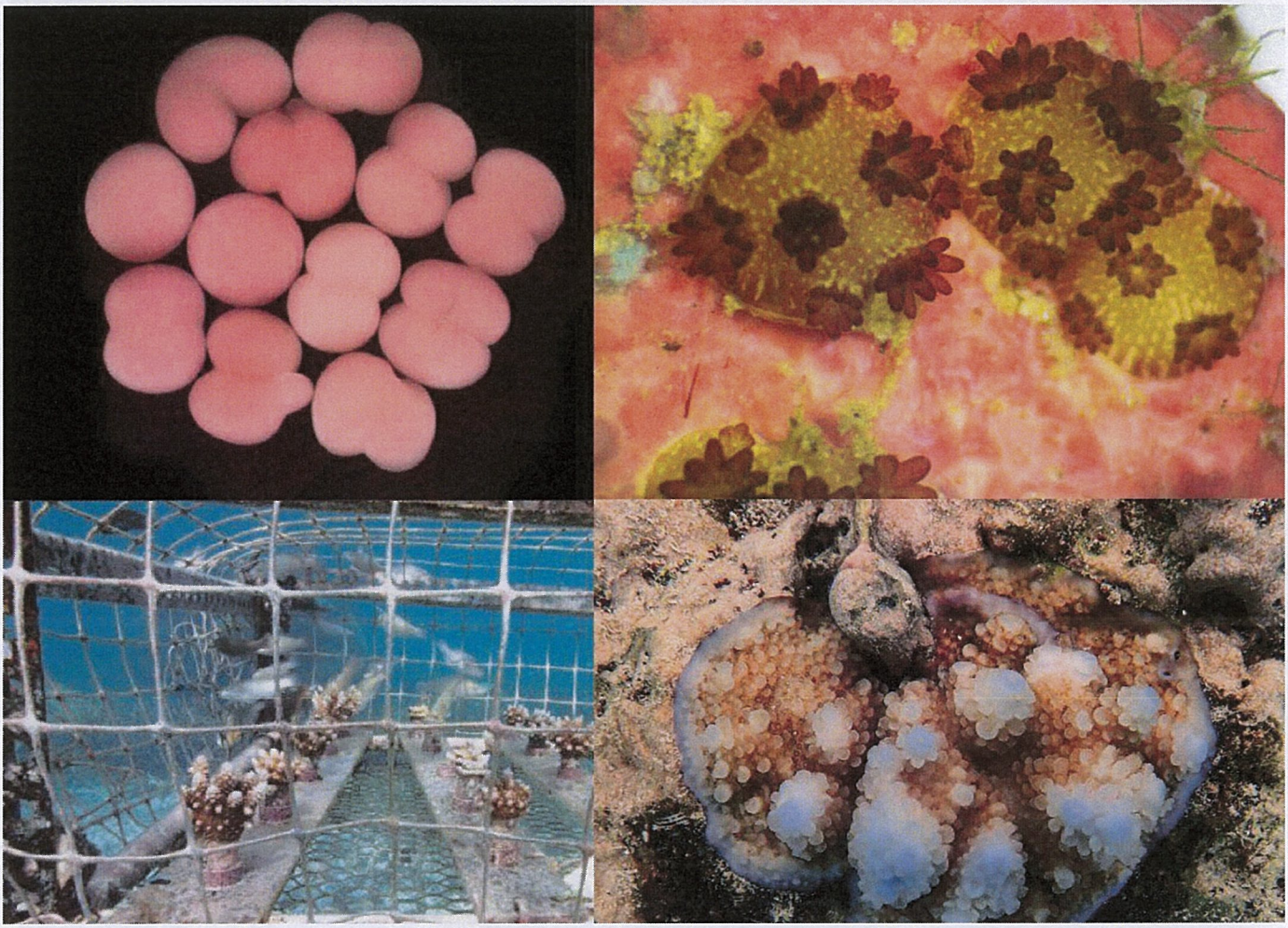
The experiments have shown that there is considerable variation in the way individual colonies respond to heat stress, even within a single population. This is important as it provides the necessary material for selective breeding. Once we know which coral colonies are the hardiest on the reef, we bring them into the lab just before they are ready to spawn to carry out selective crosses. This is by no means a straightforward task as corals tend to spawn only once a year on a specific few nights. If that one event is missed, we have to wait an entire year to get another shot. Once fertilized and settled, we grow the coral offspring, partly in aquarium tanks and partly in nurseries near to the reef, and when large enough, some baby corals are outplanted directly to the reef. The next stage is to see if offspring are as tough as their parents by doing further heat stress tests at different life stages (e.g., as larvae, juveniles and adults). If we find that our selectively bred corals inherit higher heat tolerance from their parents, the ultimate goal is to seed large numbers of these tougher corals onto reefs to test if this boosts the population's average heat tolerance. If successful, the expectation is that a higher proportion of our reared corals will survive the next bleaching event than would occur naturally.

So far, the heat stress tests that we have carried out have allowed us to identify14 potential parents for breeding from two of our study species *(Acropora digitifera* and *Goniastrea retiformis)*. We were successful in spawning and selectively breeding these corals in 2018 and 2019, and have since produced 29 unique crosses from parents for *A. digitifera* and a further 10 crosses from *G. retiformis*. To date, we have created almost 1600 first generation (F1) corals and have outplanted over 600 of these juvenile corals to the reef to assess their survival and growth rates. The remaining corals are kept in ocean nurseries near to our study sites. Unfortunately, the survivorship of small corals (less than one-centimeter diameter) we outplanted to the reef was very low due to grazing fish. Rearing corals for longer in nurseries has led to much better survival, but this requires labor-intensive husbandry.

This challenge highlights the need to develop innovative methods to overcome early mortality bottlenecks for sexually propagated corals that will reduce nursery times and increase survivorship. This may involve the development of special substrates for baby corals that provide protection from fish grazing and designs that can be attached quickly and easily to the reef. While it is still early days, the evidence from our heat tolerance tests on offspring show encouraging signs that heat tolerance has a strong heritable compo-

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Different stages of coral rearing. Newly fertilised coral embryos (upper left), 1-month old coral juveniles (upper right), 18-month old coral in an in situ nursery (bottom left) and a 2-year old coral outplanted to the reef (bottom left)(Photos Jamie Craggs, Elizabeth Beauchamp, Till Roethig, Eveline van der Steeg).

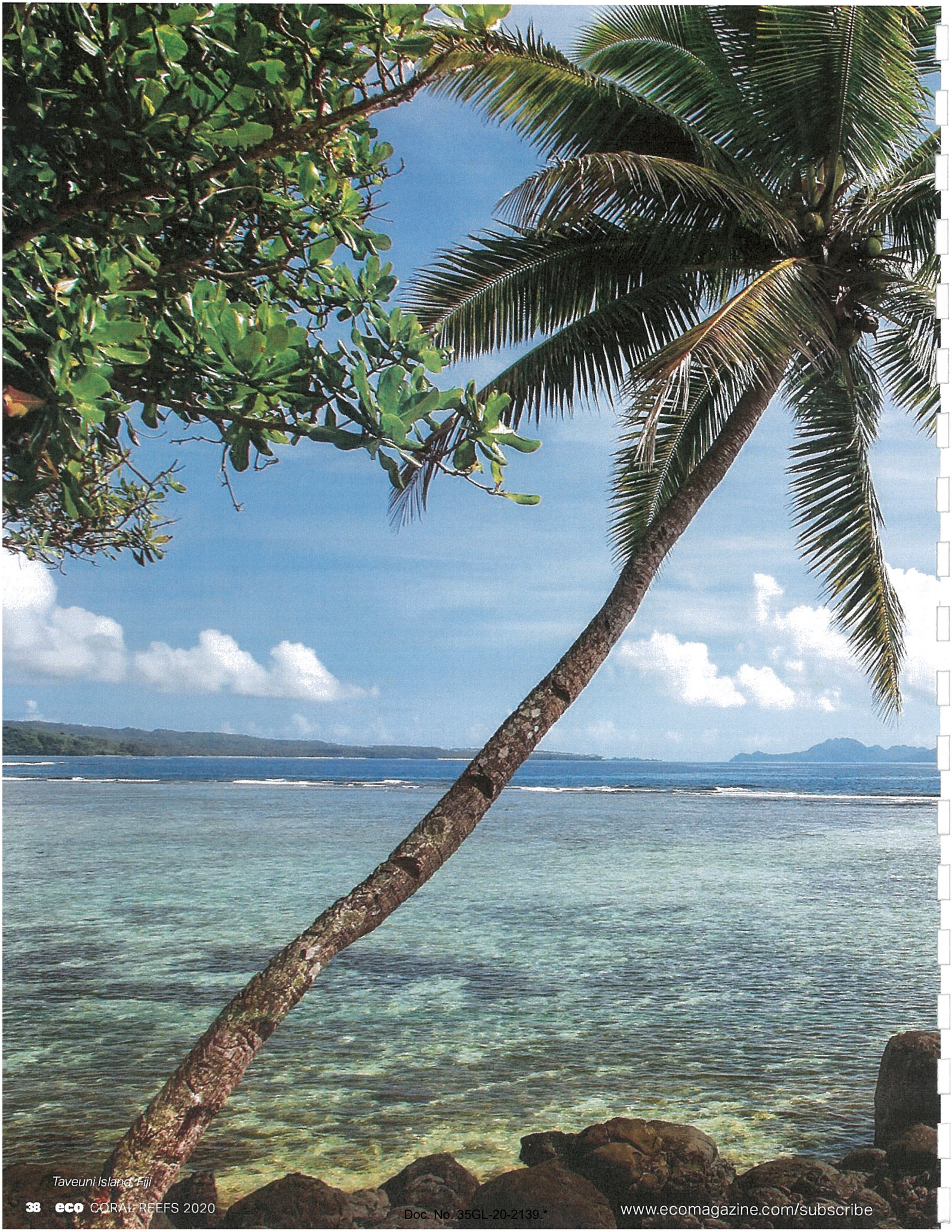
nent. However, we still need to discover whether the increased tolerance lasts throughout a coral's life. Furthermore, it is critical to know if there are any trade-offs between heat tolerance and coral growth, fecundity or reproductive output. Testing for this involves painstaking 3D-imaging of all our tagged coral colonies over time to estimate growth, and collecting and analyzing samples to assess reproductive outputs.

We also want to understand the underlying mechanisms of varying heat tolerance. One way to do this is to use next-generation sequencing techniques to study the role of coral-associated microbial symbionts in heat tolerance. This allows us to track even small-scale changes in the algal and microbial communities, for example, between generations or different genotypes, that may be related to heat tolerance. A major thrust of Coralassist is understanding the role that different proteins play in protecting corals from heat stress. So far, these experiments have focused on the overall protein expression profiles for different coral life stages and comparing the baseline protein abundance differences between coral colonies (and their offspring) with different heat tolerance levels.

The Coralassist team had planned many experiments for 2020 in Palau but, like most field researchers, we are locked-down and awaiting the opportunity to return to continue this work next year. Much is left to do and we have created more questions than answers. It is encouraging how far we have come since the project started. Just a few years ago, novel interventions that were not thought possible are now showing glimmers of hope. But there's still a long way to go before the work we are doing can have a real-world conservation impact. Time is running out for coral reefs. We urgently need to know if these innovations can be transformed into solutions.

Acknowledgments

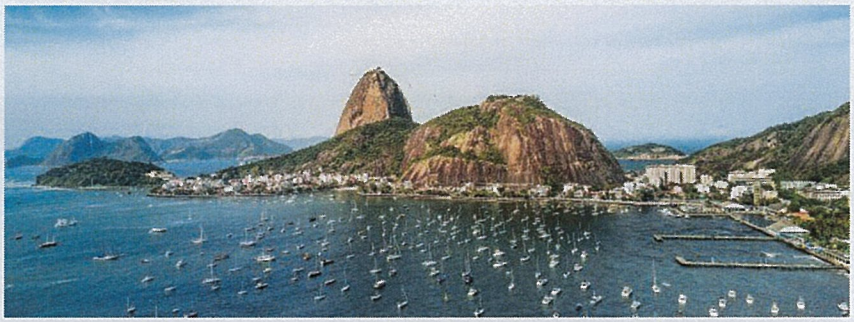
Coralassist receives funding from the European Research Council Horizon 2020 program (Project number 725848). Our collaborators include Mike Sweet, Till Roethig (University of Derby), Jamie Craggs (The Horniman Museum and Gardens), Renata Ferrari Legorreta (Australian Institute of Marine Science), Brigitte Sommer, Will Figuiera, Dan Pygas (University of Sydney), Dirk Petersen, Margaret Miller, Aric Bickel (SECORE International), Ana Sofia Lorda (University of Oxford). We are very grateful to the following for invaluable assistance Laurie Raymundo, Mitch Carl, Mike McCue, Nate Jaros, Georgia Burns. Janna Leigh Randle and all of the staff of the Palau International Coral Reef Center.



Taveuni Island, Fiji

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Hidden Archives of Environmental Change

The investigation of trace element uptake into coral skeletons provides powerful insights into the effects of marine pollution on coral reefs

By Igor Pessoa, Mauro Geraldes, and Luzia Antonioli, Rio de Janeiro State University

Corals feed by filtering plankton from the water as it flows through the reef. During this process, known as filter-feeding, chemical traces are systematically taken up and stored inside the corals' aragonitic skeletons. As the coral grows, its skeleton forms annual bands akin to the growth rings found in trees. The chemicals stored within these bands can provide insight into the changing conditions of seawater over the entire lifetime of the coral, and serve as useful environmental records (i.e., proxies) that indicate pollution events.

The study of geochemical proxies in coral skeletons, therefore, provides a reliable opportunity for understanding the impact of global warming on these critical ecosystems. These chemical proxies allow coral reef scientists to compare past and present ocean conditions. For example, the isotopic composition of oxygen in fossil corals reveals past ocean temperatures, the precise quantification of trace elements within the skeleton of deep-sea corals reveals past ocean circulation over geologic timescales, and the investigation of the carbon cycle in reefs quantifies the carbon budget of coral reef systems.

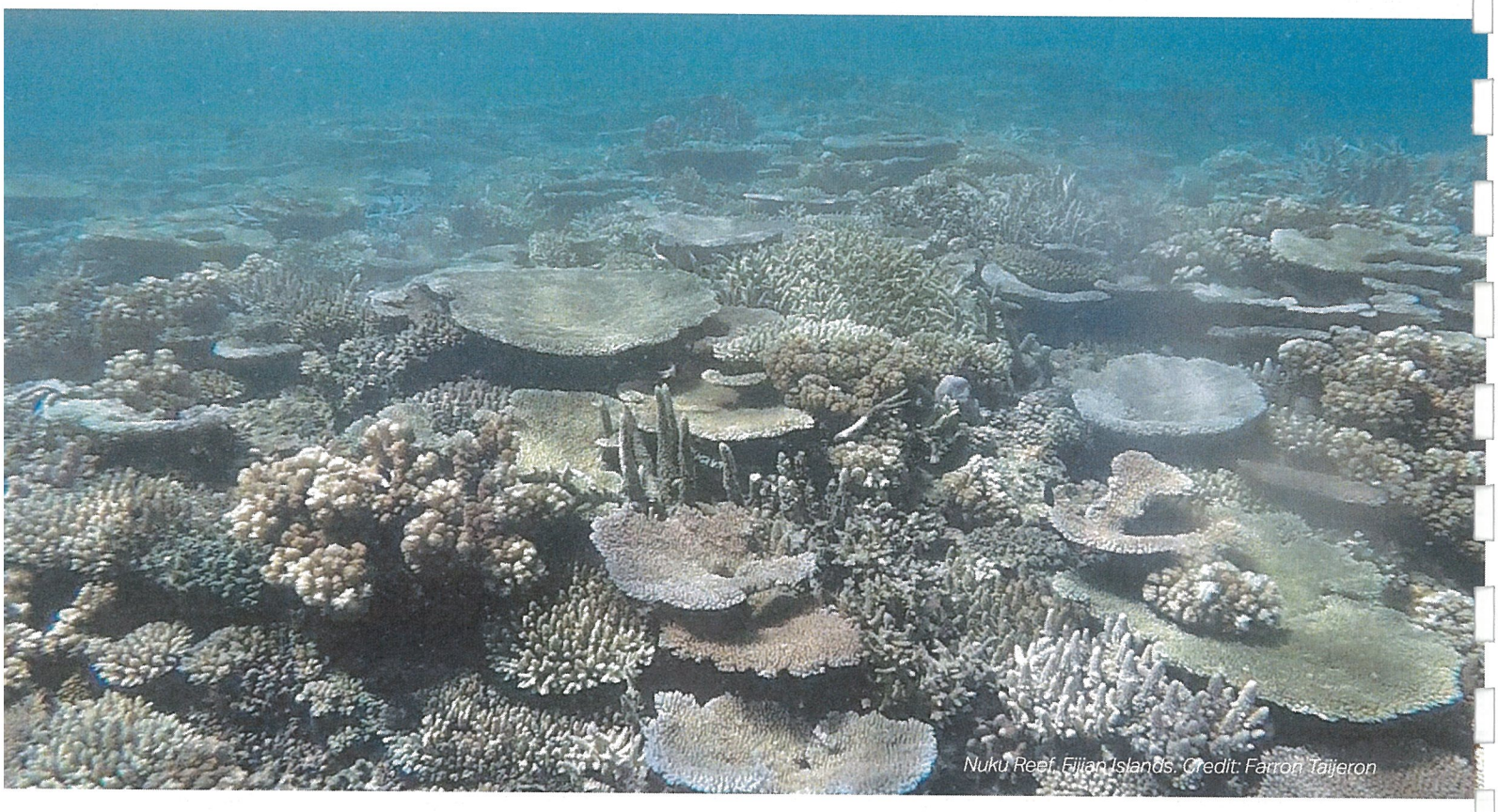
Corals incorporate trace elements that can be precisely registered using high-resolution analytical techniques. These strategies offer high levels of precision to determine the distribution of trace elements along the annual bands of the skeletons, which can serve for both fixed-point time-series and large-scale in ocean observations, as well as for water quality research. This procedure provides insights unobtainable with traditional monitoring studies, as these



Trace metal analysis of coral skeletons: Anthropogenic influences on corals at Ilha Grande Bay, Rio de Janeiro, Brazil

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Nuku Reef, Fijian Islands. Credit: Farron Taijeron

methods help us reconstruct past climate oscillation episodes and/or pollution events. As such, marine researchers are now integrating a broad range of themes—that spans a wide range of temporal (geologic time to days) and spatial (planetary to atomic) scales—to understand how local seasonal events correlate with skeletal growth rates. To examine this supremely vast field, marine geochemists apply isotopic tools in corals to take measurements to the micrometer, and down to the sub-nanometer levels.

Despite that many human activities have been causing ecological degradation and coral reef deterioration, mass spectrometry methods present a practical way for the determination of isotopic signatures in coral skeletons as a tool to monitor marine pollution. In coral reef studies, the isotopic fingerprints can be applied as a tracer system for pollution sources in coastal waters. This approach has great value because we can obtain isotopic data at high-spatial-resolution to create time-resolved records for the investigation of threats that affect the health of coral reefs. For example, land use changes associated with agricultural expansion and coastal development are significant drivers of declining inshore water quality. Metals can occur in polluted water as dissolved elements or adhered to the suspended particulate, having different forms of mobility in the seawater circulating throughout the shoreline zones. When filter-feeding in polluted water, chemicals can accumulate in soft inner coral tissues or are removed from the body by detoxification mechanisms and stored in skeletons. Therefore, high-resolution measurements of metal content in skeletons allow us to monitor the impacts of human-derived pollution.

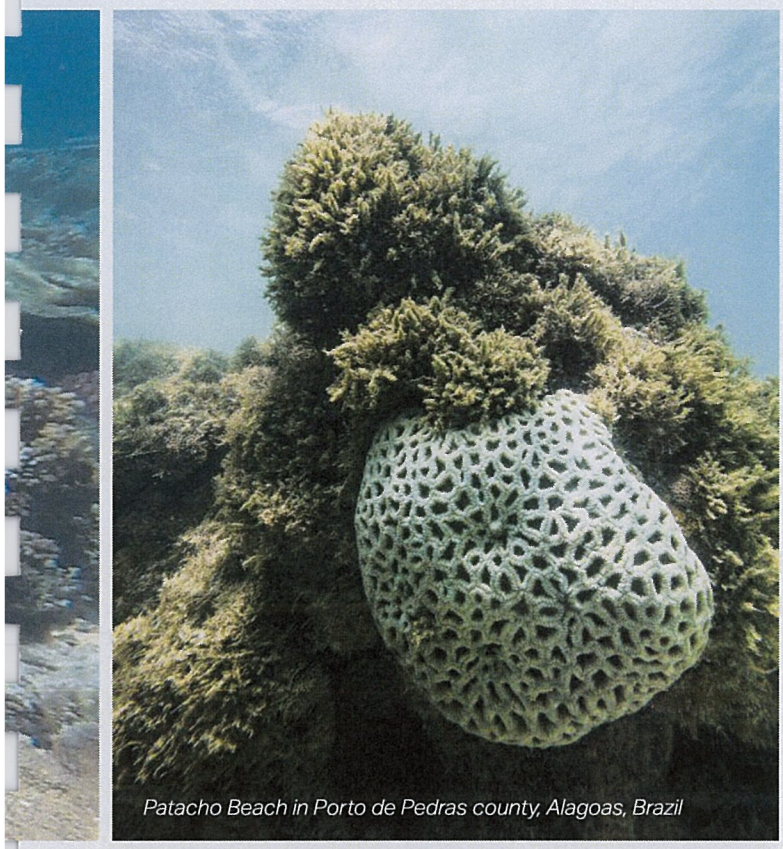
Besides the chemical concentration in the water, there are other factors that need to be considered when using corals as environmental proxies to monitor marine pollution: (1) biologic and vital effects on trace element uptake into corals (species niche and physiology, metabolic rates and growth speed), (2) environmental conditions and stress parameters (water temperatures, light levels, seawater nutrients, sedimentation rates, bleaching levels and heat stress), and (3) time of sampling and the duration of the events of pollutants to precisely evaluate the dose and exposition length of toxicants on corals.

Mass spectrometry methods have become a powerful technique for biological analysis that are suited to the investigation of fields including ecophysiology, biogeochemistry, (paleo) oceanography, and marine pollution. So that we can precisely reconstruct the environmental conditions from the isotopic tools, scientists are trying to understand how the biogeochemical cycles of the ocean evolved over time. Marine researchers are using the isotopic signatures to constrain local, regional, and global distribution of chemical elements. This strategy lies in the field of coral sclerochronology, while the isotopic proxies mean we can assess the biological and physio-chemical process that governs the cycles of elements in the ocean.

Currently, mass spectrometry enables coral reef scientists to perform high resolution measurements of trace elements in growth increments of a diverse range of calcareous marine organisms, including corals, echinoderms, bivalves and foraminifers, among other genera. Ultimately, this technique

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Patacho Beach in Porto de Pedras county, Alagoas, Brazil

provides great insights of seawater conditions from a small number of samples. However, distinct reef-records such as those mentioned above, often differ in the temporal ranges and/or temporal resolutions. Thus, comparison between different species has to consider fraction and physiological processes. The interpretation of data also differs among these organisms, since the biomineralization processes are physiologically very different, as well as the chemistry of shell or skeletal components. Most importantly, combining different marine records is one of many promising tasks for future studies owing to the crucial need for integration and expansion of our knowledge. Rather than using only one proxy to get environmental information, contrasting different environmental archives provide an in-depth analysis of climate issues relating to global warming and how they are connected with marine biogeochemical cycles.

Given the capabilities of mass spectrometry methods in obtaining data at high spatial resolution, these techniques have become a powerful method for elemental and isotopic analyses that are well suited for several applications. These methods combine the advantages of high-spatial-resolution with high ionization efficiency, provide reliable analysis in sample size on the micrometer scale, and the possibility of highly sensitive compared to other methods. However, there are some limitations with respect to measurement accuracy. The accuracy and precision in the analysis may be affected by a number of significant factors such as instrumental drift, isotopic fractionation, mass-interferences, matrix effects, and the lack of sufficiently matrix-matched reference materials. These tasks are interrelated and advances on one improves development over the other. On the other hand, scientists and industrial managers are thriving by addressing whether the yield of the measurement uncertainties can be improved to obtain precise and accurate results.

For that reason, researchers are taking advantage of the remarkably high sensitivity of new generations of mass spectrometers and developing a series of quality controls and new analytical specialties to overcome these problems. As a matter of fact, the analytical perceptions of top-ranking instrumentations have the detection limit down to a part-per-billion level for many elements. Rather than using only one analytical procedure, using different methodological approaches improve the results in measurement uncertaincy. This topic incorporates many questions; What level of detection limits are necessary to get precise results? Do differences in the limits of detection between different systems affect data interpretation? Do elemental fractionation and mass-load-dependent matrix effects vary significantly between different instruments? A comprehensive strategy is the key to overcoming these challenges and choosing the right methodological approach is critical to achieving accurate and precise results.

Over the course of the last decade, marine geochemists have been studying the magnitudes and rates of environmental changes, correlating the cycling of chemical elements with numerical modeling of ocean processes. To address this, academics are applying mass spectrometry methods to obtain isotopic data at high-spatial-resolution. Based on the capabilities and implications of distinct methodological approaches to generate results with high spatial and temporal resolution, scientists are able to constrain the duration and frequency of climate oscillations. Aside from measurement accuracy, the need for a more robust model to discuss ocean changes is crucial for the integration and expansion of our knowledge on global warming.

The benefits of techno-scientific aspects of new and established isotope applications in coral reef environments hold great promise that may continue to be improved in future studies. Given the current climate crisis, this issue requires accurate measurements to increase our understanding on the impacts that have become more frequent and intense.

We are now situated at a critical time in history. Coral reefs are facing a crisis, while our ocean faces immense challenges. Enhancing the quality of scientific studies that applies isotopic proxies offers valuable insights into the importance of the upcoming consequences of ocean acidification. This accomplishment demands new applications for time-resolved records of seawater parameters that are necessary to develop ocean models. Future development of environmental proxies would be useful to determine valuable time-sensitive archives of climatic and/or environmental changes (depending on the element used). Mainly, to understand coral reef's geochemical systems, unraveling their complexities, quantifying them, and devising new methods of probing them.

A Love Story for the Coral Reef Crisis

TED
IDEASWORTHSPREADING

Over the course of hundreds of scuba dives, marine biologist and policy expert Ayana Elizabeth Johnson fell in love — with a fish. In this ode to parrotfish, she shares five reasons why these creatures are simply amazing (from their ability to poop white sand to make colorful "wardrobe changes") and shows what's at stake — for us and them — as climate change threatens the future of coral reefs.

This talk was presented at an official TED conference, and was featured on the TED home page.



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Coral Spawning: A Wonder of the Underwater World

Dr. James Tan from Universiti Malaysia Terengganu is a coral biologist researching coral reproduction. Hong began work on coral reproduction as an undergraduate and continued throughout his masters and Ph.D programs.

The coral spawning event in Malaysia is rarely documented. The study site featured in this video is Pulau Bidong, a small island on the east coast of Peninsular Malaysia.

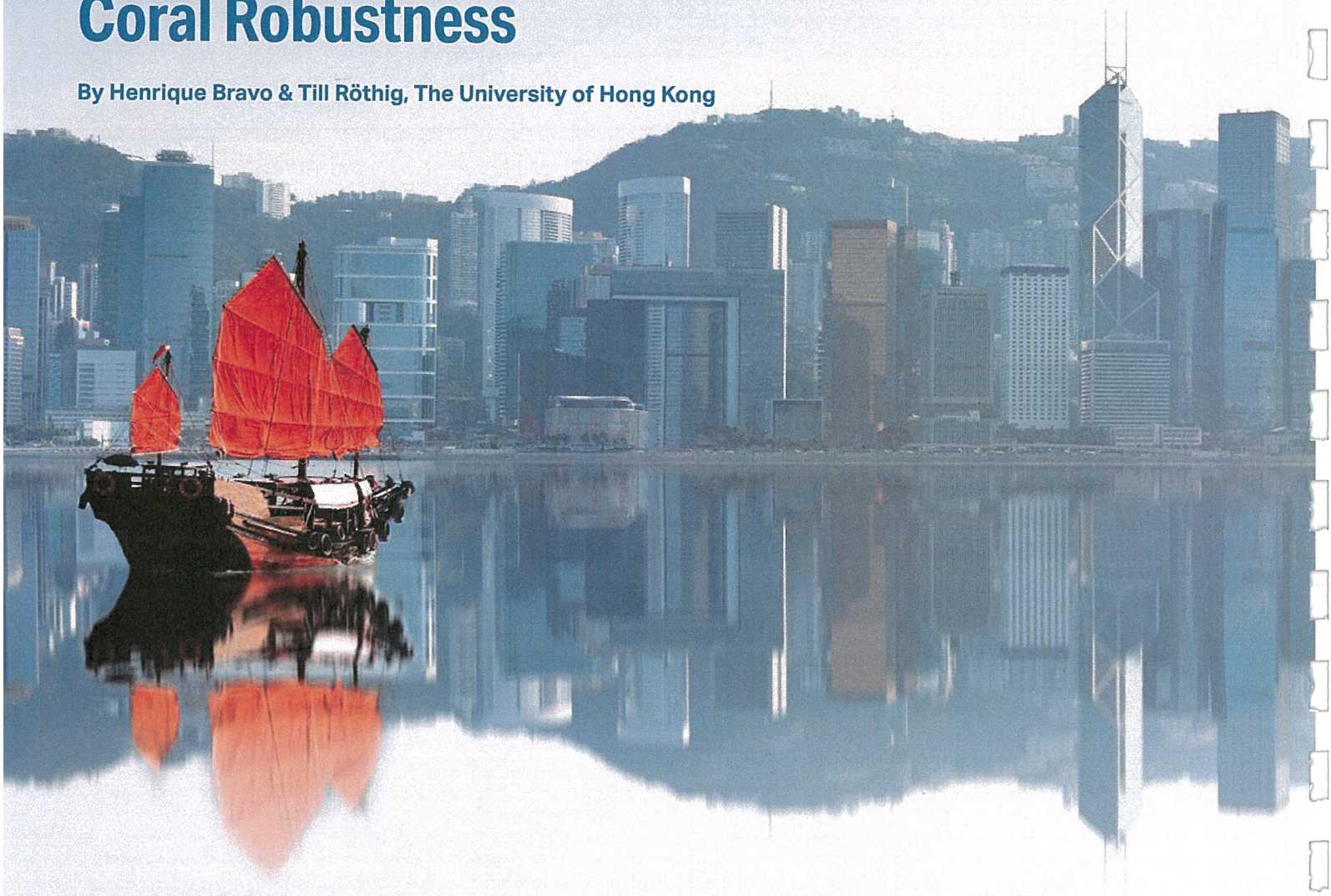
Along with his team, Hong is on a mission to document the coral spawning *in-situ* and after 3 years, they were finally able to record the spawning event. Beside from the two species in this video, Hong and his team also recorded spawning of 10 other coral species.

"This was the highlight of my years of research," said Tan.



Looking at Microbes to Understand Coral Robustness

By Henrique Bravo & Till Röthig, The University of Hong Kong



Hong Kong is one of the last places you would expect to find corals, and yet, you can find more coral species in its waters than in the entire Caribbean. Among this teeming coral biodiversity there is one species in particular that seems to defy all odds by surviving in the most inhospitable places. Its name is *Oulastrea crispata*.

It is hard to predict what our future coastal areas will look like, but I have a feeling places like Hong Kong will become the norm rather than the exception. So, conducting research in one of the most densely populated places on the planet might give us a glimpse into what marine biodiversity might look like and which challenges it is expected to face.

There are many advantages to doing coral research in a place like Hong Kong, but we believe one of the best is the ease of accessibility to field sites. In two days we were able to collect samples from five different sites across most of the distribution range of *O. crispata* in Hong Kong waters. These sites are exposed to different levels of man-made pressure with some in almost clear

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waters and others in such murky conditions that you can barely check your diving gauge due to the high sediment loads.

We wanted to understand what could be promoting this unlikely survival across such different environments and for that we decided to look at the microbiome composition of this coral across our sampling range. We thought that the extremely variable environmental parameters could be the main driver in shaping differences in *O. crispata's* microbial communities, so we also included environmental data for the three-month period that preceded our coral sampling. These parameters included temperature, salinity, dissolved oxygen, pH, nitrate, nitrite, ammonia, total nitrogen, phosphorus, turbidity and chlorophyll a.

Corals are considered holobionts, meaning that they rely on symbiotic relationships with their microbiome including eukaryotic dinoflagellates (i.e. from the family *Symbiodiniaceae*) and a whole range of other microbial partners such as bacteria, archaea, fungi and viruses. This intricate relationship is what keeps the host (the coral) alive, by being provided with otherwise inaccessible







nutrients, for example. There are some environmental parameters that appear to fundamentally alter the microbial composition, often with a negative impact on the host, leaving it debilitated and even causing mortality. Water quality, temperature, salinity, nutrient variability, are all parameters known to affect coral's microbiome composition.

Recently it has been suggested that coral microbiomes can be understood as two types: 1) microbiome regulator and; 2) microbiome conformer. The first group, as the name suggests, host microbiomes that remain relatively stable and are not fundamentally changing due to environmental changes. The latter are holobionts that are more "flexible", adapting and swapping their microbial partners to suit the environment.

Corals are in dire-straits suffering increased pressures from humans with the most worrisome of them all being human induced climate change that results in longer and more frequent coral bleaching events. It has, therefore, been suggested that corals relying on a flexible microbiome would be able to more easily adapt to changing conditions and will be the so-called climate change winners. Our goal in this study was to test whether the microbiome of *O. crispata* – as an environmentally flexible coral – would be flexible and contribute to its distribution to extremely impacted environments.

Top: Coral reef in Hong Kong. Credit: Phil Thompson

Middle: Cape D'Aguilar, the only Marine Reserve in Hong Kong

Bottom: Oulastrea crispata. Credit: Till Röthig

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The results proved interesting and somewhat unexpected. The wide distribution range of *O. crispata* and the different, extremely variable environments it can survive in, attest to a flexible coral that can adapt, compared to other corals. That was, however, in contrast to the microbial community composition. Despite there being differences in the microbiomes across sites, these were not fundamental shifts as one would expect from sites that arguably push the coral to the limits of its environmental niche. The environmental parameters we considered explained only ~23 percent of the microbiome composition variations, suggesting that either other environmental parameters play a role, or that the microbiome responds to other factors like diet.

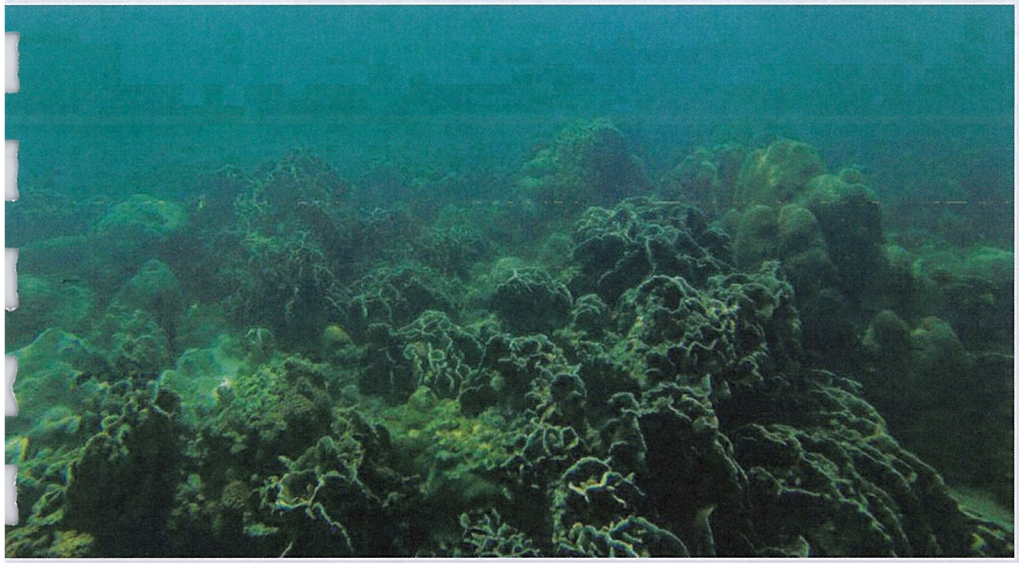
Spatially and temporally variable environments are expected to become the norm in the not so distant future. Microbiomes certainly play a role in supporting their hosts adjustment to extreme environments, but our data suggests that the ability to (quickly) adjust microbiome composition does not necessarily confer robustness.

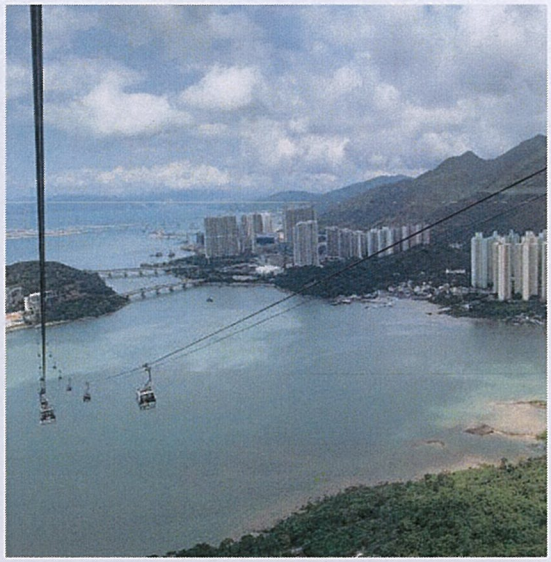
We revealed another piece of this complex puzzle that is the relationship between microbiomes and hosts, but the story is not yet complete. More secrets await to be unveiled in the murky and clear waters of Hong Kong, secrets that hopefully will help us in keeping corals alive in the future.

Top Left: Coral reef in Hong Kong. Credit: Phil Thompson

Top Right: Tung Chung. Credit: Henrique Bravo

Bottom: Oulastrea crispata feeding with its tentacles fully extended Credit: Phil Thompson





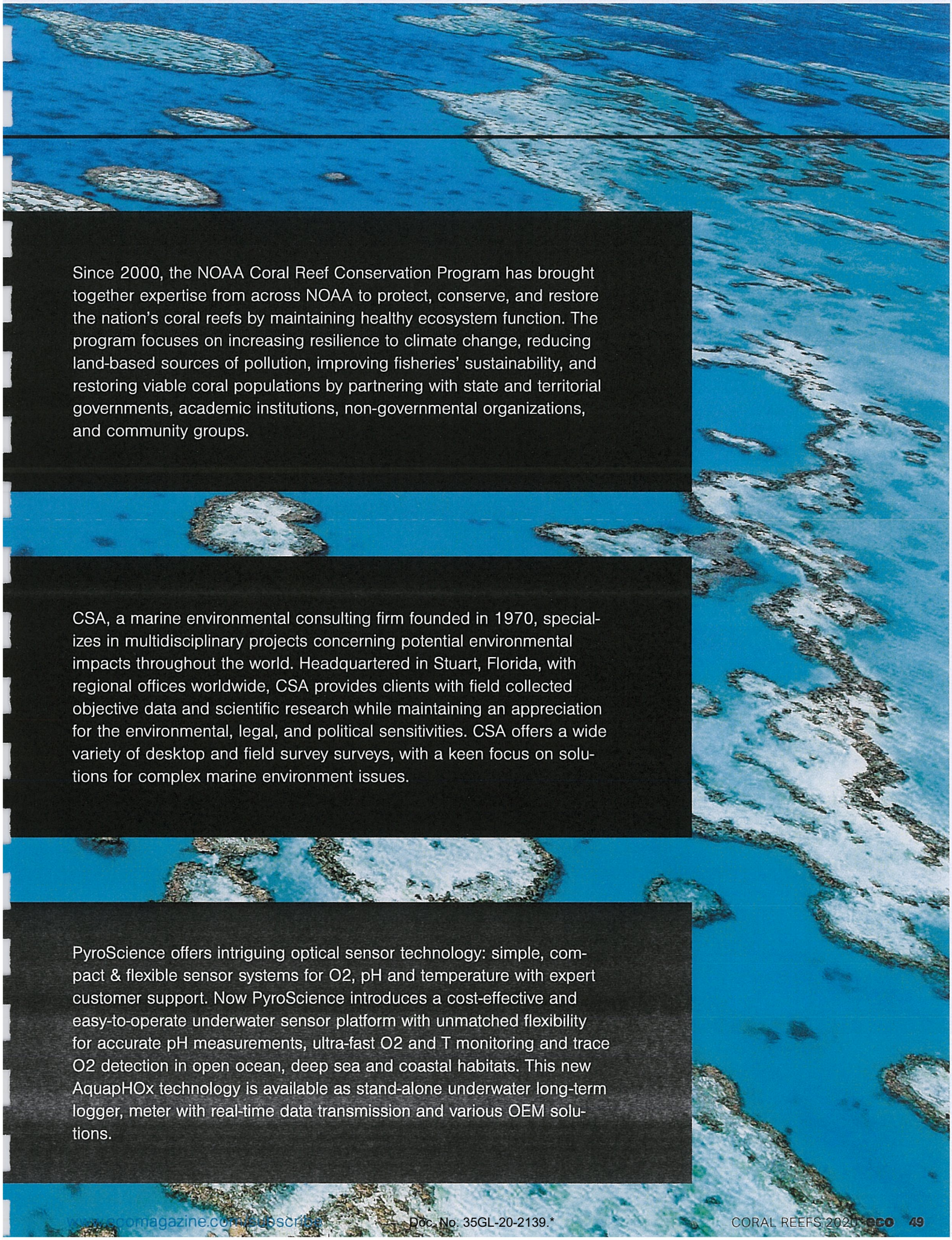


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Since 2000, the NOAA Coral Reef Conservation Program has brought together expertise from across NOAA to protect, conserve, and restore the nation's coral reefs by maintaining healthy ecosystem function. The program focuses on increasing resilience to climate change, reducing land-based sources of pollution, improving fisheries' sustainability, and restoring viable coral populations by partnering with state and territorial governments, academic institutions, non-governmental organizations, and community groups.

CSA, a marine environmental consulting firm founded in 1970, specializes in multidisciplinary projects concerning potential environmental impacts throughout the world. Headquartered in Stuart, Florida, with regional offices worldwide, CSA provides clients with field collected objective data and scientific research while maintaining an appreciation for the environmental, legal, and political sensitivities. CSA offers a wide variety of desktop and field survey surveys, with a keen focus on solutions for complex marine environment issues.

PyroScience offers intriguing optical sensor technology: simple, compact & flexible sensor systems for O2, pH and temperature with expert customer support. Now PyroScience introduces a cost-effective and easy-to-operate underwater sensor platform with unmatched flexibility for accurate pH measurements, ultra-fast O2 and T monitoring and trace O2 detection in open ocean, deep sea and coastal habitats. This new AquapHOx technology is available as stand-alone underwater long-term logger, meter with real-time data transmission and various OEM solutions.

eco *i*

Counting only the economic value of fisheries, tourism, and shoreline protection, the costs of destroying 1km of coral reef ranges between US$137,000-1,200,000 over a 25-year period

Southeast Asia's coral reef fisheries alone are estimated to yield US$ 2.4 billion annually

The total economic value of reefs in Indonesia and the Philippines is estimated at US$1.6 billion, US$1.1 billion annually (respectively)

Source: WWF

Chapter 2: Economy

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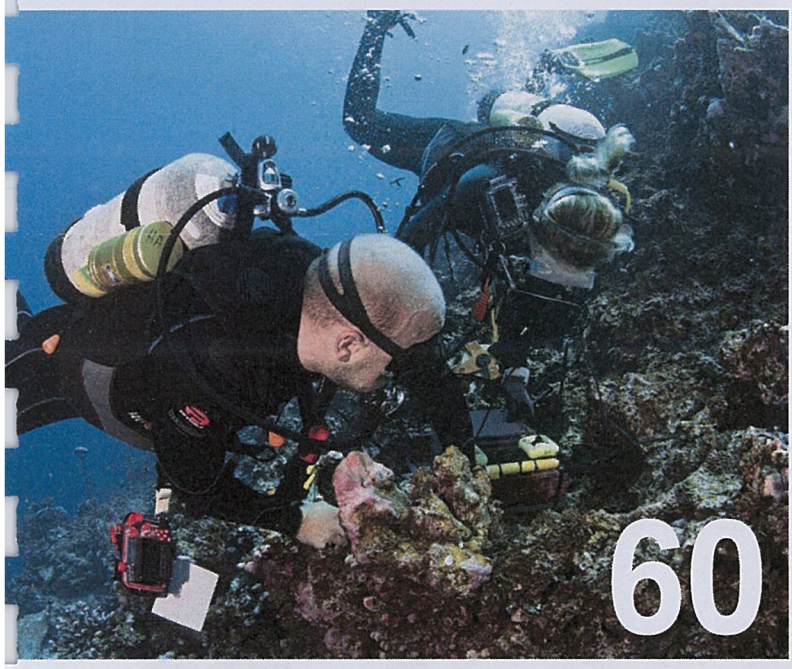
66 Caribbean King Crab: A Delicious Solution for Coral Reefs

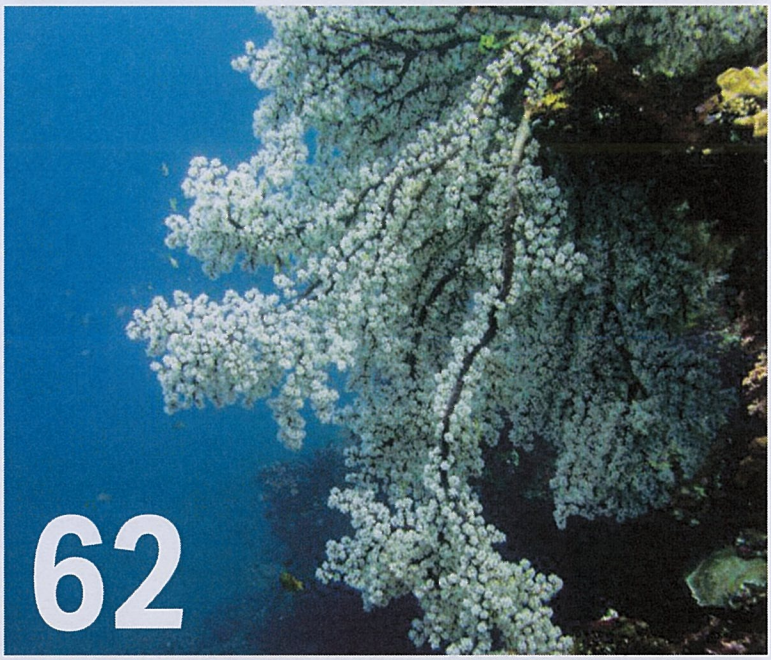
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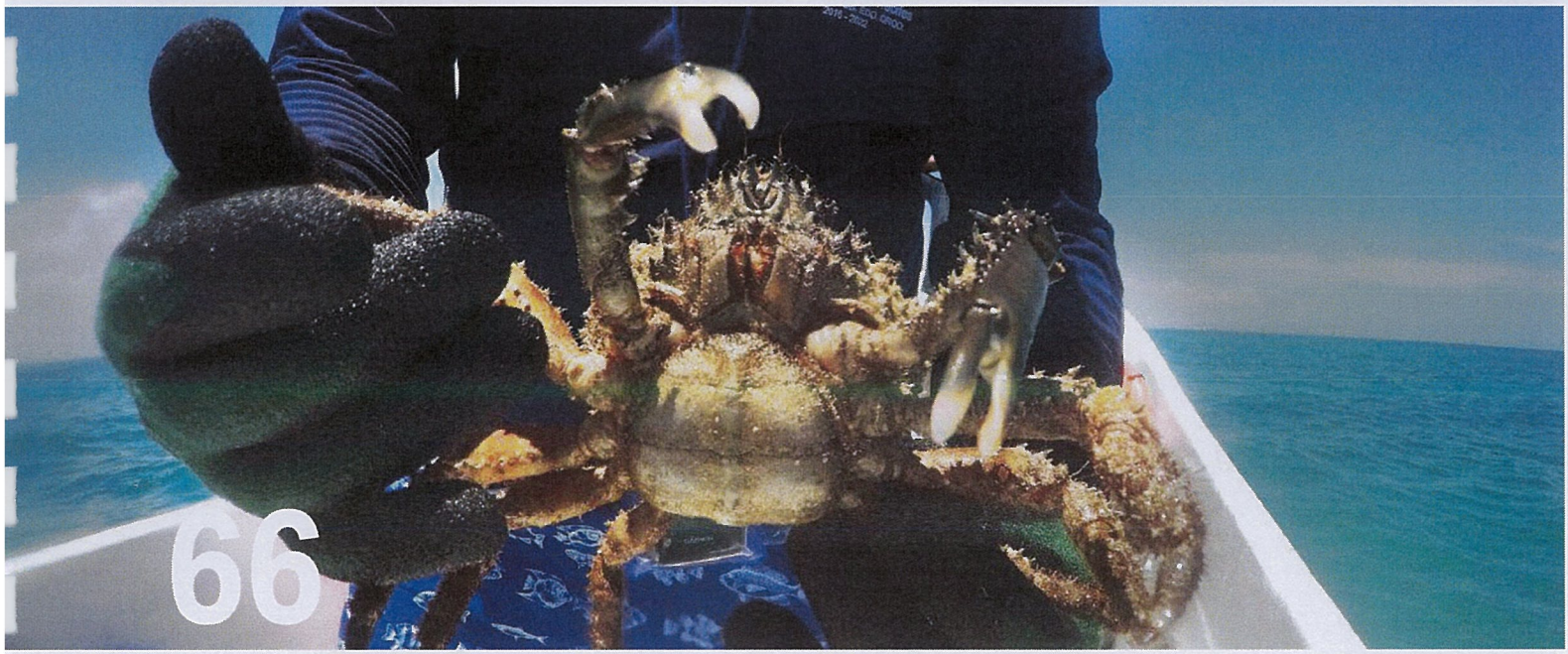
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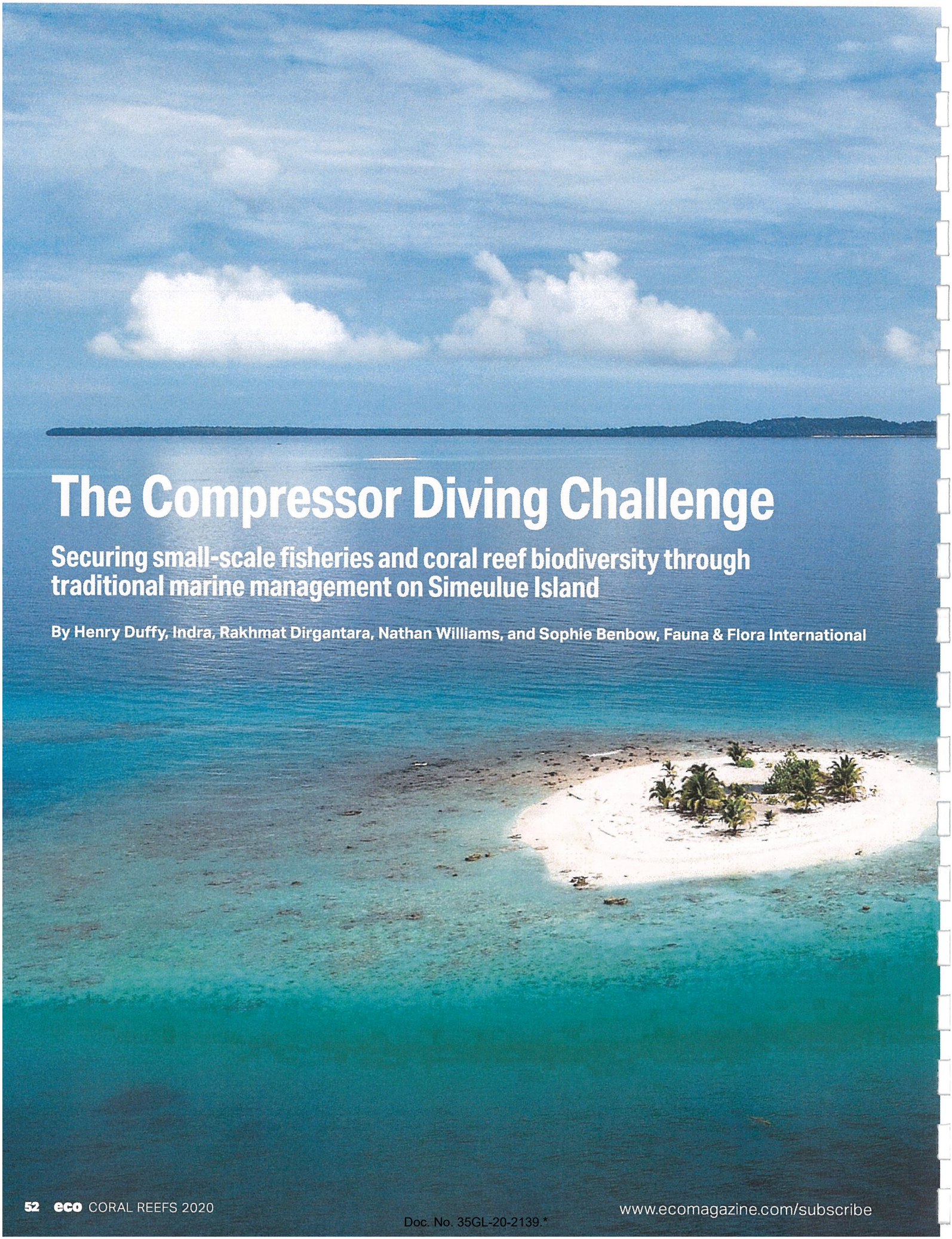

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The Compressor Diving Challenge

Securing small-scale fisheries and coral reef biodiversity through traditional marine management on Simeulue Island

By Henry Duffy, Indra, Rakhmat Dirgantara, Nathan Williams, and Sophie Benbow, Fauna & Flora International

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Adrift from the coastline of mainland Sumatra, Simeulue Island sits at the western tip of the sprawling Indonesian archipelago, within the province of Aceh. Coral reefs in this area are often "unsung" compared to areas of Indonesia situated within the iconic Coral Triangle. And yet, the waters of Simeulue contain valuable marine biodiversity and rich fisheries, sitting at the meeting point of the Indian Ocean and Southeast Asia.

Aceh province has a unique maritime cultural heritage, epitomized by the *"Panglima Laot"* which translates from Bahasa Indonesian as "Sea Commander." These traditional community decision-making bodies have governed inshore fishing grounds for over 400 years, although the system was significantly weakened by more than 30 years of armed conflict in the region during the late 20th and early 21st centuries. This was compounded by the 2004 tsunami in which many fishers and community leaders perished across Aceh's coastal areas, with reef ecosystems also severely affected.

Fauna & Flora International (FFI) have worked in coastal Aceh since 2004, initially providing aid to stricken communities after the tsunami, and seeking to understand the effect of the disaster on coral reefs and associated small-scale fisheries. As the province recovered, FFI's work evolved into a program of support to Marine Protected Area (MPA) management. We focus on harmonizing the *Panglima Laot* system with spatial protection approaches being taken at the provincial level and ensuring that fishing community interests are represented through close government partnerships.

Since 2011 this effort has focused primarily on Pulau Pinang, Siumat and Simanaha (PiSiSi) MPA on the north coast of Simeulue, with work recently expanding to three further proposed MPAs around the island. PiSiSi MPA contains significant areas of healthy reefs, with coral cover above 80 percent in places, in addition to diverse reef fish assemblages. FFI works with an increasing number of villages whose fishing grounds lie within the MPA, supporting local monitoring and ownership of marine resources, and connecting the *Panglima Laot* with responsible authorities to ensure that community voices are heard in governance dialogues. In addition, FFI is supporting Simeulue fishers and seafood market stakeholders to better understand their supply chains and achieve fair natural resource market systems for fishers around the MPA. Ultimately, this multi-faceted approach is designed to deliver a vision whereby the coral reefs of PiSiSi MPA are resilient and support productive fisheries, achieved through locally-driven management which protects marine biodiversity and yields benefits for coastal communities.

However, in order to achieve this vision, a critical threat must first be addressed, namely illegal and destructive fishing practices which continue to occur within PiSiSi MPA and around Simeulue. The most widespread of these is a technique known as compressor diving. The complex drivers of this practice have no single solution, and compressor fishing results in a range of negative social, medical and ecological consequences which are very difficult to avoid.



Spread: An aerial view of the stunning coastal Aceh seascape. Credit: Radinal/FFI .

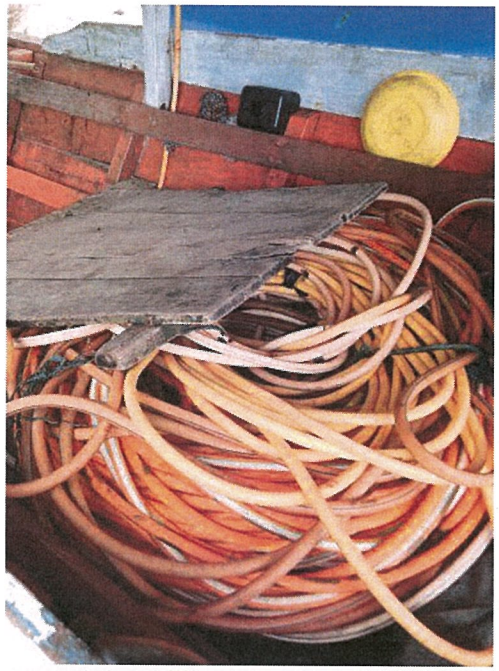
Left: A compressor fisher searches for catch, tethered to the surface by his air hose. Credit: Indra/FFI.

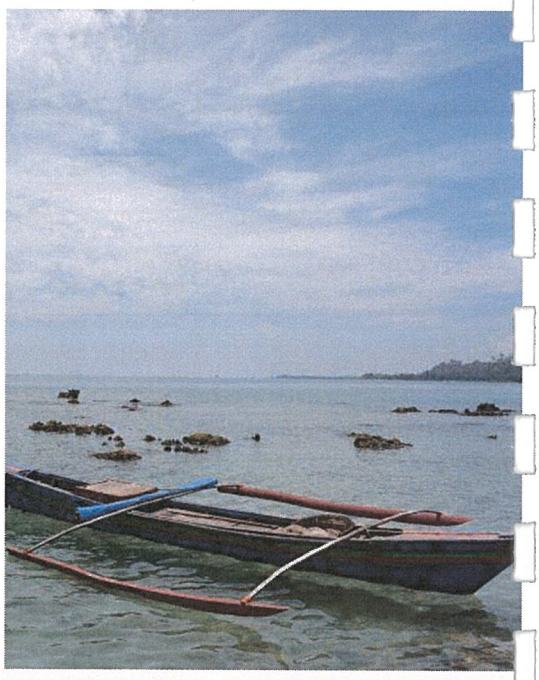
Compressor Diving

Compressor diving is a fishing practice that involves divers searching the seabed for lucrative octopus, grouper and sea cucumber, all the while relying on air supplied from a motorized pump through a single plastic lifeline, snaking precariously up to a boat on the surface. The rewards can be great – fishers are able to stay deep under water for long periods, harvesting catches that would be inaccessible to those using other fishing techniques. Those involved use a variety of gears to land their catch, ranging from handheld spears or hooks to large nets which are suspended in the water by a cooperating group of compressor divers. However, whilst fishing in this way can be prolific, the method is fraught with dangers, as local Simeulue fisher, Anhar, can testify.

On a previous compressor fishing trip, while he was searching among corals and rocks for his catch, Anhar's air supply was accidentally turned off. Fighting to survive, he rapidly swam 30 meters to the surface to catch his breath, but this fast ascent resulted in decompression sickness – an excruciating and potentially deadly condition (more commonly known as 'the bends') – where blood vessels are blocked by expanding gas bubbles, which can badly affect joints and nerves. Consequently, Anhar suffered permanent partial paralysis, a devastating injury often seen among compressor divers. Although he is still able to fish from a boat at the surface, Anhar's life has been profoundly changed by this accident.

A recent FFI survey saw 98 percent of Simeulue's compressor fishers reporting some form of mishap or injury as a result of engaging in this hazardous practice. Furthermore, between 2012 and 2014, 12 deaths in Simeulue were attributed to compressor diving. The situation is exacerbated by poor understanding of the health risks and limited access to proper medical care for pressure-related injuries, which require urgent treatment in specialist recompression chambers. Currently, victims are often treated through traditional methods, which may have limited efficacy.







Despite being incredibly risky, and illegal under Indonesian law, compressor fishing remains widespread. Beyond the dangers faced by the compressor fishers themselves, this fishing technique can also have severe impacts on coral reef biodiversity. Able to remain underwater for long periods, compressor fishers can quickly harvest their catch from across vast areas of reef. This increases the risk of ecological damage due to fishers trampling on coral reefs, intensively using spears and hooks to target a small reef area, and deploying the large suspended nets. The latter is an especially unselective method which indiscriminately captures all marine life trapped within the fine net mesh. This severe fishing pressure can deplete populations of economically and ecologically important species such as grouper, octopus and sea cucumber, and deprive small-scale fishers of vital resources that they access with legal traditional harvesting methods.

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Compressor fishing gear stowed on the deck of a fishing vessel. Credit: Rakhmat Dirgantara/FFI.

A traditional fishing vessel moored in Simeulue Island. Rob Harris/FFI.

A traditional Simeulue fisher casts their net. Credit: Syafrizaldi/FFI.

Schooling fish above a coral reef in Air Pinang traditional fishing ground. Credit: Rakhmat Dirgantara/FFI.

A grouper rests amongst the soft coral inside PiSiSi MPA. Credit: Indra/FFI.

Untangling the Issue

Illegal compressor fishing has been identified as a key threat to both the local fisheries and the marine biodiversity of Simeulue Island. FFI supports communities to observe, report and deter compressor fishers through patrols, as well as resolve fisheries conflict through traditional customary courts, which have a strong legal mandate and are part of the legislative privileges of Aceh as a semi-autonomous Indonesian province.

This work appears to be paying off, with reported compressor fishing incidents in patrolled areas declining by more than 75 percent between 2015 and 2018, compared to areas not yet under active community management. Collaborative patrols involving *Panglima Laot* and government officers have also successfully confiscated compressor fishing equipment, and some of those using this illegal fishing gear have been prosecuted and tried in court. Recent underwater surveys by FFI and partners at the University of Syiah Kuala also indicate the biomass of reef fish in community-protected areas within PiSiSi MPA is up to three times higher than in nearby control sites. However, whilst these are encouraging early signs, compressor fishing incidents continue to occur, and community management initiatives must be considerably expanded to deliver impacts across Simeulue Island.

To fully address the social and ecological issues posed by compressor diving, it is essential to engage with those involved in this activity, to understand their motivations and search for ways to enable a transition towards safer, more sustainable fishing practices. Our surveys of compressor fishers are the first step to developing a more in-depth understanding of this complex problem, and we are collaborating with regional government to increase awareness in communities of the risks associated with compressor diving. Some compressor fishers, like Rosmalian, have already seen enough to move out of the profession: "I stopped diving 15 years ago. I don't want to dive using a compressor anymore because the risk is very high. I also don't allow my child to dive like I did before," he told FFI staff during recent discussions with fishers on Simeulue Island.

Without robust deterrents and economically sound alternatives, however, many fishers will continue to pursue this high-risk, high-reward activity. By engaging with the issue systematically, and with the support of funding from the UK government's Darwin Initiative and Arcadia – a charitable fund of Lisbet Rausing and Peter Baldwin, FFI and partners will continue working to improve prospects for both the fishers and the coral reefs of Simeulue Island.

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Managing for Multiple Functions of Coral Reefs

By Sebastian C.A. Ferse, Leibniz Centre for Tropical Marine Research (ZMT), and Joshua E. Cinner, ARC Centre of Excellence in Coral Reef Studies

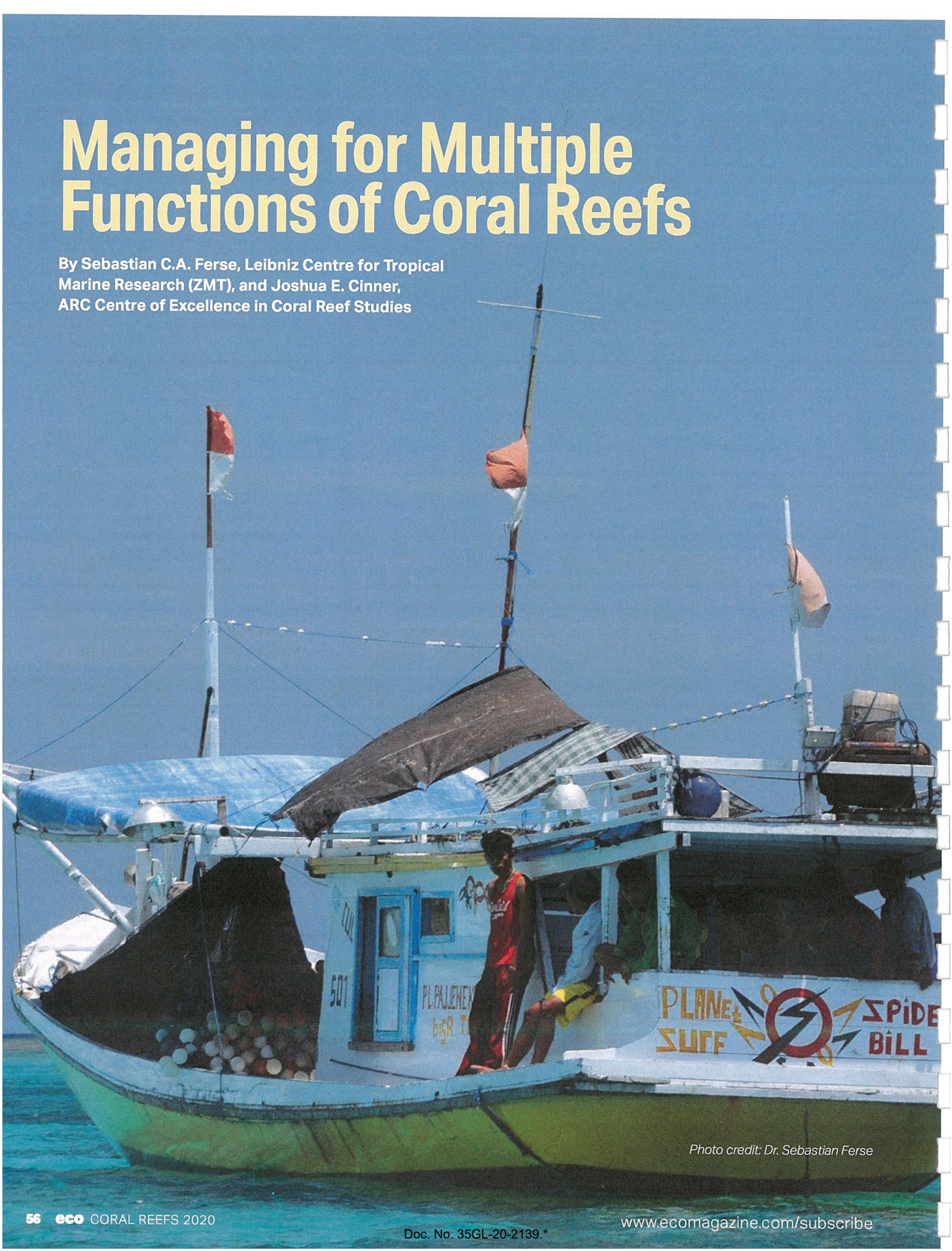


Photo credit: Dr. Sebastian Ferse

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Coral reefs are not only one of the most biodiverse ecosystems on the planet, but also (relative to their area) the most valuable, as they provide vital ecosystem services to humanity. Their value has been estimated at a stunning near 10 trillion USD per year which supports the livelihoods of half a billion people.

The rich biological communities of coral reefs contribute in many ways to the ecosystem services provided by them – for example, reef-building stony corals are the most effective wave breakers, reducing wave energy by more than 90 percent and protecting shorelines from erosion and flooding. Fish and invertebrates are the basis for fisheries along most tropical shorelines. Extracts from sponges, sea squirts, snails and other organisms provide some of the most effective drugs that treat cancer, Alzheimer's and viral diseases. And the colorful and diverse reef communities are a major draw for tourists, thus contributing a sizeable amount to the GDP of countries such as Palau and even Australia.

However, approaches to management rarely address particular ecosystem services, let alone the conditions under which management is most effective. Together with an international team of scientists, we set out to change this.

Assessing Multiple Functions

We studied nearly 1800 reef sites right across the tropics, including openly fished reefs as well as sites under different degrees of management, to find out how to help reefs meet multiple goals. There are now more than 2800 protected areas worldwide that restrict or completely prohibit the use of reef resources. The motivation for setting up protection measures can vary – in many places the aim is to preserve reef biodiversity or to support fishing, but in some cases, it is also to maintain key ecological functions. Managing for even one of these goals is extremely difficult, but we wanted to find out whether some reefs can have it all.

To do so, we focused on three representative management goals: the biomass of large fish, the grazing potential of parrotfish, and the diversity of specific reef fish traits such as their food source, home range and schooling behavior.

The biomass of large fish is an indication of the value of a reef for the nutrition of the population. Parrotfish fulfill an important function for the reproduction of corals. They scrape surfaces free of algae and thereby provide space for coral larvae to settle. The diversity of traits, in turn, is a dimension of biodiversity and a measure of the resilience of an animal community to negative impacts.

To determine the human influence on the reefs, we also recorded data on socio-economic characteristics of each site such as population density, the development status of the respective country and the distance and accessibility of markets. Finally, the protection status of the reefs was also noted when they were located in a marine protected area.

With these data, we fed a model that calculated how management measures affect the three parameters: large fish biomass, parrotfish scraping potential and trait diversity. The model showed that the effectiveness of conservation measures varies considerably depending on the context and the objectives.



Corals grow in the shallows around a small island in Kimbe Bay, Papua New Guinea.. Credit: Tane Sinclair-Taylor



Some Reefs Have It All

Using little-disturbed reefs as reference points, we established a high, medium, and low target for each goal. For example, for the fisheries goal, were there lots of fish there? A medium amount? Or not so much? Sites that met the most stringent target for all three goals were on our A-list. The ones that met the middle target for all three goals were our B-listers, and the ones that met our least stringent targets for all three goals were our C-listers.

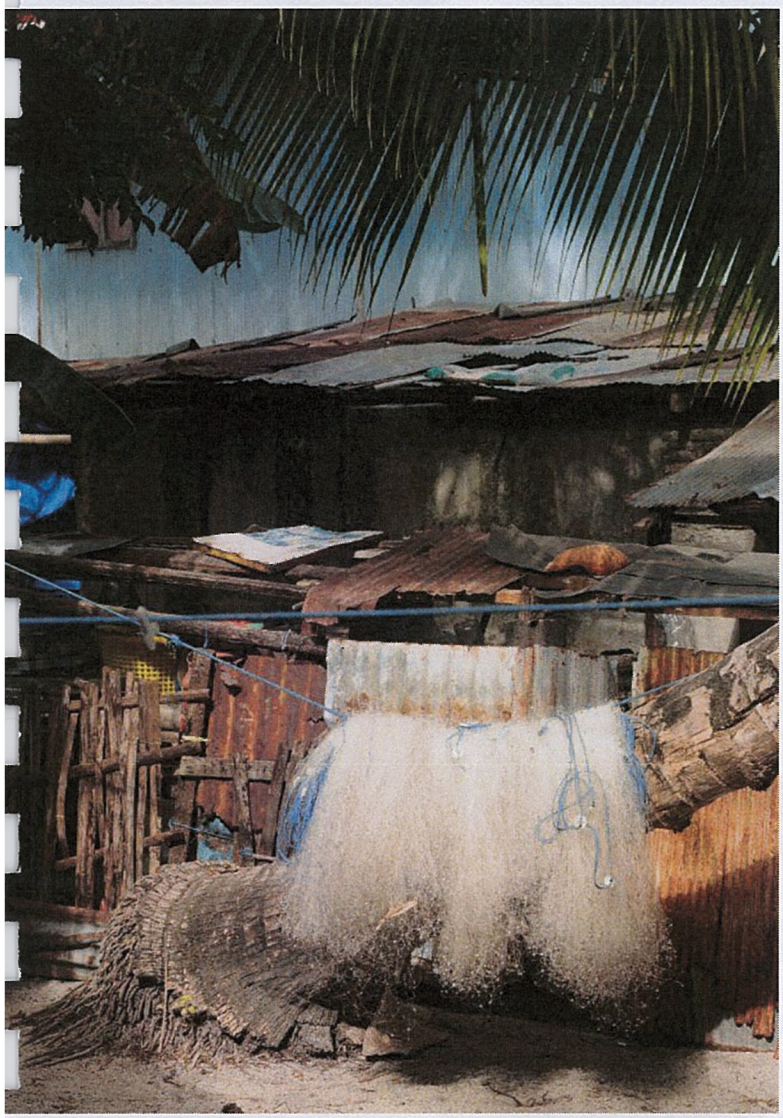
We were not only interested in finding out where the A-listers were, but also how other reefs could get on the A-list. In short, we wanted to find out how local management efforts, such as no fishing marine reserves, could help reefs get on the A-list, and how effects of management were influenced by the local setting of a reef.

There are two important results from our study. The first is that A-listers are rare, but geographically widespread. Only five percent of openly fished reefs were A-listers, but these were widely distributed – in about 1/3 of the countries we studied – and occurred in the Caribbean, Indian, and Pacific Oceans. About 12 percent of fished reefs met our medium targets across all three goals (B-listers), and about 1/3 of fished reefs met the least stringent targets across the three goals (C-listers). More than half of our reefs didn't even make the C-list. Looking at these underperformers, for almost half of them, even the introduction of strict protected areas would not lead to any significant improvement. One of the reasons for this is that the biomass of large fish reacts sensitively to human influences, and that a high level of human influence outside the boundaries of protected areas generally means that even strict protection does not work effectively.



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Photos left: Early morning in the densely-populated Spermonde Archipelago, Indonesia (above). Fish from reefs is an important source of protein in many tropical countries (fish market in Kupang, Indonesia; below).Credit: Dr. Sebastian Ferse

Photo top right: A net hangs out to dry on Rote Island, Indonesia . Credit: Sebastian Ferse

Photo bottom right: The bright green tentacles of a magnificent sea anemone (Heteractis magnifica) waft in front of its pink mouth, on a coral reef in Papua New Guinea, Pacific Ocean. Credit: Tane Sinclair-Taylor

This leads to the second important result, which boils down to: location, location, location! Local management efforts can help coral reefs sustain multiple goals, but only if they are placed in the right location, which varies depending on the objective. For the most stringent targets (our A-list), we found that marine reserves could make the biggest difference in locations with low human pressure. As our targets become less stringent (our B and C lists), marine reserves make the biggest difference in locations with intermediate human pressure. However, local management doesn't make much of a difference where human pressure is most extreme. In these locations the degradation is too severe and local management isn't enough, therefore, seascape wide conservation would be required.

Guiding Management: Goals and Context

These results are important to determine how managers can maximize certain conservation goals. Our study makes clear the pros and cons of placing reserves in different locations. For example, where there is strong human influence, even very restrictive protection measures, so-called "no take zones", achieve only a low fish biomass, while in reefs with little human influence the biomass is high even without protected areas.

Often, strict protection areas are difficult to enforce among the local population, as locals are usually heavily dependent on the use of the reefs in their area. Our results show that the introduction of strict restrictions has the greatest influence on fish biomass, but whether less restrictive or particularly strict rules are introduced does not make a significant difference for the other parameters examined.

Of the three parameters we looked at, local management had the least impact on the diversity of traits. This is mainly due to the fact that the mechanisms that lead to a loss of biodiversity generally do not act locally, but at a more regional level.

We show where managers will be able to maximize their ability to simultaneously meet multiple goals, such as fisheries, biodiversity, and ecosystem function, and likewise, where they will be wasting their time. It appears that remote reserves are critical to supporting multiple goals.

Publication

Cinner J.E., J. Zamborain-Mason, G.G. Gurney, N.A.J. Graham, M.A. MacNeil, A.S. Hoey, C. Mora, S. Villéger, E. Maire, T.R. McClanahan, J.M. Maina, J.N. Kittinger, C.C. Hicks, S. D'agata, C. Huchery, M.L. Barnes, D.A. Feary, I.D. Williams, M. Kulbicki, L. Vigliola, L. Wantiez, G.J. Edgar, R.D. Stuart-Smith, S.A. Sandin, A.L. Green, M. Beger, A.M. Friedlander, S.K. Wilson, E. Brokovich, A.J. Brooks, J.J. Cruz-Motta, D.J. Booth, P. Chabanet, M. Tupper, S.C.A. Ferse, U.R. Sumaila, M.J. Hardt & D. Mouillot: Meeting fisheries, ecosystem function, and biodiversity goals in a human dominated world. Science 368: 307-311. Doi: 10.1126/science.aax9412



Hope for the Future of Coral Reefs

The National Oceanic and Atmospheric Administration (NOAA) has many reasons to be hopeful for the future of coral reef ecosystems, and we encourage coastal communities to share that hope

By the NOAA Coral Reef Conservation Program

While coral reefs face threats such as fishing impacts, land-based sources of pollution, and the effects of a changing climate, the NOAA Coral Reef Conservation Program and its partners have been working diligently for 20 years to improve coral reef conditions in the United States and worldwide.



NOAA is focused on maintaining coral reef structure and function for future storm protection. Since the 2017 Atlantic hurricane season, NOAA has worked with the Department of Interior, Federal Emergency Management Agency and other federal and local organizations on the recovery and restoration of coral reef ecosystems in Puerto Rico. Reefs reduce up to 97 percent of the energy from a wave, protecting communities and infrastructure from the effects of storms and flooding. The restoration of coral reef ecosystems will ultimately provide sustained defense for coastal communities in Puerto Rico and other states and territories in light of sea level rise and stronger storms.

Recognizing that coral recovery is a massive undertaking requiring the expertise and commitment of many people, NOAA is supporting innovative partnerships to increase interest in coral reef conservation. In 2018, NOAA staff served as subject matter experts for teams focused on coral reef restoration at the XPRIZE Visioneering Summit. An audience of

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CEOs, world leaders, philanthropists, influencers, and thought leaders selected "Saving Coral Reefs" as the best competition concept. XPRIZE is currently raising the prize funding for the competition, which will increase capacity to successfully restore larger areas of reefs by increasing the number of corals that can be outplanted and the survival rate of restored corals. Recently, NOAA partnered with FORCE BLUE for "100 Yards of Hope," a year-long coral reef restoration project to celebrate the National Football League's 100th season and honor the nation's military veterans in a unique way. FORCE BLUE veteran divers are working with local scientists in Florida to restore a football-field length area of coral in Key Biscayne.

Various groups are rapidly developing new intervention techniques, and NOAA is looking to utilize this new science. NOAA commissioned a two-part study by the National Academies of Science, Engineering, and Medicine on "Interventions to Increase the Resilience of Coral Reefs." The first report reviewed 23 intervention strategies ranging from those that are feasible now such as coral propagation to those that offer promise in the next decade like atmospheric shading to prevent coral bleaching. The second report evaluated the benefits and risks of the reviewed strategies, provided frameworks to help managers select and apply strategies, and included a case study. NOAA is a leading agency in the response team for stony coral tissue loss disease in Florida, which is making regular advancements in disease treatment and prevention. NOAA staff are specifically involved in research, rescuing corals from the field before they become diseased, and information exchange across the Caribbean region.

In response to the disease and other stressors attributed to the decline of corals in Florida, NOAA announced Mission: Iconic Reefs. NOAA and partner organizations will proactively restore seven iconic sites within Florida Keys National Marine Sanctuary by removing nuisance and invasive species, and outplanting disease and climate-resilient corals. NOAA has also introduced a new grant competition, the Ruth Gates Coral Restoration Innovation Grants. Funded projects will support techniques that improve coral resilience to environmental stressors and increase the effectiveness of coral outplanting.

Individuals can also take steps to conserve coral reefs. Anchoring boats away from reefs, not touching corals while diving, and volunteering at beach cleanups are activities that everyone can put into action. People can even protect corals from the comfort of their own homes by conserving water, reducing fertilizer use, and choosing sustainable seafood.

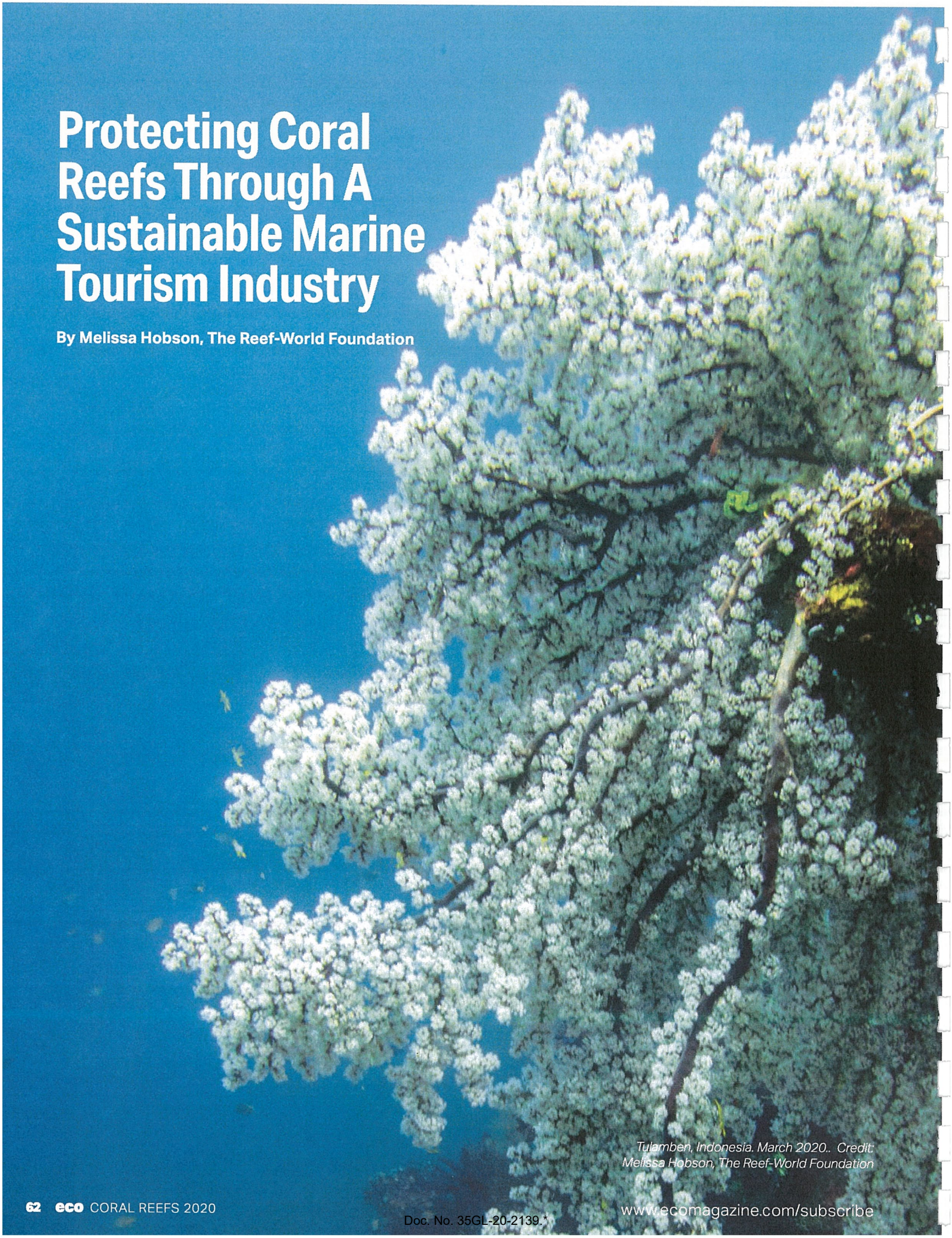
There is plenty of work to do, but the future is full of possibilities. It is up to us to decide the type of future we want for these precious ecosystems.



Infographic on "10 Ways to Protect Coral Reefs." Credit: NOAA.

Protecting Coral Reefs Through A Sustainable Marine Tourism Industry

By Melissa Hobson, The Reef-World Foundation



Tulamben, Indonesia. March 2020.. Credit: Melissa Hobson, The Reef-World Foundation

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With around one million new scuba divers being certified each year and millions more snorkeling worldwide on coral reefs, the marine tourism industry is booming. The huge number of people visiting coral reefs presents both threats and opportunities. By making simple changes to become more sustainable; the marine tourism industry is playing its part in protecting these fragile ecosystems.

David McCann, Scuba Junkie Mabul, explains why this is so important: "Conservation of the local environment, both above and below the waves, has been at the heart of Scuba Junkie's ethos right from our inception in Semporna in 2004. We believe that, as divers and snorkelers, we are fortunate to experience the joy and beauty of the underwater world, and with this comes a duty to protect and conserve. As a dive operator, this is not just a moral obligation, but also a sound business decision. From a moral perspective: we love diving, so we should do what we can to protect the reefs, and be sensitive to the needs of the local communities whose livelihoods and sustenance comes from the reefs on which our operations are based – for both now, and for the generations in the future. From a business perspective: we want our operations to continue to exist, so we need to take care of the reefs. Healthy reef means healthy business."

Scuba Junkie Mabul is one of hundreds of marine tourism businesses around the world which have joined Green Fins – an initiative of The Reef-World Foundation and UN Environment Programme which focuses on driving environmentally friendly scuba diving and snorkeling practices.

But what is sustainable diving and why is it so important?

Coral reefs – one of the world's most valuable ecosystems – are under threat. According to the World Resources Institute, more than 90 percent of the world's reefs will be threatened by local human activities, warming and acidification by the 2030s.

Sadly, unmanaged marine tourism can also be a factor and the people who come to see these magical underwater habitats – often because they care deeply about the ocean – can, unknowingly, contribute to the problem.

Because coral is so fragile, an accidental knock from a careless diver or snorkeler can easily break it and, as it's so slow growing, even a small breakage could take months to recover from. While one knock from one diver might seem negligible, the cumulative impact can be huge; particularly considering the scale of the rapidly growing marine tourism sector; one million new divers become certified each year, according to scuba training organization PADI.

The negative impacts from irresponsible tourism such as diver damage, anchoring, marine litter and fish feeding, make coral more vulnerable to global threats such as overfishing or the effects of climate change. Think about it in human terms – if you're fighting off coronavirus (heaven forbid!), the last thing you need is an already compromised immune system.

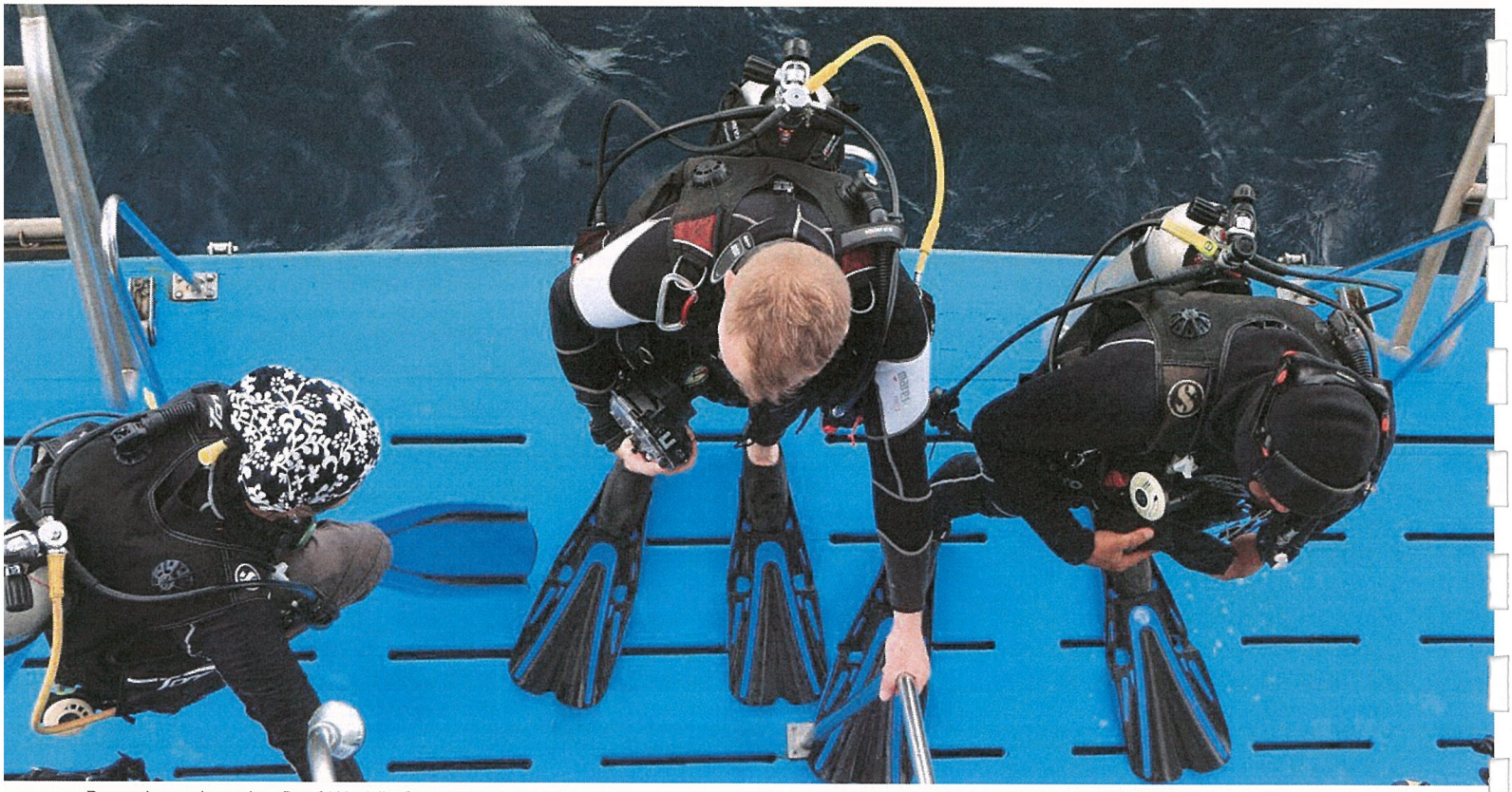
It may seem dire, but coral reefs are resilient. Remove these direct local threats and reefs become better able to survive wider stressors. Chloe Harvey, Director at Reef-World, explains, "While irresponsible tourism can pose a threat to corals, well-managed tourism provides many benefits, including economic opportunities for local communities reliant upon coral reefs. By acting responsibly, we can each help reduce the pressures tourism puts on sensitive marine ecosystems; thus, making reefs healthier and more resilient to other global stressors."

That's exactly what the Green Fins initiative sets out to do. By encouraging and empowering members of the diving industry to minimize their potential impact on coral reefs, the Green Fins program helps make corals healthier and more resilient.

Gabriel Grimsditch, UNEP's marine ecosystems expert, adds, "Reef-World's global implementation of the Green Fins initiative for sustainable diving and snorkeling has been proven to reduce the negative impact on coral reefs in the local areas the initiative is active. This, in turn, helps increase coral reefs' resilience to larger global threats, such as the effects of climate change. Coral reefs are hugely valuable in terms of marine biodiversity, harboring at least a quarter of all marine species and providing support to the livelihoods of hundreds of millions of people around the world. So, protecting them from the impacts of a burgeoning tourism industry is vital to the health of our ocean."



Green Fins - Beach, Community and Reef Cleanup on White Beach, Puerto Galera, Oriental Mindoro, Philippines. Credit: The Reef-World Foundation



Preparing to jump in . Reef-World's Green Fins initiative helps dive and snorkel operators reduce their environmental impact. Credit: The Reef-World Foundation

Whether you're a marine tourism operator based in an active Green Fins location (currently 11 countries and counting), an operator in a non-active location or a tourist visiting a coral reef on holiday, everyone can play a part in protecting these precious marine ecosystems by following these simple guidelines, as outlined by the **Green Fins Code of Conduct:**

- **Don't step on coral:** Divers and snorkelers can easily break coral with their feet or fins. This can cause injury and kill coral reefs
- **Don't touch or chase marine life:** This can lead to stressed and scared animals that will swim away, leaving nothing for guests to see. Shark species, in particular, should be left alone as our presence can influence and disrupt their natural behavior
- **Don't stir the sediment:** Careless divers and swimmers who stir up the sand can cause damage, smother coral animals, and spread disease on reefs
- **Do not buy souvenirs of shell, coral or other marine life:** This encourages people to take marine life from the ocean, removing the beautiful creatures that play a vital role in the ocean life cycle. The shells are often from marine snails that are now extremely rare due to this trade
- **Do not take marine life – dead or alive:** Removing species that would normally break down and be recycled into the sea leaves other animals without nutrients and elements they need for growth. Even empty shells on the beach play an important role in the wider ecosystem. Take nothing but pictures, leave nothing but bubbles
- **Don't litter:** Throwing trash in the ocean kills marine life, poisons seafood and can cause injury – minimize your use of single-use plastics and recycle or dispose of your litter properly. You can also pick up any litter you see in the ocean or on the beach
- **Don't wear gloves:** Gloves can encourage tourists to touch things underwater, which could cause fatal injury and damage marine life. In Egypt, the use of gloves is not permitted
- **Don't feed the fish:** This can make fish sick or aggressive, causing them to attack and injure humans. Fed fish are also more likely to leave their nests empty and vulnerable to predators
- **Dispose of litter responsibly:** Throwing trash in the ocean kills marine life, poisons seafood and can injure tourists. Encourage recycling and proper disposal
- **Wear reef-safe sunscreen:** Some chemical components in sunscreen – including Oxybenzone and Octinoxate - may have a negative impact on coral reefs. Help protect coral from harmful chemicals by using alternatives which are reef-safe and covering up with clothing when in strong sunshine
- **Report environmental violations:** If you see any destructive practices or violations of environmental laws, tell your dive guide, dive operator or government officials. By informing key authorities, you are being part of the solution as your actions can lead to appropriate action
- **Participate in conservation projects**: By taking part in conservation projects, you can have a positive effect on the environment and help educate others

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Grimsditch added, "Tourists can have a tangible impact on the marine biodiversity hotspots they visit by always following the Green Fins guidelines for best practice. Together, we can all take positive actions that will protect our coral reefs, keeping them healthy and thriving for years to come."

As well as providing these guidelines, Green Fins supports dive and snorkel centers by offering practical, low-cost alternatives to harmful practices as well as providing strategic training, support and resources to help them become more environmentally friendly.

Since joining Green Fins in 2014, Scuba Junkie Mabul has become one of the program's top 10 most environmentally friendly members. Given the fact that this initiative provides the only internationally recognized environmental standards for the diving and snorkeling industry (and has a robust assessment system to measure compliance!), making it into the Green Fins Top 10 is a significant achievement.

While improving sustainability benefits the environment, it also benefits business. McCann explains, "Customers to Scuba Junkie always highly commend the environmental and sustainable practices we have – in fact, we believe that many of them choose to come and dive with Scuba Junkie as part of the growing market in eco and conscious travel."

Yet, while hundreds of operators are competing to get a coveted Top 10 spot, it's imperative to remember the importance of collaboration when it comes to conservation. McCann said, "There's so much more that can be achieved if the industry worked together more proactively, beyond just adhering to Green Fins practices. For example – coral restoration, tackling marine debris, conservation activities for specific animals (e.g. turtles or mantas), awareness and outreach activities. If all operators in an area worked together – imagine the net benefit to the marine ecosystem. Then multiply that with a network of operators in different areas acting for the common good of the oceans... This is something that we would like to happen."

Together, we can make sustainable diving the social norm globally. For more information visit www.reef-world.org and www.greenfins.net.



A dive guide gives a pre-dive environmental briefing. Credit: The Reef-World Foundation

Caribbean King Crab: A Delicious Solution for Coral Reefs

Smothered by thick, fleshy algae, Caribbean corals—and human fisheries—stand to benefit from an innovative mariculture project in the Mesoamerican Reef region

By Michelle Z. Donahue, Smithsonian Marine Station

Just as beautiful furnishings in a home can become obscured with grime and dust from neglect, so, too can coral reefs.

In low concentrations, fleshy macroalgae species like *Dictyota, Lobophora* and *Halimeda* are normal components of a healthy reef. But across the Mesoamerican Reef, fleshy macroalgae cover has exploded. The combination of increased nutrient runoff from human developments, along with fewer herbivores like parrotfish and urchins to keep algae in check through grazing, has allowed algae to flourish throughout the reefs of Belize, Guatemala, Honduras and Mexico.

The algae are outcompeting corals for space on the reef as well as interfering with coral recruitment. In the 1980s, many reefs had over 60 percent coral cover, while as of 2018 the regional average has shrunk to around 19 percent. With drastically reduced coral cover, valuable income from tourism is also threatened: in Belize, tourism accounts for just over 14 percent of the nation's GDP, valued at $244 million in 2016.

Caribbean king crabs present an intriguing potential solution for the macroalgae problem while also supporting human economies. Building on a recent study conducted in the Florida Reef Tract, a project by the Healthy Reefs for Healthy People Initiative (HRI) is investigating the use of *Maguimithrax spinosissimus*, to be grown in culture and transplanted onto overgrown reefs in no-take zones on the Mesoamerican Reef, as a way to mow down weedy macroalgae.



For the initial pilot project in Mexico in 2018, researchers collected adult crabs to be relocated to experimental patch reefs for the purpose of studying how effectively the crabs could clean the reefs of overgrowth of macroalgae. Only mature crabs were selected for relocation. Credit: Eloy Ramirez

In a 4-month pilot experiment conducted on patch reefs, the addition of just 12 crabs in Belize and 24 crabs in Mexico gave some promising early results. In Mexico, reefs showed a strong reduction in coverage of turf algae, from 34 percent to 15 percent on experimental sites; in Belize, macroalgae cover was reduced from 32 percent to 8 percent. And at both sites, percent coverage of crustose coralline algae, which plays an important role in coral larval settlement,

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showed strong increases: from 3 to 13 percent cover in Mexico, and 5 to 25 percent in Belize.

"Herbivorous crabs may prove to be unsung heroes of the reef," said HRI director Dr. Melanie McField, a marine biologist with the Smithsonian Marine Station in Fort Pierce, Florida. "We have protected parrotfish in the four Mesoamerican reef countries and will now work to further enhance herbivory with these crabs, in addition to our parallel efforts to reduce nutrient pollution from wastewater and land run-off."

"When you add crabs to reefs, not only does it reduce algae cover directly, but it also has the cascading effects of increasing fish density and the density of living juvenile corals," added Dr. Jason Spadaro, a professor at the College of the Florida Keys, in a recent webinar on the project. Spadaro's Ph.D. research in the Florida Keys with Old Dominion University inspired the expansion of the work to Mexico and Belize.

The pilot trials were conducted in partnership with organizations including National Fisheries Institute Mexico (INAPESCA) and Fragments of Hope, with funding from the Smithsonian's Working Land and Seascapes initiative and Lindblad Expeditions-National Geographic.

But it's not just corals that benefit from more crabs on reefs. The crabs also happen to be quite tasty to human palates, and by involving local fishers in the raising, placement and recapture of market-size crabs to sell, the project also builds up an underdeveloped industry that creates jobs and boosts livelihoods.

Top photo: Herbivores like parrotfish, urchins and crabs play an important role in preventing fleshy macroalgae from dominating corals in the Mesoamerican Reef. However, a double-whammy has allowed macroalgae to proliferate in recent decades: overfishing and population collapses of herbivores, combined with increased nutrient flow from human development, has resulted in an abundance of fleshy and turf algae on reefs. In Mexico and Belize, a pilot project by the Healthy Reefs for Healthy People Initiative is investigating how to leverage the herbivorous Caribbean king crab to improve reef health as well as build and bolster local fisheries throughout the Mesoamerican Reef. Credit: Mélina Soto/HRI

Bottom photo: An adult crab rests and feeds on a patch of test reef. Credit: Javier Iturrieta

Ultimately, the project aims to train local fishers to undertake their own small-scale mariculture operations, allowing juvenile crabs to feed naturally on the fisher's home reefs where they can be harvested when fully grown.

"We're looking for creative solutions to fight macroalgae--and it's the local fishers who are the true experts," said Mélina Soto, HRI's Mexico coordinator.

It's the resurrection of an idea that dates to the early 1980s, when the Smithsonian's Walter Adey investigated, then championed, the idea of raising



Top: Researchers measure a captured adult crab to determine whether it is large enough to be relocated to experimental reef patches. Credit: David Gonzalez

Left: Mélina Soto takes adult crabs to their new homes in crevices on experimental reefs. As soon as the crabs were reintroduced, they began eating turf and fleshy macroalgae, mainly Dictytota. Credit: Claudia Padilla

Bottom Right: Tiny larval crabs are too small to be placed on reefs – hard to relocate once released and vulnerable to predators, Caribbean king crabs grown from eggs for the HRI mariculture project are kept in cages until their carapaces are around 30 millimeters across. Credit: Sara Gutierrez





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these Caribbean King crabs using algae grown on screens. In 1985, Adey predicted that algae-fed, farm-raised Caribbean king crab might even eventually supplant the lucrative Alaskan king crab market, and create thousands of jobs for local fishers. However, the project faltered when funding dried up just a few years later.

Now in the second phase, the project is piloting the development of two different mariculture systems using locally caught crabs in Mexico and Belize. The Healthy Reefs staff are working with local partners to raise crabs from larvae to juveniles inside cages to reduce predation. They plan to seed them onto nearby patch reefs inside no-take zones to enhance reef health and foster natural reproduction, while local fishers can seed their baby crabs onto their favored fishing reefs to be harvested when fully grown. The project also seeks to create a manual that would enable fishers in other regions to adapt the methods for their own use, potentially in conjunction with seaweed mariculture and other coral restoration efforts.

"The project also has the potential to engage fishermen in reef stewardship as well as diversifying their income," said Nicole Craig, who coordinates the crab project in Belize for HRI.

"A sound, circular blue economy with income opportunities for local communities is key to achieving long-standing success benefiting both the community and the ecosystem," added McField.

Top: One challenge to the successful development of a Caribbean king crab fishery is their natural camouflage. Highly cryptic, even adult crabs can be difficult to locate on a reef, though they can often be found in the same types of habitats as spiny lobster. Credit: Christian Amador

Bottom: Adult crabs collected for the patch reef experiments spend some time acclimating in coolers before being introduced to the test sites. Credit: Mélina Soto

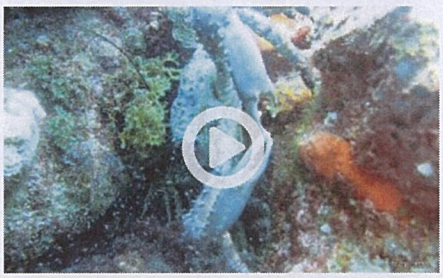




A diver places adult Caribbean king crabs on a patch of coral reef in Mexico at the start of an experiment to determine how well the crabs might graze on macroalgae overgrowing the reef. Compared with control patches, researchers saw reductions in turf algae coverage from 34 to 15 percent. There was also a significant increase in coverage of crustose coralline algae, which is associated with coral larval recruitment and settlement: from 3 to 12 percent coverage on test sites. Credit: Mélina Soto/HRI

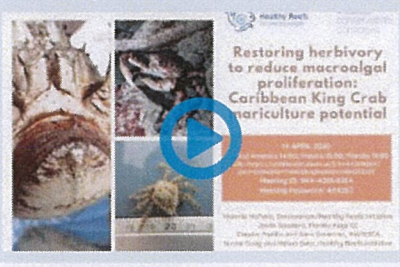


An adult Caribbean king crab (Maguimithrax spinosissimus) grazes on macroalgae growing on a patch of coral reef in Mexico. Credit Claudia Padilla/CRIAP-INAPESCA



Webinar: Caribbean King Crab Mariculture Potential

Caribbean king crabs present an intriguing potential solution for the macroalgae problem while also supporting human economies. Building on a recent study conducted in the Florida Reef Tract, a project by the Healthy Reefs for Healthy People Initiative (HRI) is investigating the use of *Maguimithrax spinosissimus*, to be grown in culture and transplanted onto overgrown reefs in no-take zones on the Mesoamerican Reef, as a way to mow down weedy macroalgae.



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58% of the world's coral reefs are potentially threatened by human activity

Coral reefs are found in 109 countries; significant reef degradation has occurred in 93

From 1876-1979 only three bleaching events were recorded, whereas 60 are on record from 1980 until 1993; in 2002 more than 400 events were recorded

Source: WWF

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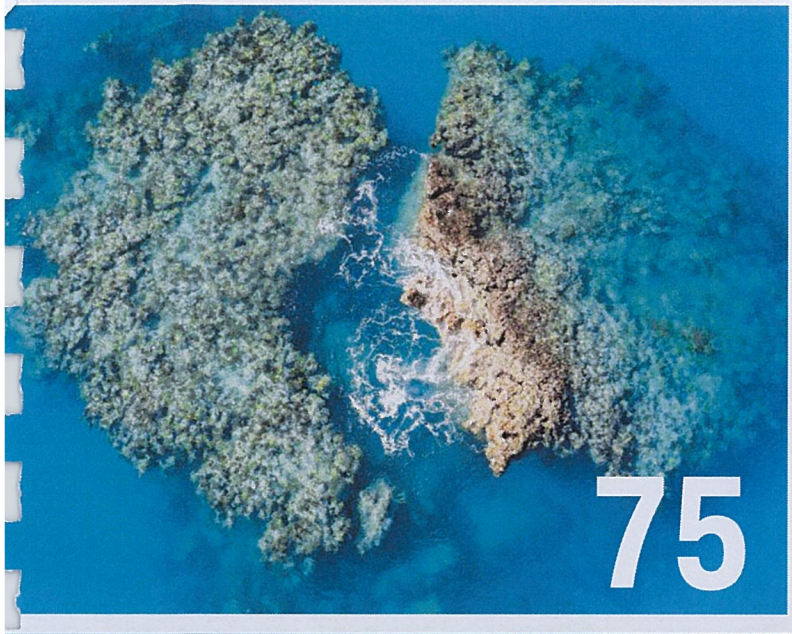
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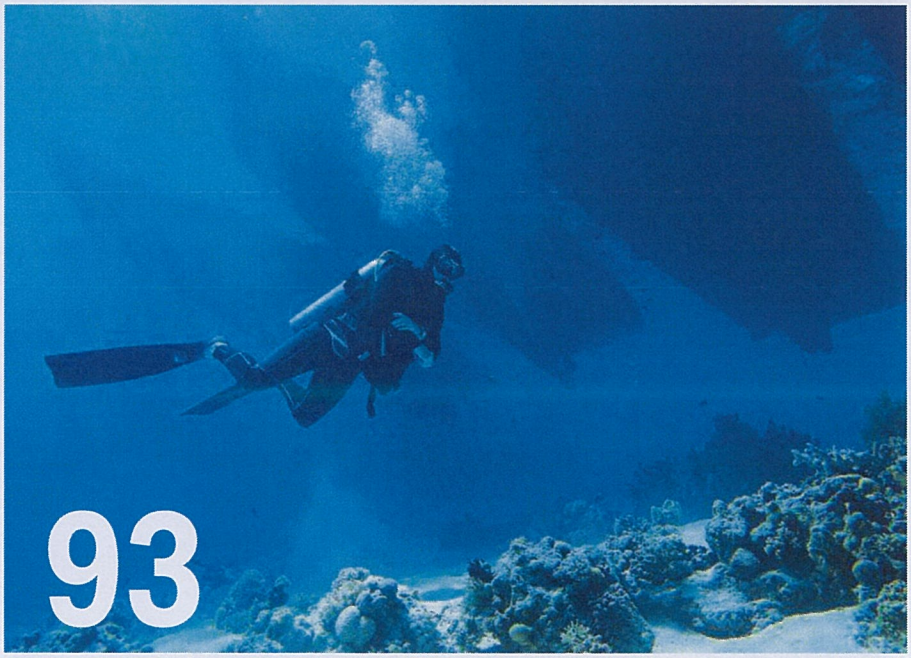

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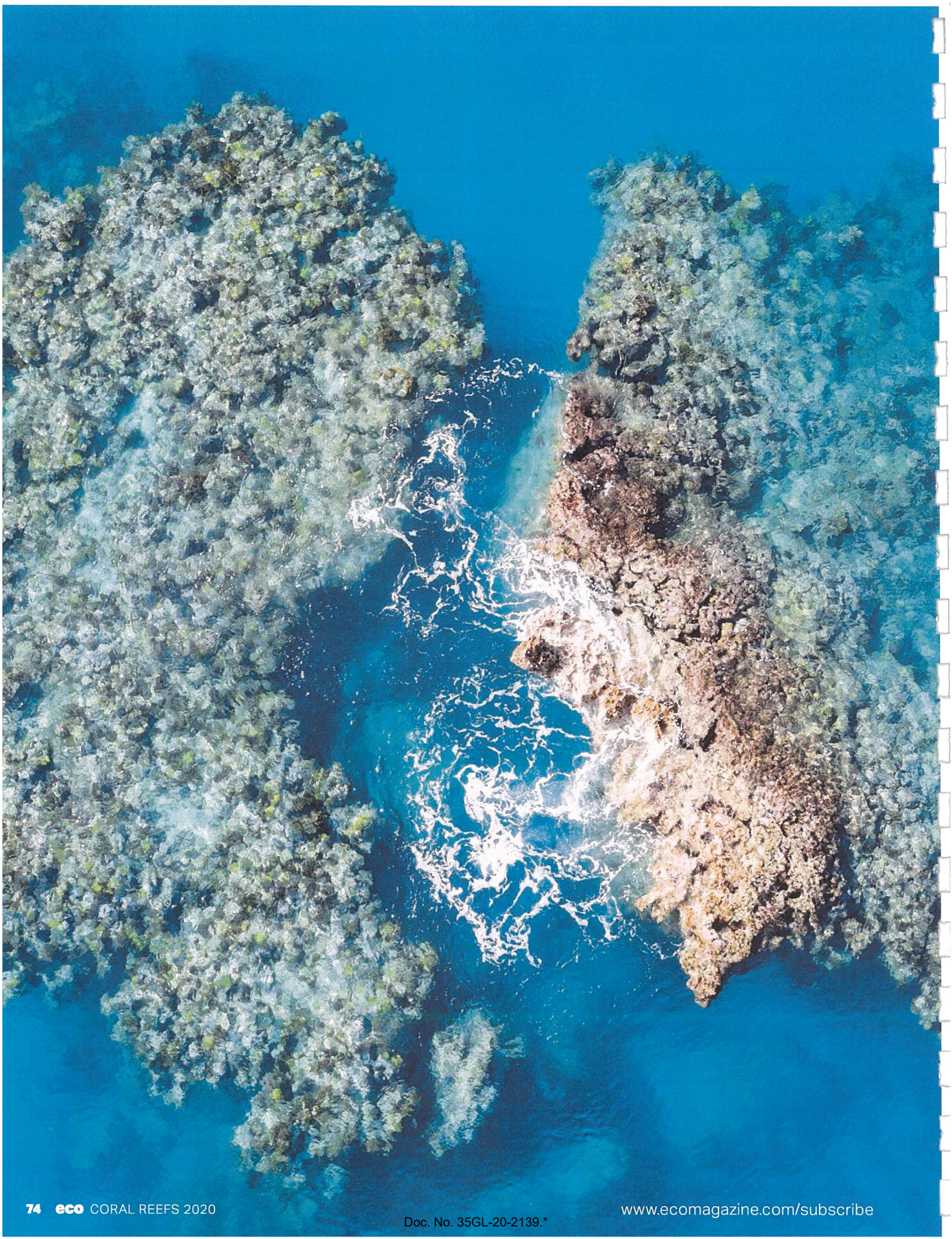

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Weathering the Storm

The Fate of Coral Reefs Post Hurricane Dorian

By Angela Rosenberg, ANGARI Foundation and Craig Dahlgren, Perry Institute for Marine Science

On September 1, 2019, Category 5 Hurricane Dorian approached the Abacos of The Bahamas, making landfall on Elbow Cay as one of the strongest Atlantic hurricanes on record. The slow-moving storm continued west over Great Abaco and stalled on top of Grand Bahama Island. Days after its initial landfall in The Bahamas, Dorian finally departed as a Category 2 hurricane. The intense, sustained winds, heavy rainfall, and significant storm surge brought on by Dorian, along with the lengthy duration it sat over the northern Bahamas, left catastrophic damage onshore. And we could assume similar effects offshore.

Perry Institute for Marine Science (PIMS) Executive Director Dr. Craig Dahlgren thought, "We had a great data set from before the storm and a rare opportunity to conduct a comprehensive assessment of damage from such a major hurricane that caused so much damage on land. While Dorian's impacts on infrastructure were tremendous and may require years to replace, the potential damage to reefs may have lasting impacts on critical ecosystem services for decades." PIMS is a nonprofit organization committed to protecting the ocean and has dedicated decades to researching coral reef habitats, sustainable fisheries and marine protected areas in The Bahamas.

Over the past few years, PIMS has partnered with ANGARI Foundation to assess coral reef health throughout The Bahamas. ANGARI Foundation is a nonprofit dedicated to supporting and promoting marine science research and education. Headquartered in West Palm Beach, Florida, the Foundation owns and operates a 65-foot research vessel christened R/V *ANGARI*, which completed its 34th expedition in March 2020. Foundation Co-founder, President and Captain of R/V *ANGARI*, Angela Rosenberg, describes the vessel, "We designed a very comfortable and capable vessel to support research expeditions in remote locations, and meeting the needs of scientific divers and their research requirements was especially important to us."

Together, PIMS and ANGARI have completed 90 comprehensive coral reef health assessments throughout The Bahamas. Serendipitously, about 10 months before Hurricane Dorian, the team had surveyed reefs off Grand Bahama and southern Abaco, and only two months before Hurricane Dorian, the team had spent two weeks collecting data on Abaco reefs. After Hurricane Dorian passed, they had a unique opportunity to revisit recent sites to discover the effects of a Category 5 hurricane on a variety of reef habitats and structures.

A 30-meter-wide coral head lays broken and exposed post Hurricane Dorian. Researchers observed various scales of reef destruction - from physical damage to bleaching to silt and sediment coverage - throughout the northern Bahamas. Photo credit: Will Greene/Middlebury College

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Surveying a Disaster Zone

Surveying reefs in remote locations for two weeks straight can be challenging on a normal day, but after a catastrophic event, it can quickly become a logistical nightmare. The *ANGARI* crew had to prepare for the expected demands of this type of work, as well as the possibility of unanticipated needs that may not be easily met once offshore and operating in a disaster area. During the two-week expedition, R/V *ANGARI* only touched land twice - a quick stop in Port Lucaya to clear customs and immigration, and a few hours in Marsh Harbour to refuel. Both stops had been scheduled well in advance.

"Having done these types of survey trips with PIMS before, we prepared and provisioned for two weeks at sea. We knew that we would be asked to maneuver the vessel into shallow, uncharted waters and had a planned itinerary with weather options ready," explains Captain Rosenberg, "but you can't foresee everything."

Only a week into the project, a major failure on the dive compressor seriously threatened the expedition's success. With a little luck, perseverance and help from contacts back in Florida, replacement parts were acquired and flown in a day later. The dive compressor was quickly returned to full operation, and the team was back underwater later that same day.

Devastating Effects

We found that Hurricane Dorian had devastating effects on a few of the reefs around Abaco and Grand Bahama, but little impact on other reefs short distances away. Furthermore, the type of damage varied considerably from reef to reef. This is illustrated at the Mermaid Reef and Sandy Cay Reef, two sites PIMS scientists have been studying for nearly a decade. Before Hurricane Dorian, both reefs had the highest amount of live coral in The Bahamas with nearly five times the average.

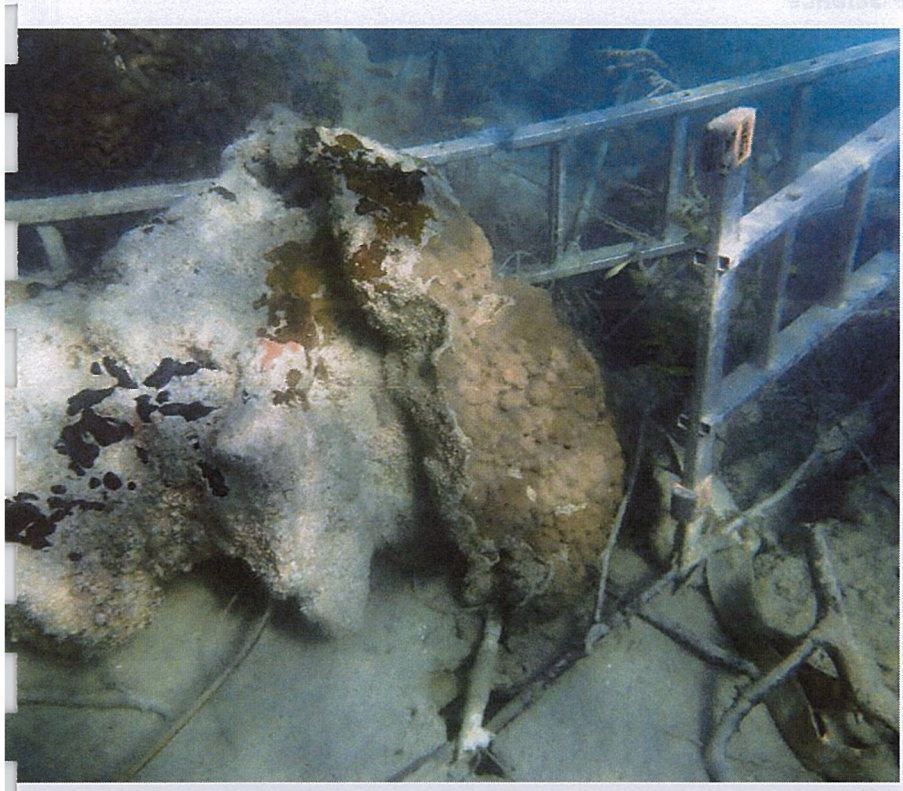
Mermaid Reef, a popular shallow reef just a few hundred feet offshore from Marsh Harbour, saw some of the worst damage from Hurricane Dorian. The reef was composed of large mounding coral colonies that had proven particularly resilient to mass bleaching events over the past decade and survived major storms like Hurricane Floyd in 1999. This reef took a direct hit from Hurricane Dorian at its peak strength when it first made landfall. The majority of the homes nearby were destroyed, with some razed to their foundations, leaving pieces of houses, household contents and even whole trees scattered across the reef. Large coral colonies up to the size of small cars, were moved by the strong storm surge and waves. As a result, there was a reduction in live coral cover by about 40 percent, with up to 30 percent of the coral colonies on the reef rolled from their position or broken into smaller pieces. In

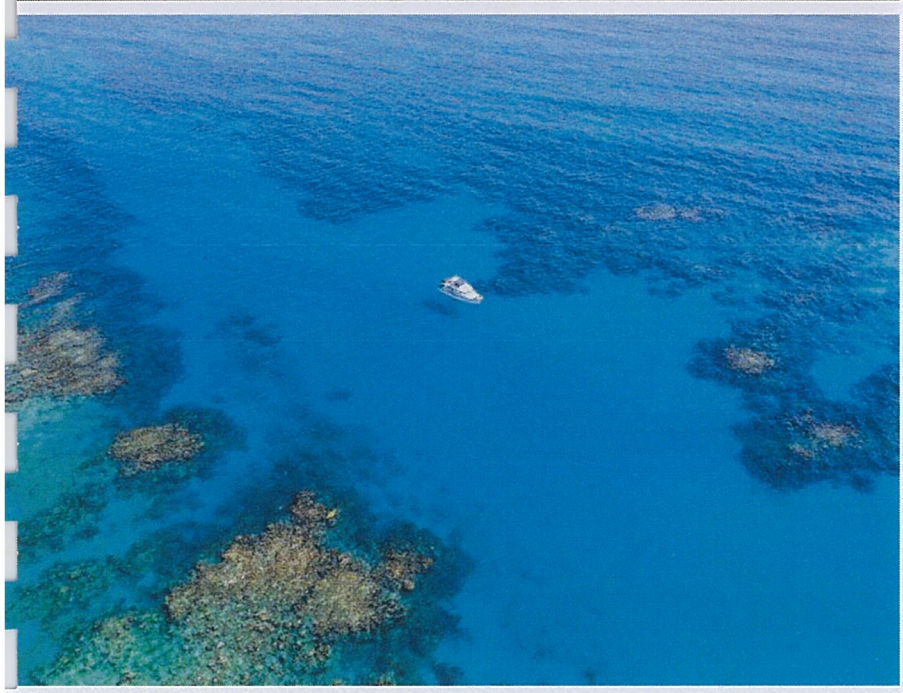
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contrast, Sandy Cay reef just 11 miles to the south was close to the southern eyewall of Hurricane Dorian at its strongest. But this reef, dominated by much more delicate branching staghorn and elkhorn coral, saw minimal loss or breakage of corals, debris or other storm damage.

Farther away from where the hurricane made its first landfall and began to slowly move across east Grand Bahama and the northern Abaco Islands between little Abaco and Grand Cay, several reefs also saw severe damage. Off east Grand Bahama, trees from shore, mostly invasive Australian pines which have shallow root systems, were uprooted and rolled across the reef, demolishing corals and anything in their way. In the northern Abacos, shallow patch reefs up to 100 feet across were pounded by waves and fractured, and in several cases, large chunks were calved from the main reef. Other reefs in the area had sand, silt and mud from inshore areas smother corals, burying them in up to three feet of sediment. At several of these sites, many corals were observed to be bleached.





Signs of Hope

There were signs of hope, however, in our assessments. Coral restoration sites off south Abaco saw minimal damage from the storm, and coral nurseries growing critically endangered staghorn and elkhorn corals (*Acropora cervicornis* and *A. palmata*) off Grand Bahama and Abaco, even those in the eye of the storm at its peak strength, survived. These nurseries can provide a means to restoring populations where they were damaged by the storm.

Our expedition was the first step in assessing impacts of Hurricane Dorian on the reefs of Abaco and Grand Bahama. It gave us a very broad look at what types of damage different reefs experienced across the full range of hurricane conditions encountered throughout the northern Bahamas. We are currently following up on this expedition by partnering with oceanographic modelers to gain a better understanding of the conditions experienced on the various reefs surveyed. Our hope is to better explain the damage that was observed and predict areas at risk from future storms. We are also planning more assessments for areas that received the most damage and monitoring many of the sites surveyed in October 2019 to determine the long-term impacts of the storm and track recovery. PIMS and ANGARI plan to return to the area to continue this work later this year.

For more information on ANGARI Foundation visit https://angari.org/ and the Perry Institute for Marine Science visit http://www.perryinstitute.org/.

Researchers from the Perry Institute for Marine Science (PIMS), The Nature Conservancy, Middlebury College and Walt Disney World surveyed reefs around Grand Bahama and Abaco to assess the environmental effects of Hurricane Dorian. Credit: Kevin Davidson, ANGARI Foundation

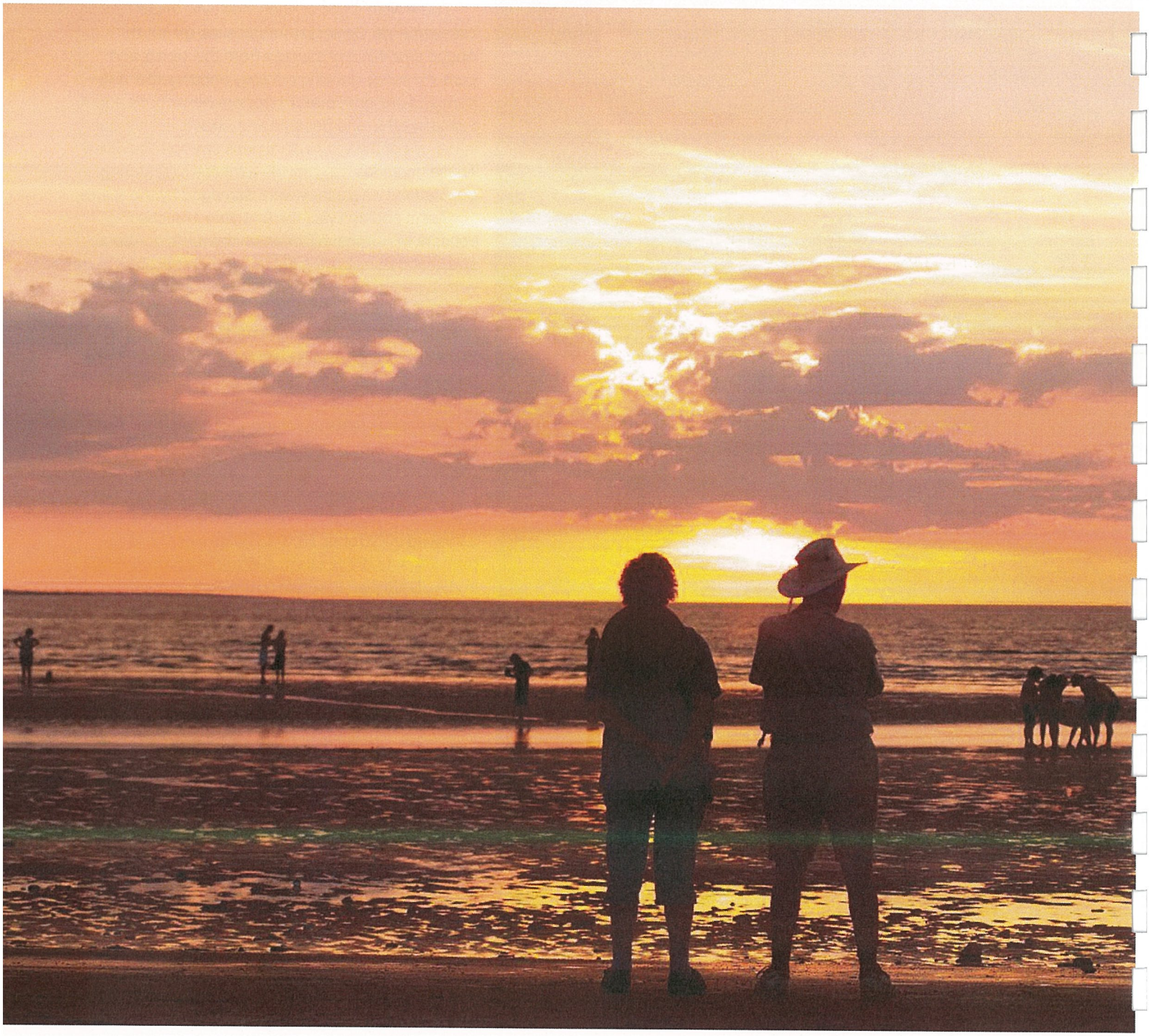
Mermaid Reef, a shallow reef just a few hundred feet offshore from Marsh Harbour, saw some of the worst damage from Hurricane Dorian. Pieces of houses, household contents and even whole trees were scattered across the reef. Craig Dahlgren/Perry Institute for Marine Science.

R/V ANGARI squeezes in among the shallow reefs off southeast Abaco.. Photo credit: Will Greene/Middlebury College

How Cyclones Damage Distant Reefs

When it comes to extreme weather, distance does not always provide corals safety from the destruction caused by hurricanes and typhoons

By Marji Puotinen, Australian Institute of Marine Science



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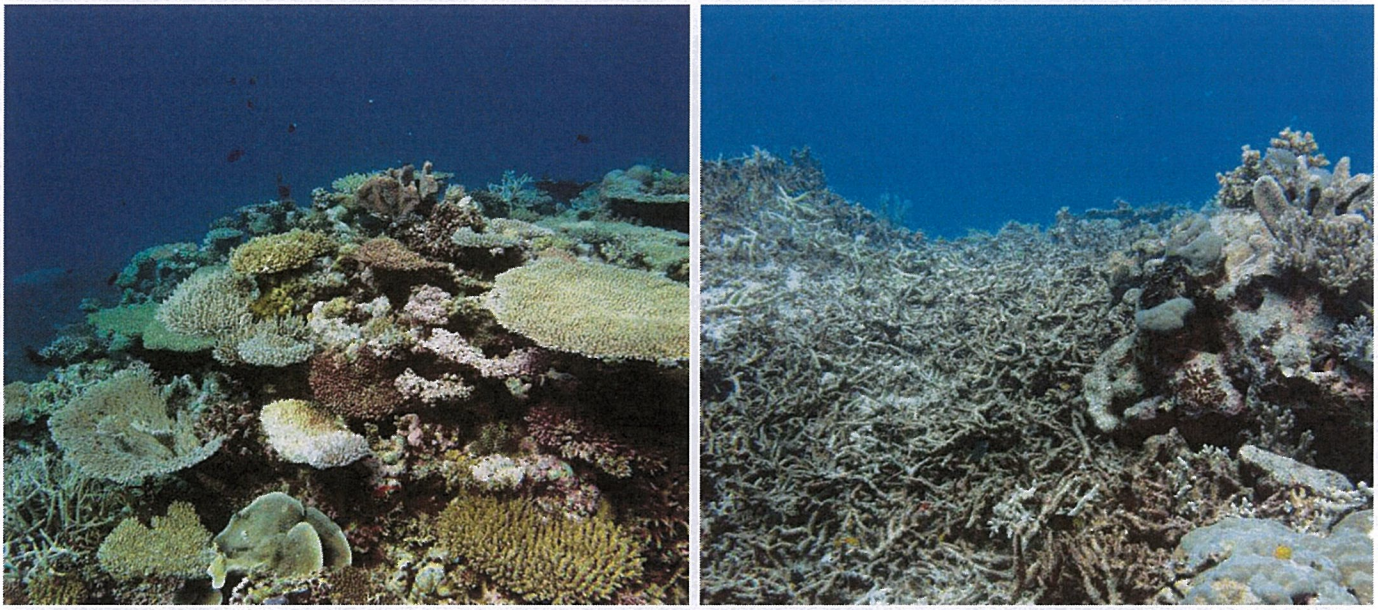


Figure 1 - The same area of Scott Reef photographed in 2010, and again in 2012 after Cyclone Lua. Credit: James Gilmour/AIMS

It started as a mystery.

In October 2012, Dr. James Gilmour from the Australian Institute of Marine Science (AIMS) in Perth, Australia, noticed considerable damage to coral reef communities on Scott Reef, an isolated coral atoll in the Indian Ocean. At its most exposed sections, Scott Reef lost 50 percent of its massive and robust *Porites* corals and virtually all its more fragile branching *Acropora* coral species (Figure 1).

Damage like this is often caused by tropical cyclones, known as hurricanes or typhoons in other regions. In March 2012, severe cyclone Lua tracked through the Indian Ocean at just the right time. Still, it came no closer than 500 kilometers, much further than the accepted wisdom that cyclone waves only damage reefs located within 100 kilometers of the storm.

Enter AIMS spatial data scientist, Dr. Marji Puotinen, who has long studied cyclone wave impacts on coral reefs. Using models, Puotinen reconstructed the hourly spread of high winds from the cyclone and discovered that, regardless of the distance, Scott Reef was struck by Cyclone Lua's damaging waves. State-of-the-art numerical wave modeling by Dr. Edwin Drost, a colleague from the University of Western Australia (UWA), revealed that Scott Reef was battered by these waves for up to three and a half days (Figure 2).

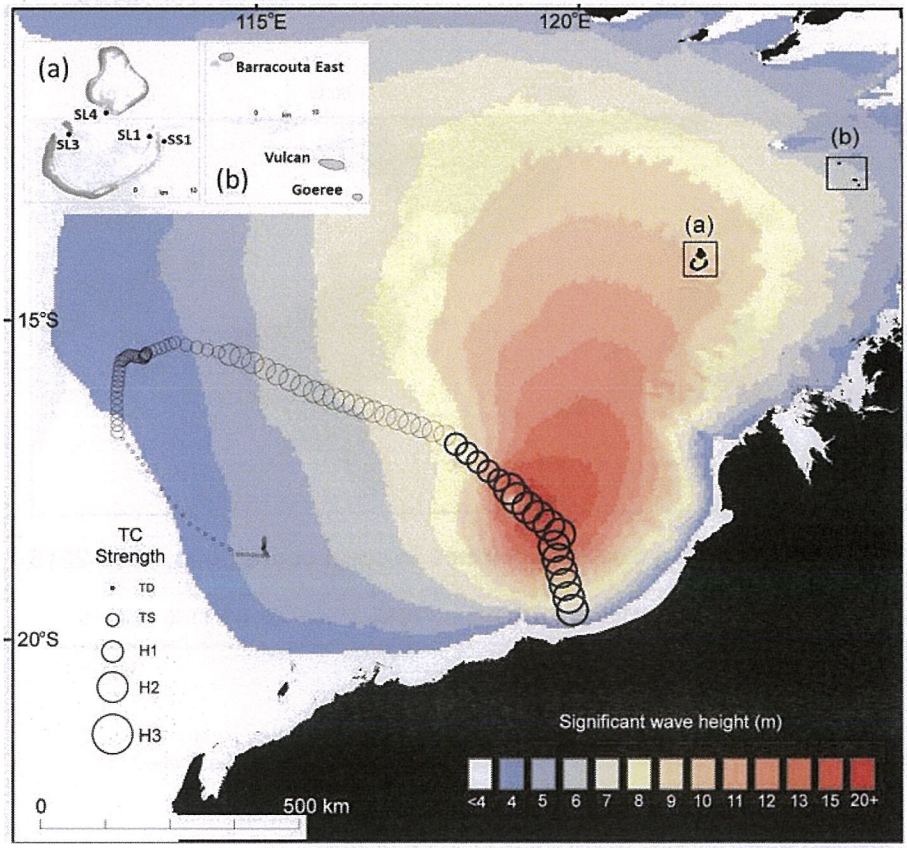


Figure 2 – The modeled spread of damaging waves from severe tropical cyclone Lua (colored areas) extended up to 1,000 km from the cyclone track. The severe coral loss was observed at Scott Reef (a) and the Shoals (b), which were ~500 and ~900 kilometers away. Credit: Marji Puotinen /AIMS; Edwin Drost / UWA.

Subsequently, AIMS scientists observed similar damage at submerged shoals located a further 300 kilometers to the north-east. The unexpected reach of Lua's damaging waves – up to 1000 kilometers from the track - was due to the generation of strong winds alongside the cyclone's vast size and slow movement.

"This example demonstrates that if we assume damage from all cyclones occurs within only 100 kilometers of the track, we can underestimate the spatial extent by up to 10 times for strong cyclones that are big in size," Puotinen said. "This could lead to making unfortunate choices when trying to prioritize conservation targets."

She added that using a simple model is preferable whenever possible, but only if it works most of the time. Unfortunately, field data from around Australia shows how assuming cyclone wave damage fits within a set distance can both under- and over-estimate the spatial extent of reef damage. This happens because cyclones constantly change along their tracks, varying in strength, size and speed. Physics-based wave theory tells us that a strong, large cyclone moving slowly can produce the largest waves.

The team then explored how often a simple distance-based model would underestimate the spatial extent of cyclone damage. Puotinen and her AIMS colleagues collected existing information on cyclone size and frequency, crunching data gathered between 1985 and 2015 for 150 coral reef ecoregions around the world.

Each cyclone's position and strength were recorded every six hours, allowing variations to be plotted in great detail.

They found that more than 70 percent of the ecoregions were exposed to at least one cyclone at peak strength and size during the 30-year period (Figure 3). Some, however, experienced them roughly every five years, and others roughly every 10.

"Coral reefs have been living with cyclones for millions of years," said Puotinen. "But recovery after a big battering can be a slow process, which can take a decade or more."

Climate change models present a complex picture for cyclones. The total number occurring in any given period may not increase – but that's not necessarily good news for vulnerable reefs.

"Changes in the atmosphere mean it will be harder for cyclones to form in the first place, but warmer ocean water, which fuels their intensity, means it will be easier for them to strengthen once they do," Puotinen explained.

She added that her team's findings carry strong lessons for reef management and conservation strategies. "When deciding where on the Great Barrier Reef, for instance, to invest millions of dollars in repairing or enhancing reefs, you don't want to select a location which may be regularly battered by cyclone waves," she said.

Researchers have long observed that damage to coral communities varies considerably across very small distances. One part of a reef can be devastated by cyclone waves, while another part can be left untouched. This happens, in part, because the hard structures that make up coral reefs do an excellent job of dissipating wave energy. As a wave approaches the reef, the first area of impact ends up protecting the rest. For example, as part of the study, Dr. Ryan Lowe of UWA used a

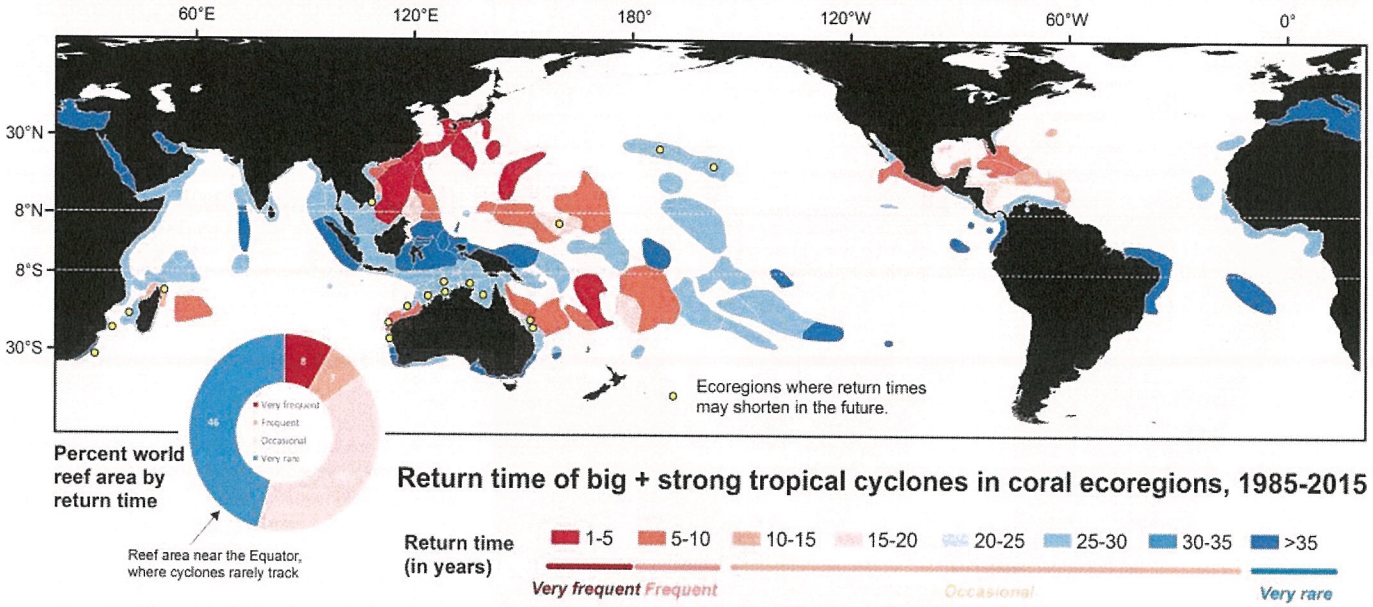


Figure 3 - Current expected number of years between exposure of coral ecoregions to cyclones that are both big and strong (return times). Return times at ecoregions currently range from very frequent (dark red) to very rare (dark blue). Yellow dots indicate where return times may shorten in future as the climate warms, increasing the threat of wave damage to coral reefs. Credit: Marji Puotinen / AIMS.

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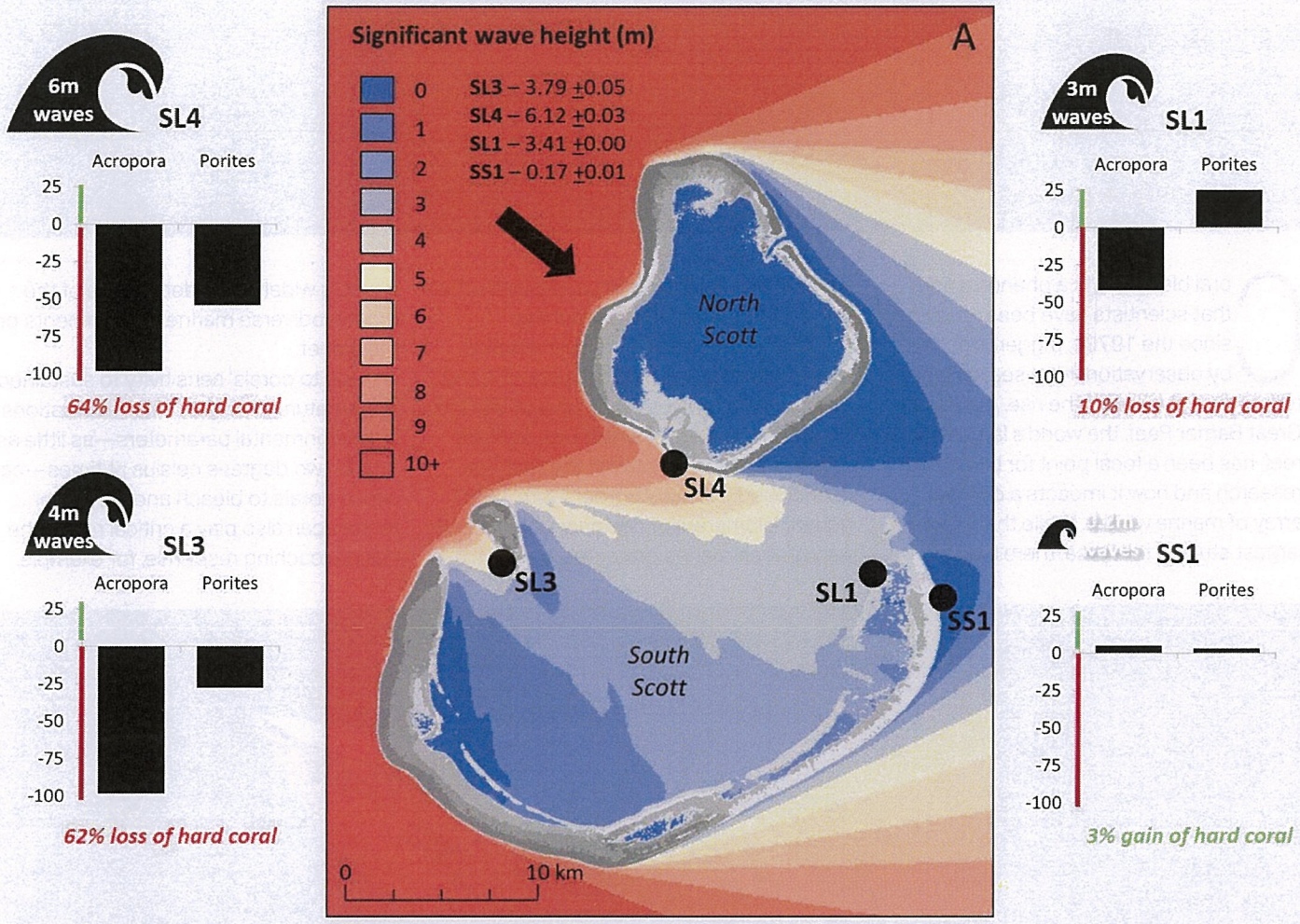


Figure 4 – A numerical wave model showing how cyclone Lua's wave heights dropped with movement across the hard structures of the reef. High wave energy (red) was reduced completely by the time the lee side of the reef was reached (blue). Credit: Marji Puotinen / AIMS; Ryan Lowe / UWA.

high-resolution numerical wave model to show how huge waves approaching the western side of Scott Reef (Figure 4, in red) were quickly reduced in size. By the time it reached the lee side, the waves were almost entirely absent (Figure 4, in blue).

Field observations of coral loss at Scott Reef matched this – the greatest coral loss was seen where wave heights were the highest (Figure 4 - SL4, SL3), and the least coral loss where wave heights were the lowest (Figure 4 - SS1).

This approach to modeling can help identify the locations within a reef least likely to suffer cyclone damage to be chosen for coral restoration.

Gilmour said the study's findings illustrate the complexity and severity of the threats facing reefs around the world.

"Coral reef communities around the world are under increasing threat from a range of stressors, and we must understand which parts of the reef should be the focus of conservation efforts," he said.

"It is the combination of cyclones with exposure to these other stressors – most notably rising water temperatures – that is the most significant emerging threat to reefs globally."

Continuing to unravel the mystery of where future cyclones are most likely to frequently damage the world's coral reefs, the researchers conclude, will provide vital clues for the management of at-risk areas.

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Authors on the paper, recently published in the journal *Global Change Biology*, include Dr. Marji Puotinen, Dr. Martial Depczynski, Dr. Ben Radford, Dr. Andrew Heyward, Dr. James Gilmour (AIMS); Dr. Edwin Drost, Dr. Ryan Lowe (UWA). doi 10.1111/GCB.15136

Coral Nations:
A Comparative Study of Reefs in The Maldives and Egypt

By Shannon Nailor, Cornwall College in Partnership with Plymouth University

Coral bleaching is a phenomenon that scientists have been studying since the 1970s, triggered in part by observations that sea surface temperatures were on the rise. Australia's Great Barrier Reef, the world's largest coral reef, has been a focal point for bleaching research and how it impacts a diverse array of marine wildlife. While this is the largest studied reef area, there are also smaller, less-studied reefs and islands that are equally impacted by bleaching.

The Maldives is a small island nation in the Indian Ocean and consists of 1,192 coral islands with a surface area of 90,000 square kilometers, of which only 200 are inhabited. Egypt, located in the Red Sea, is enclosed by inland borders with 3,800 square kilometers of designated reefs and established marine protected areas. North Egypt is widely regarded as one of the most biodiverse marine environments on the planet.

Due to corals' sensitivity to sustained temperature changes, small fluctuations in environmental parameters—as little as one to two degrees celsius at times—can cause corals to bleach and die. Other factors can also play a critical role in the rising bleaching response, for example,



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pollution and overfishing. Since corals have a thermal threshold of 25 – 30 Celsius, an average global increase of only 1 – 2 Celsius each year will inevitably result in further bleaching in the not-too-distant future.

The Maldives is an ideal location to study the interaction between sea temperature rise and bleaching response given that the local reefs are home to a variety of marine life dwelling within coral mounds, underwater mountains (known as Thila and Giri), and a large barrier reef. 240 species of hard coral can be found within this location. However, the marine biodiversity was impacted significantly by the 1998 mass bleaching event, which led to the loss of 80 percent of the localized corals. Since then, reefs are recovering at a slow rate, impacted further by another bleaching event later in 2016. This type of severe bleaching response to the elevated sea temperatures will alter the species diversity of both coral and other marine organisms in the future.

Egypt, by way of comparison, is host to complex reef systems, islands, and fringing reefs, which approximately 300 hard corals and 125 soft corals call home. The region also has designated marine protected areas for the protection of marine biodiversity. The reefs are thought to be resilient within the changing global climate, as very little or no bleaching has been observed to date.

In collaboration with Reefcheck, a desk-top review of data collected between 2007 – 2019 was used to investigate the resilience of Egyptian reefs, as well as the sensitivity of the Maldivian reefs. Reefcheck provided the data gathered during dive surveys of 169 reefs at both locations. The review focused on three components: the variation between five and ten meters depths; the variation between coral colony (singular coral structures) and population (overall coral cover within one transect) bleaching response; and the temperature variation alongside natural seasonal cycles within Maldives and Egypt.

Over 13 years (2007- 2019), significant variation in coral response to bleaching events was witnessed in the Maldives, parallel to an increase in response within colonies compared to the overall population (Figure 1). Egypt was previously reported to be resilient to current climate change. This study has found that during the mass bleaching event of 2014 – 2017, there was an increased shift in response, though only slight in 2016 for both Egyptian coral colony and population (Figure 2). This is the first recorded temperature increased observation of bleaching taking place at Egypt's reefs.

At five and ten meters, we found that the Maldives was significantly impacted, with figures being close to the average temperature range of 28 – 29 Celsius (84 - 85 Fahrenheit) in which bleaching is triggered. In Egypt, however, it was significantly lower, with an average of 25- 26 Celsius (77 -78 Fahrenheit) (Figure 3). The review demonstrated that the Maldives is more susceptible to bleaching than Egypt, perhaps because the islands are more exposed, while Egypt is bordered by Jeddah and so is essentially an enclosed channel. However, change is occurring in Egypt, suggesting that its reefs may not be as resilient in the future.

Through this review, we have gained insight and understanding of how bleaching impacts coral reefs in these locations. And it is clear that change is taking place. Egypt is in danger of becoming less resilient, and Maldive coral colonies are significantly more susceptible to bleaching than other countries. While the data may reveal a low figure compared to the overall population, it highlights the possible long-term impacts of ever apparent shifts in global climate change. www.reefcheck.org

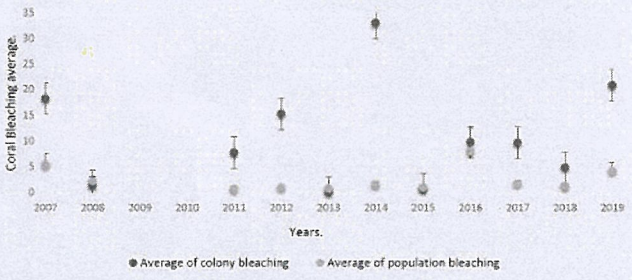


Figure 1: Scatter plot of Maldives average coral colony (Dark) and population (Light) bleaching data recorded between the years of 2007 – 2019. Significant bleaching response within Maldivian reefs.

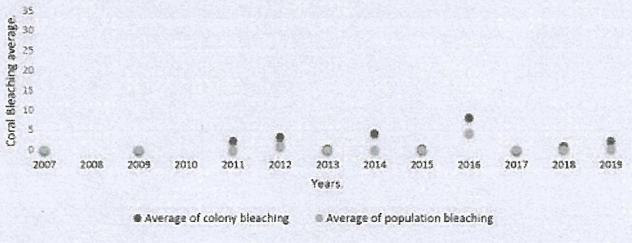


Figure 2: Scatter plot of Egypt average coral colony (Dark) and population (Light) bleaching data recorded between the years of 2007 – 2019. Egyptian reefs appear not significantly impacted with exception of the increase in bleaching activity in 2016.

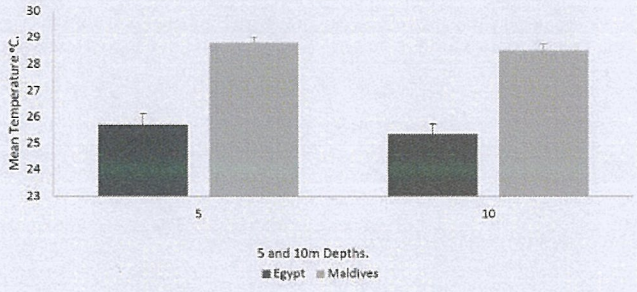
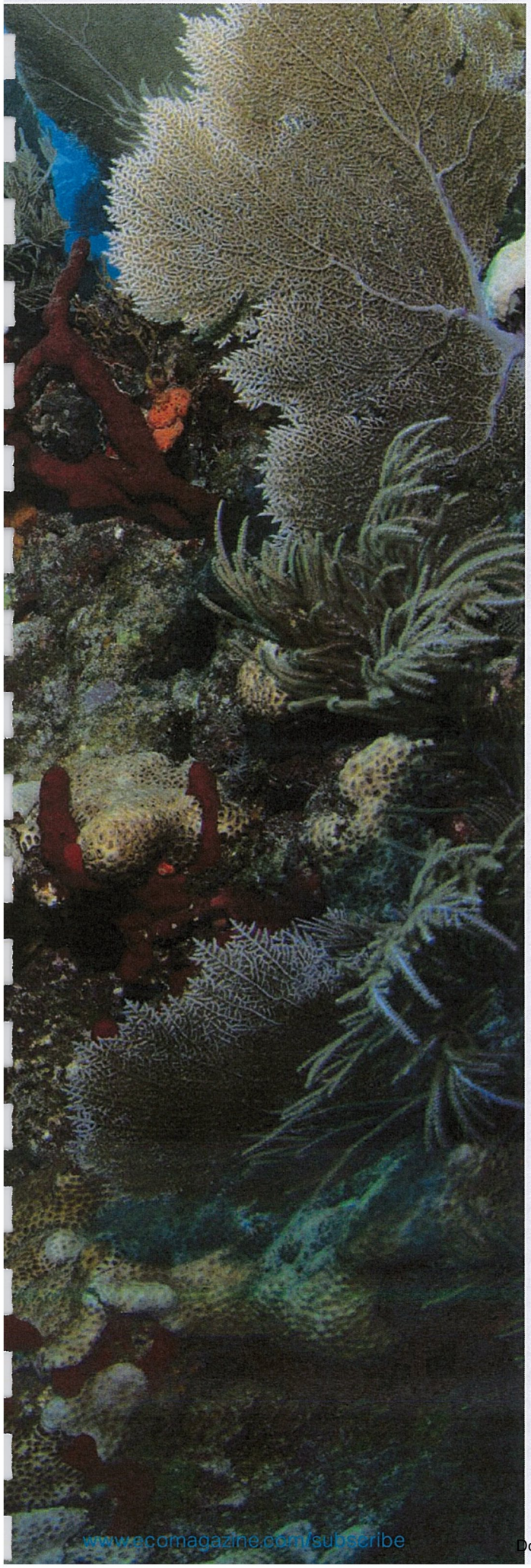


Figure 3: Temperature records at 5m and 10m in Egypt (Dark) and Maldives (Light). The Maldives is significantly closer to the thermal threshold of 29-30 0C in which bleaching is observed while Egypt's reefs are within the threshold of 25-26 ^{0}C.



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Florida's Diseased Reefs

An unprecedented coral disease is laying waste to reefs in Florida and the Caribbean

By William F. Precht, Director of Marine and Coastal Programs, Dial Cordy and Associates

Starting in September 2014, the warmest year on record for South Florida corals, a region-wide coral bleaching event immediately preceded a coral disease outbreak. The disease was first documented at sites directly adjacent to a leaking outfall pipe of the Miami-Dade Central Wastewater Treatment Plant located off Virginia Key. While the precise etiology of the disease remains enigmatic, it is likely that the synergistic effects of a weakened coral host due to temperature stress, combined with exposure to these unfavorable waters, provided the conditions necessary to initiate the disease.

The appearance of this new disease was similar in many respects to a previously identified coral disease known as the white plague. White-plague disease generally affects massive boulder and brain corals and has commonly been observed affecting reefs throughout Florida and the Caribbean over the past few decades. The signs of this new disease, however, while similar in outward appearance to white plague belies its catastrophic nature; once infected, total coral mortality is almost certain with colonies often dying within only a few weeks of becoming infected. This new emergent disease termed Stony Coral Tissue Loss Disease (SCTLD) is arguably the most lethal coral disease ever recorded on a contemporary coral reef.

By the summer of 2015, the disease was observed to extend from Whistle Buoy Reef in Biscayne National Park in the south to the Breakers Reef off Palm Beach County in the north. That is a linear spread of approximately 130 kilometers (80 miles) in less than one year. However, the disease showed no signs of slowing and by summer of 2017

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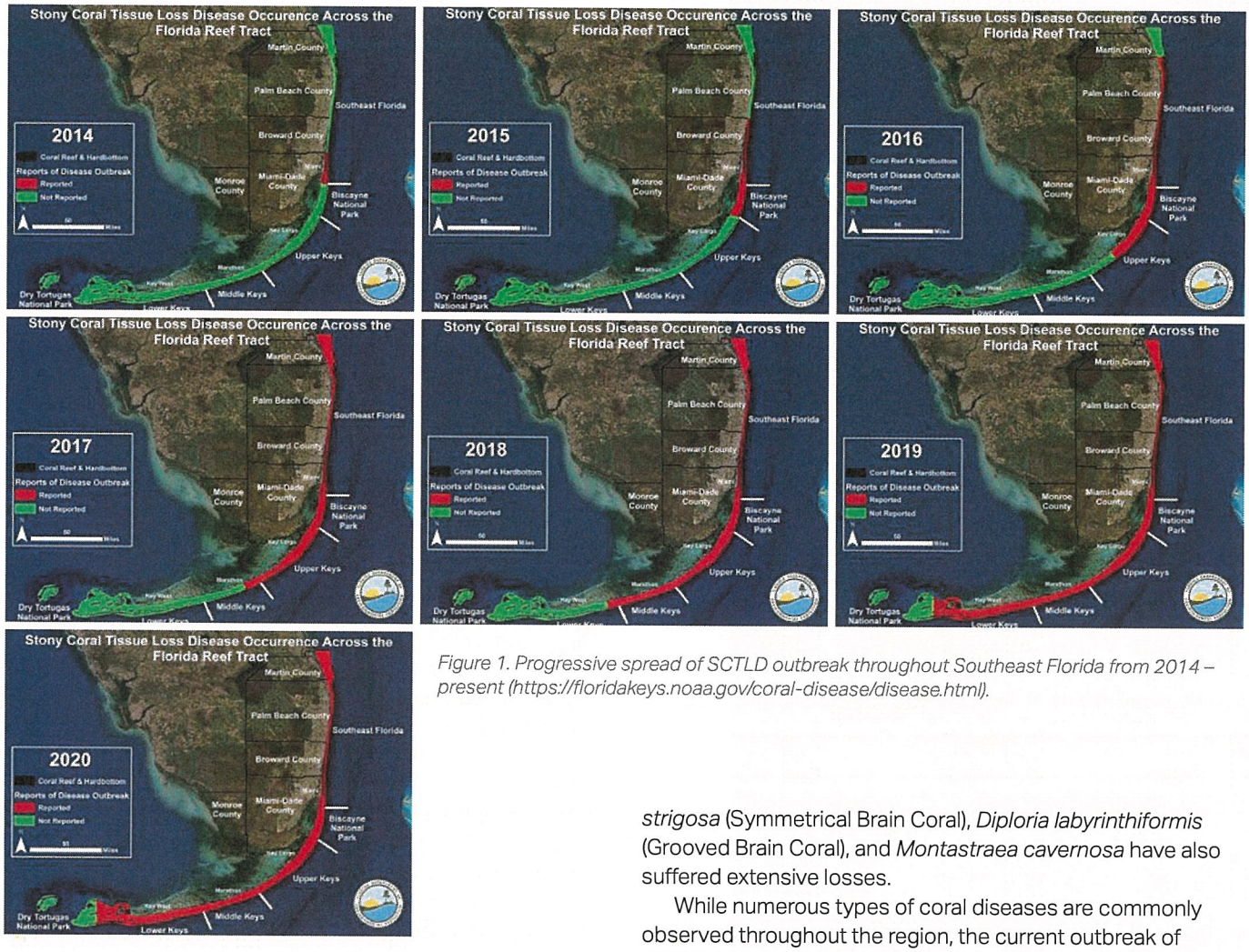


Figure 1. Progressive spread of SCTLD outbreak throughout Southeast Florida from 2014 – present (https://floridakeys.noaa.gov/coral-disease/disease.html).

reports of widespread disease hot-spots were confirmed as far north as St. Lucie Inlet in Martin County (the northern limit of the Southeast Florida Coral Reef Tract) and as far south as Alligator Reef in the Florida Keys National Marine Sanctuary (FKNMS). As of spring 2020, the disease is still actively working its way through the FKNMS and is presently impacting reef sites south and west of Key West. Since its emergence in the fall of 2014, SCTLD has spread a total distance of about 450 kilometers (280 miles); 175 kilometers (110 miles) to the north and some 275 kilometers (170 miles) to the south, impacting a majority of the reefs along the Florida Reef Tract (Figure 1).

The impact of this disease outbreak on Florida's coral reefs has been nothing short of devasting, killing around 35 percent of the entire regional southeast Florida coral population in its wake. Coral species in the family Meandrinidae have been the hardest hit. Specifically, the species *Dendrogyra cylindrus* (Pillar Coral), *Eusmilia fastigiata* (Smooth Flower Coral), *Meandrina meandrites* (Maze Coral), and *Dichocoenia stokesi* (Elliptical Star Coral) have generally suffered losses up to 90 percent region-wide (Figure 2). These four species are now essentially functionally extinct throughout the length and width of the Florida Reef Tract. Other massive coral species including *Colpophyllia natans* (Boulder Brain Coral), *Pseudodiploria strigosa* (Symmetrical Brain Coral), *Diploria labyrinthiformis* (Grooved Brain Coral), and *Montastraea cavernosa* have also suffered extensive losses.

While numerous types of coral diseases are commonly observed throughout the region, the current outbreak of SCTLD is clearly unprecedented due to the high number of susceptible species (up to 20 documented species), the near 100 percent mortality rate of infected colonies, the temporal persistence of the disease outbreak, and the large spatial scale of this event. The spread of SCTLD and the transmissibility of the disease over multiple years and covering thousands of square kilometers follows the pattern of a highly infectious, water-borne pathogen. Yet, some five years after being first observed, the direct causative agent responsible for this outbreak (likely a consortium of pathogenic bacteria) is still presently unknown.

As a response, in the spring of 2018, former US Senator Bill Nelson (FL) who was then ranking member of the US Senate Committee on Commerce, Science, and Transportation asked for the help and expertise of multiple US government agencies to identify the cause of the current disease outbreak and to mitigate the effects of the current "environmental crisis." While much research and monitoring are on-going, most of the questions regarding this catastrophic coral killer remain unanswered. Future work will hopefully identify the causative agents responsible for this region-wide devastation which, in turn, may provide methods to combat, ameliorate, and potentially cure this insidious coral killer (see article by Smithsonian Marine Station in this issue).

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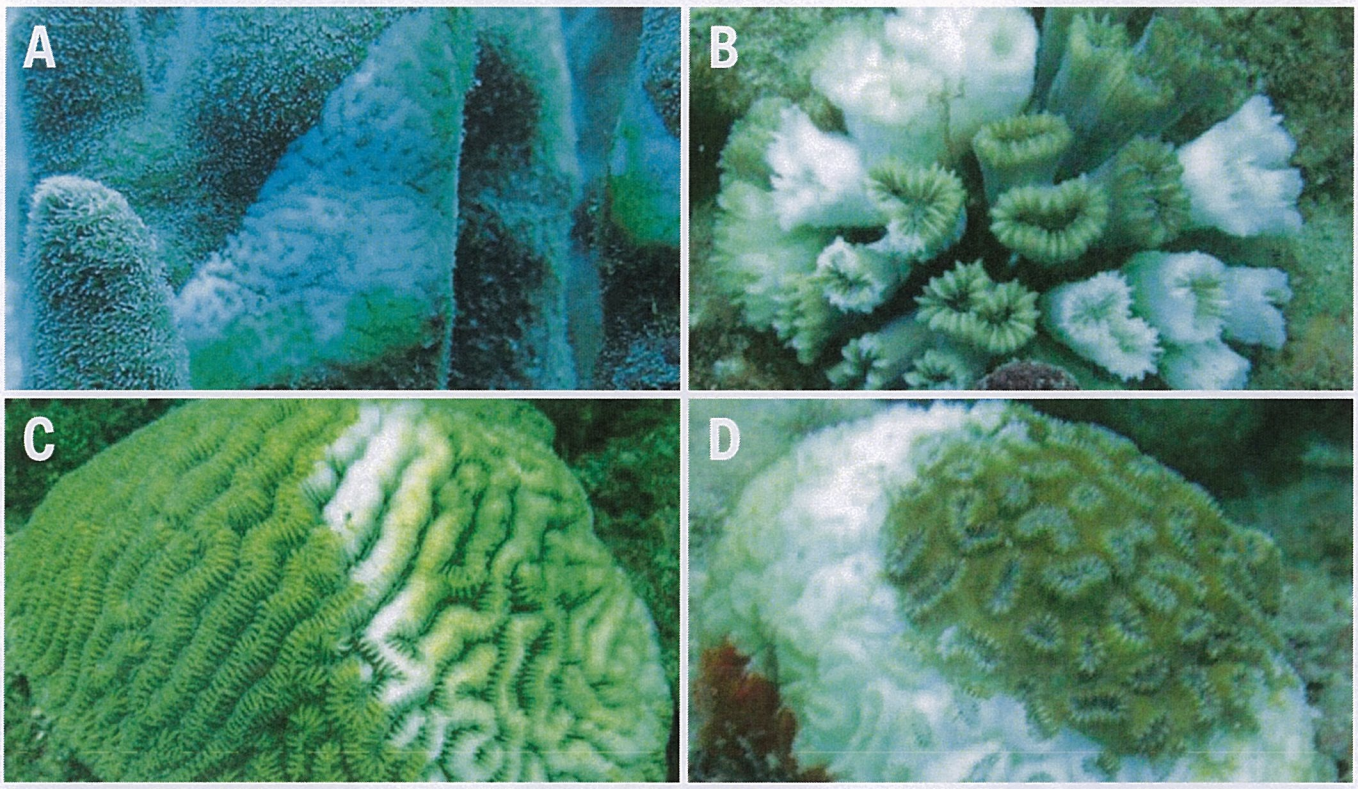


Figure 2. Outward signs of SCTLD as expressed in the corals Dendrogyra cylindrus (A), Eusmilia fastigiata (B), Meandrina meandrites (C), and Dichocoenia stokesi (D).

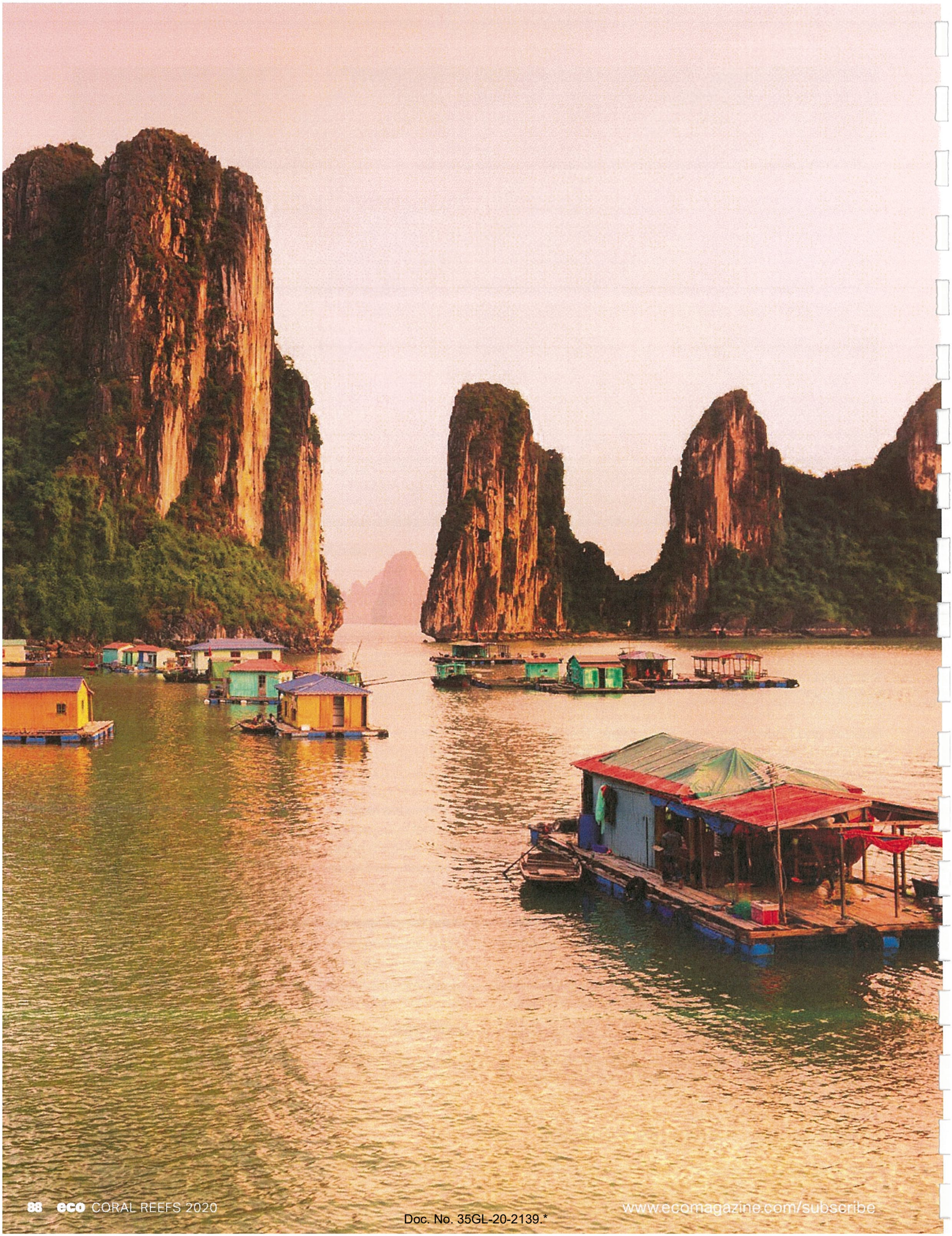
Unfortunately, the news keeps getting worse for the reefs of the region. The disease has now spread from Florida to numerous locations throughout the Caribbean. These include sites where coral cover and diversity is generally higher than that measured along the Florida Reef Tract. These include, but are not limited to, reef sites in the Bahamas, the Turks & Caicos Islands, Jamaica, Puerto Rico, The US Virgin Islands, St. Maarten, and the Mesoamerican Barrier Reef. The impacts of SCTLD on these reefs mirror those observed in Florida, both in susceptibility of affected species and overall coral mortality. The movement of ships and the release of pathogen-containing ballast water has been implicated in its recent spread to locations previously devoid of this disease. While a credible hypothesis, until we know more about the pathogens responsible and the mechanisms of infection, these claims are little more than correlative observations. However, using the precautionary principle as a guide, the US Coast Guard has recently recommended ballast water best management practices to reduce the likelihood of transporting the pathogens that may spread SCTLD (USCG 2019).

At all reef locations that have been affected by the SCTLD epizootic so far, there has been a rapid, dramatic, and catastrophic change in local coral community structure that may never fully recover on ecological time scales. On many reefs, most of the remaining massive framework building coral species have been lost, resulting in a diminution of structural complexity and reef functionality. This, in turn, has cascading negative effects on both mobile and sessile reef dwelling species. Even more dramatic, reefs that were generally considered to be low in coral cover like those north of Miami are now essentially devoid of most stony coral species and finding large living colonies of SCTLD susceptible species can be difficult at best. On these high-latitude reefs, coral cover is now often measured in fractions of a percent (<<1%).

While ocean temperatures have increased over the last few decades in the tropics and subtropics, the resulting ecosystem decline that ensued has been devastating. If this disease continues to spread unabated throughout the region, the outlook for the Caribbean reef-scape is bleak. Thus, the combination of bleaching stress and numerous coral diseases, including the recent emergence of SCTLD portends doom to a reef ecosystem already at a tipping point from multiple stressors, both natural and anthropogenic. However, these unprecedented losses, including the local extinction of some charismatic coral species, may be the wake-up call required for preserving what is left of these fragile marine ecosystems in the face of global warming and other local and regional stressors. Accordingly, the links between increased ocean temperature, bleaching, and deadly marine epizootics should not be ignored. Climate-mediated ecosystem decline should be considered a contemporary threat instead of a future one.

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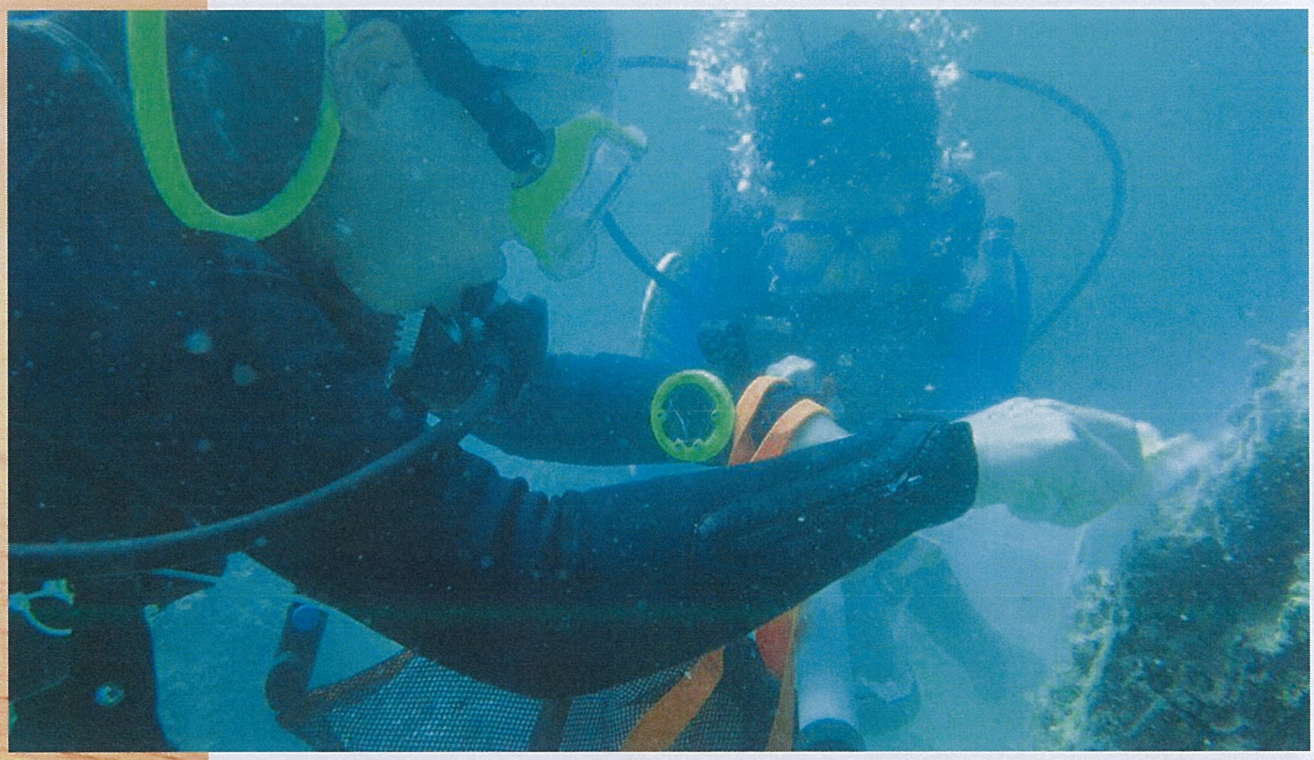


The Effects of Ocean Acidification on Coral Reefs in Southeast Asia

By Wenxi Zhu, Somkiat Khokiattiwong (IOC-WESTPAC), Katherina Schoo, Kirsten Isensee, Salvatore Arico (IOC-UNESCO)

Every year millions of travelers from around the world flock to Southeast Asia to enjoy its incredible variety of marine life, pearly white beaches, and colorful coral reefs. As a center of global marine biodiversity and endemism, the Southeast Asian region is home to one-third of the world's mapped coral reef areas which generate great environmental, social and economic benefits. According to the World Resources Institute, the total annual net benefit of only sustainable coral reef fisheries across Southeast Asia is estimated to be US$2.4 billion per year (Constanza et al., 2014)[1]. Healthy coral reefs not only support fishing industries, but also help to protect coastal populations from natural hazards. They also create important recruitment areas for marine life, helping to secure the livelihoods of millions of coastal families in Southeast Asia.

As a result of increasing human activity, however, coral reefs across Southeast Asia are subject to a broadening array of compounded threats, including overfishing, destructive fishing practices, sedimentation and pollution, and global sources such as the increased ocean temperatures and ocean acidity (Mcleod et al., 2013)[2]. As reefs weaken, they become more susceptible to disturbance or damage from



Young Thai scientist practiced collecting biological data by using Benthic and Epiphytic Toxic Algae (BETA) sampler in open water environment, Phuket, Thailand, September 2018.

Halong Bay, Vietnam. Unesco World Heritage Site

bleaching, storms, and diseases and, as a consequence, many scientists now believe that the future of coral reefs is in jeopardy unless we increase efforts to protect them (Frieler et al. 2013)[3].

One of the main threats coral reefs face is ocean acidification—the result of the ocean absorbing around 23 percent of the carbon dioxide (CO_2) emitted to the atmosphere through human activity. As this CO_2 dissolves in seawater, it changes the ocean's chemical balance and leads to an increase in seawater acidity (i.e., a decrease in pH). These changes are subtle yet sustained and have been shown to impact several biological processes, including the construction of calcium carbonate shells and skeletons of many marine organisms, among them corals. Ocean acidification makes it more difficult for marine calcifying organisms such as corals, mollusks, and calcareous plankton to form biogenic calcium carbonate (Kleypas and Yates, 2009)[4]. Thus, ongoing and increasing acidification may result in the loss of biodiversity (IPCC, 2019)[5], negatively affecting important ecosystem services that human societies depend upon for food security and livelihoods (Moberg and Folke, 1999)[6].



Training on DNA sequencing of reef organisms

Meanwhile, other processes in coastal areas such as eutrophication, ocean deoxygenation, and coral bleaching (caused by warming ocean waters) are exacerbating the effects of ocean acidification on coral reefs (Hoegh-Guldberg et al., 2017)[7].

Despite widespread recognition that coral reefs in Southeast Asia are among the most threatened habitats in the world, information about their biological components, status, threats, and response is limited in many areas. More research and long-term monitoring are critically needed at the local, national and international level to enable ongoing assessments, inform management decisions, and to develop effective long-term mitigation and adaptation strategies for the impacts of ocean acidification on marine ecosystem in the region.

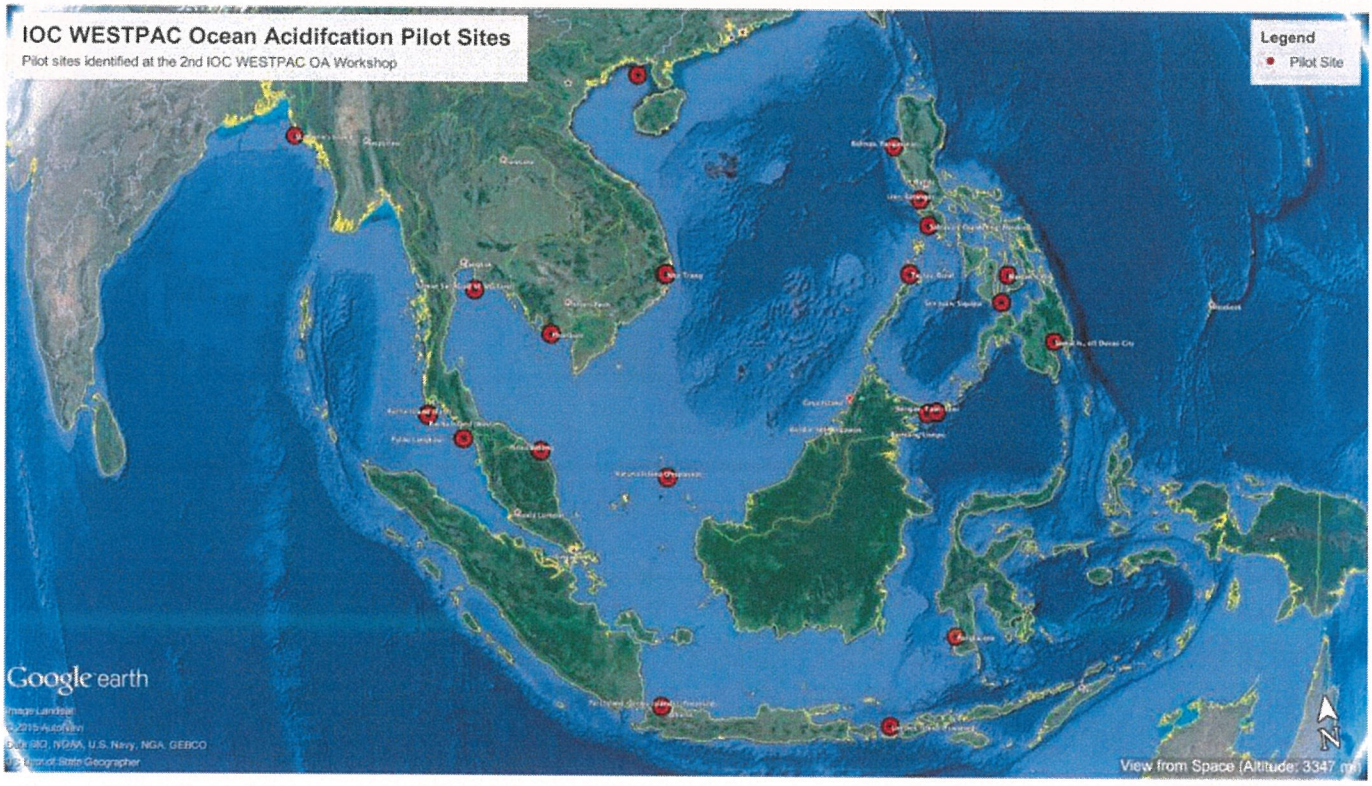
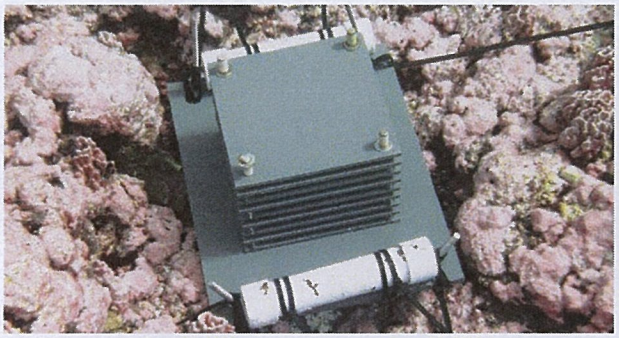


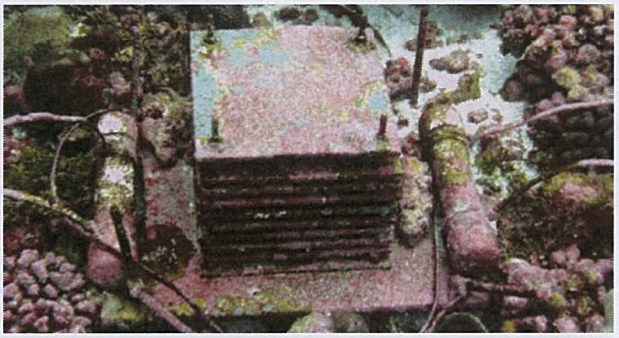
Figure 1: Map showing the pilot monitoring sites for ocean acidification in the Western Pacific Region. The details for each pilot site can be found at http://www.iocwestpac.org (Source: IOC-WESTPAC)

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Deployed ARMS





IOC Sub-Commission for the Western Pacific

To fill some of these knowledge gaps, the IOC Sub-Commission for the Western Pacific (IOC-WESTPAC) endeavors to promote marine science collaborations, develop research capacity and transfer marine technology. IOC-WESTPAC's ambition is to assist Southeast Asian countries in the conservation of coral reefs and associated ecosystems and inform the development of national and regional coral reef conservation strategies.

Through collaboration, we can achieve a better understanding of the impacts of ocean acidification on organisms and ecosystems in the SEA region, which remain poorly understood and mostly reliant on simplified laboratory experiments and model projections.

Within the 2030 Agenda for Sustainable Development the Sustainable Development Goal (SDGs) target 14.3[8] calls upon all countries to minimize and address the impact of ocean acidification and enhance scientific cooperation at all levels. In support of this target, IOC-WESTPAC has established—and continues to support—the regional research and monitoring network on ocean acidification in the Western Pacific and its adjacent regions. This was set up as part of the Global Ocean Acidification Observing Network (GOA-ON), whose goals are in line with future developments of this global effort (Tilbrook et al., 2019)[9], and with technical assistance from the United States National Oceanic and Atmospheric Administration (NOAA).

To monitor the health and composition of the reef ecosystems, Autonomous Reef Monitoring Structures (ARMS) and Calcification Accretion Units (CAU) have been developed and deployed at selected monitoring sites in the region. Additionally, with the joint development of standardized observational and analytical protocols on measuring ocean carbonate chemistry (pH and Total Alkalinity), it is expected that these interdisciplinary monitoring stations (Figure 1) will soon provide quality data and information and reveal the spatial and temporal variability of ocean acidification and its impacts on reef communities.

The use of novel "DNA Barcoding" methods in parallel with traditional taxonomic tools enhances national and regional capacities for species identification, and allows researchers to monitor and understand the taxonomic composition of coral reef ecosystems. DNA Barcoding, together with bio-acoustic methods, is also used to understand the life cycle of a variety of coral reef species, including the recruitment of larvae and fries into the coral ecosystem.

Coral reef ecosystems in Southeast Asia lie at the heart of the social, cultural, and economic development of the region, and they are severely threatened. Marine scientific communities will need to partner with decision-makers and resource managers, private sectors, NGOs and the public, as well as increase efforts to generate the knowledge and understanding needed to achieve the sustainable management of coastal resources. We consider the coming UN Decade of Ocean Science for Sustainable Development (2021-2030) the best opportunity to accelerate research for the ocean we need.

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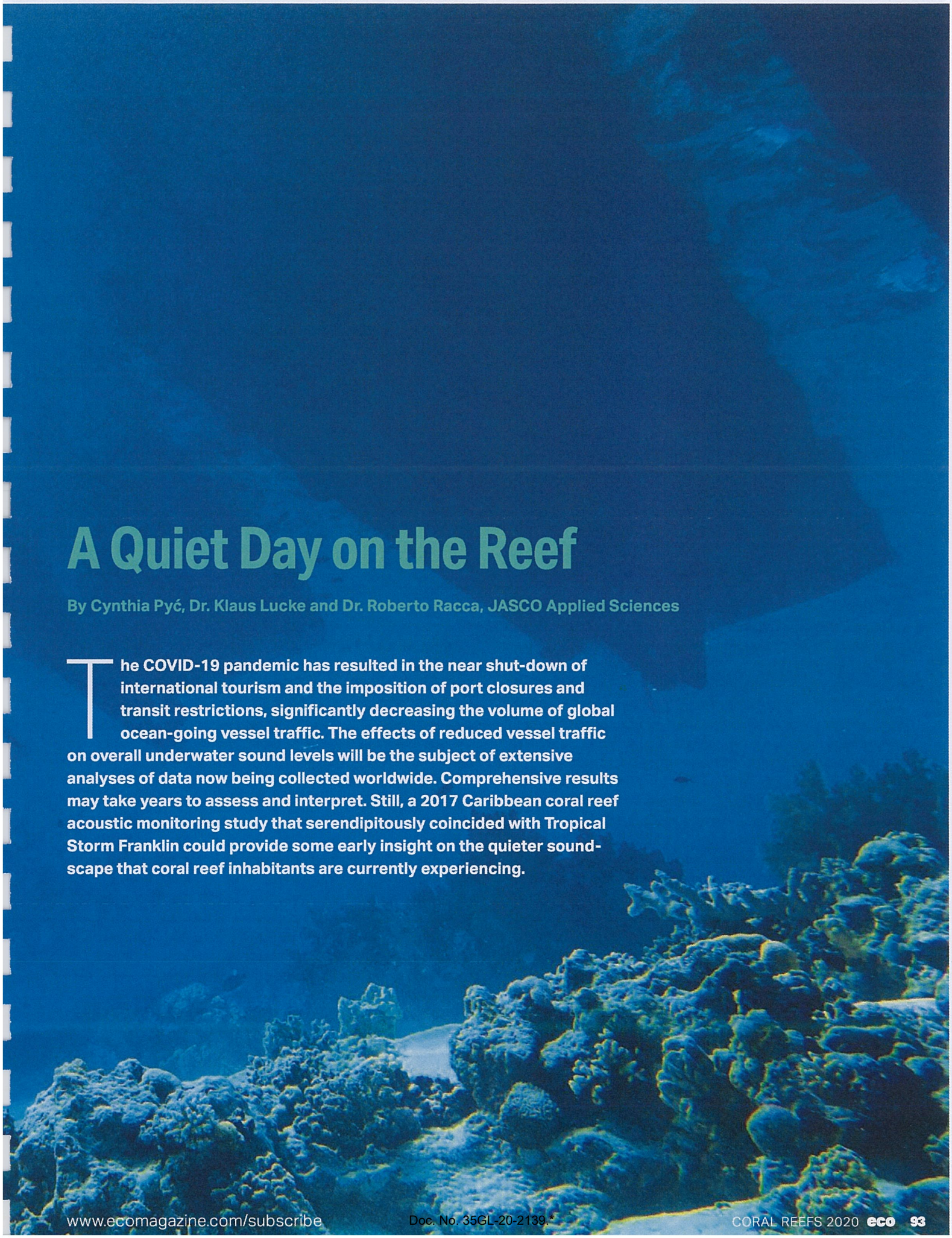
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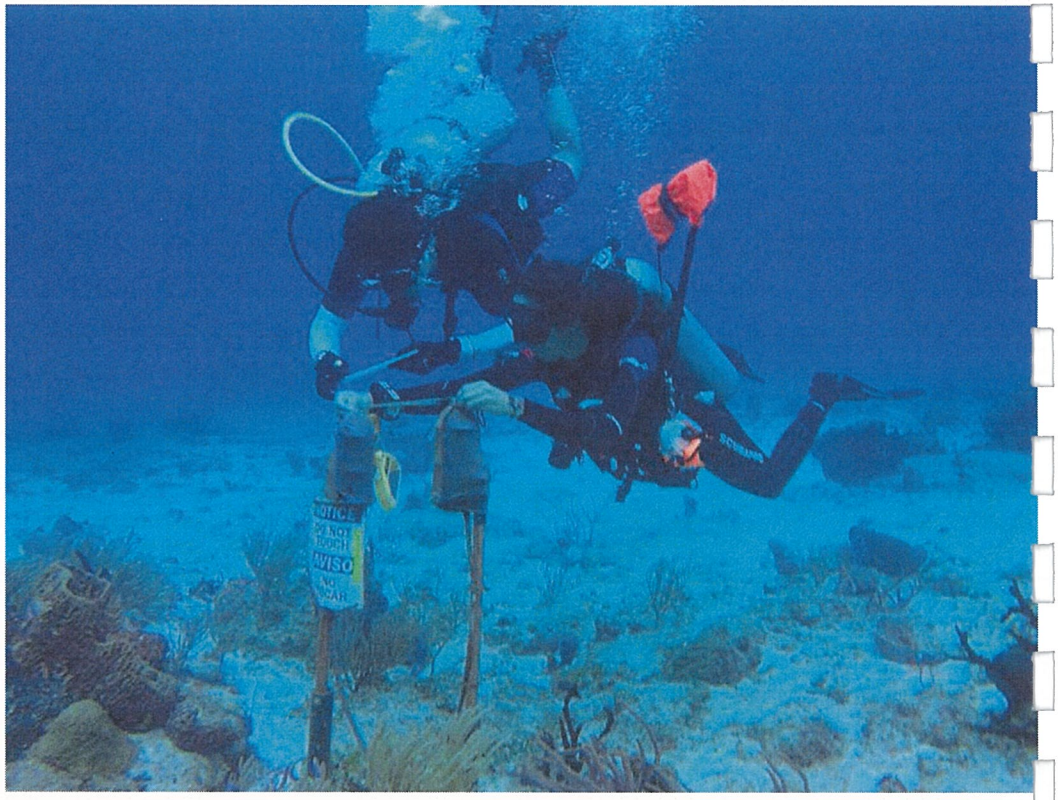
A Quiet Day on the Reef

By Cynthia Pyć, Dr. Klaus Lucke and Dr. Roberto Racca, JASCO Applied Sciences

The COVID-19 pandemic has resulted in the near shut-down of international tourism and the imposition of port closures and transit restrictions, significantly decreasing the volume of global ocean-going vessel traffic. The effects of reduced vessel traffic on overall underwater sound levels will be the subject of extensive analyses of data now being collected worldwide. Comprehensive results may take years to assess and interpret. Still, a 2017 Caribbean coral reef acoustic monitoring study that serendipitously coincided with Tropical Storm Franklin could provide some early insight on the quieter soundscape that coral reef inhabitants are currently experiencing.



In July 2017, a team of Canadian, Mexican, and American marine scientists prepared for immersion at a popular dive site in Parque Nacional Arrecifes de Cozumel, Mexico. Located not far from a port, the Cozumel reef system is part of the Mesoamerican Barrier Reef System, the second largest coral reef system in the world. The scientists' mission was to deploy a JASCO Autonomous Multichannel Acoustic Recorder (AMAR) for three months to obtain the first scientific recording of the endangered splendid toadfish *(Sanopus splendidus)*. The study also aimed to record the volume and determine the sources of human-made sound on the reef, assessing the potential effects of noise on toadfish and other fauna. Local stakeholders were concerned that vessel sounds transiting to and from the port, especially from cruise ships, could be negatively impacting coral reef dwellers.



Scientists positioning hydrophones on the sea floor near a toadfish den on the coral reef. Photo: Robert Mills, JASCO.

To date, all fish studied have the ability to hear sounds. Many are known to actively produce sounds to communicate, mainly for reproduction or in aggressive contexts. Invertebrates can also create sound by striking or rubbing together skeletal components, a process called stridulation. Larvae of reef-associated fish species use sound to find coral reefs for settlement after some time in the open ocean. In this rich, context filled natural soundscape, the introduction of human-made noise makes it harder for marine life to perceive relevant sounds, an effect called 'acoustic masking'. Acoustic masking reduces the effective range over which fish and other marine organisms can communicate with one another, navigate to important habitats, find mates, or detect an approaching predator.

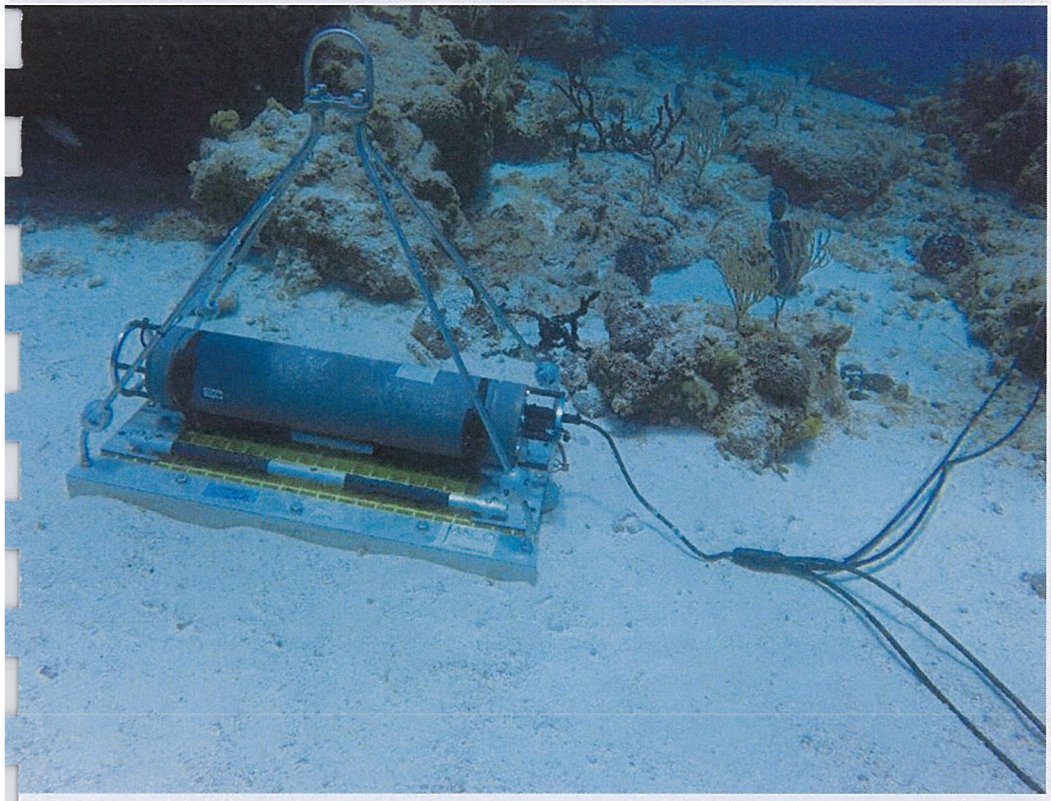
The Cozumel study indeed showed that cruise ships and, even more so, dive boats contribute substantially to underwater noise at reefs. On a typical day in this busy tourist destination, reef fish experienced sound pressure levels (SPL) ranging from 114 to 129 decibels relative to one micropascal (dB re 1 µPa) with an average SPL of 122 dB re 1 µPa (the decibel represents the ratio between two quantities on a logarithmic scale). This is 10 dB higher than the sound level of the night-time soundscape with no human-made noise. Drawing meaningful parallels between sound levels in water and in air is an arduous task and prone to misinterpretation, even more so between the corresponding effect on aquatic species relative to humans. However, if we compare fish communicating in the night-time soundscape with two humans having a conversation near a washing machine on a normal cycle, then the additional 10 dB of human-made noise would be like having the washing machine enter the spin cycle as they talk.

The study's goal was to compare against the night-time baseline and the daily sound levels for two periodic regimes of vessel activity in the area where the AMAR was deployed. It envisaged "normal" activity days, with the traffic of both dive boats and cruise ships, and "moderate" activity days (usually Sundays) when no cruise ships visit Cozumel, but dive boats operate regularly. An unforeseen event occurred during the recording period that provided an intriguing accidental addition to the experiment—Tropical Storm Franklin passed by Cozumel island on August 8, 2017. Although the weather event was not significant enough at that point to affect the natural underwater noise levels, its impact on human activity was captured in the acoustic data as a notable change in the soundscape. As a precaution before the storm's arrival, the Carnival Breeze cruise ship was diverted to a different port of call that day, reducing the cruise ship arrivals at Puerto Maya to one, and Cozumel ports were closed to all small vessels. This provided a unique glimpse of what reducing human activities can mean for the subsea acoustic environment.

As a chart of daily average SPL shows (see figure 1), the day of no vessel traffic exhibits a prominent notch to a minimum unparalleled by any other day of the study period, from mid-July to the end of August. Compared to the profile for August 8, the hourly average sound level profiles of the daylight period for two days—exemplifying the previously described "normal" and "moderate" activity regimes respectively—evidence how the nearly complete lack of vessels, in particular dive boats, lowered dramatically the underwater noise throughout the day.

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The AMAR recorder deployed on the bottom, with cables fanning out to multiple hydrophones. Photo: Robert Mills, JASCO.

If underwater acoustic energy is regarded as a pollutant—indeed a definition ensconced in the Marine Strategy Framework Directive of the European Union—it holds an almost unique trait compared to other contaminants. The presence and direct effect of this noise pollution can be altered almost instantaneously by changing the activity producing the noise, with no appreciable lag on a biological scale due to accretion, dilution, diffusion, or transport medium. Thus, the single day of August 8, 2017 was a sharply bounded "noise holiday" for the creatures of the Cozumel reef. There was no gradual decrease to introduce it or gentle ramping to the loud normality of the next day. Such infrequent gifts of silence happen on a regional scale during unusual natural events. Even more rarely, this can also happen globally when dramatic social impacts, such as the September 11, 2001 terror attacks, throw much of humankind into a short-lasting travel freeze. And then there are the once in a lifetime events that have the potential to induce changes beyond their own direct effect, such as the current COVID-19 pandemic.

The pandemic has induced in the global blue economy a slowing down which began in February 2020 and is ongoing as of this writing, resulting in a period of maritime calming of unprecedented scale. Scientists are rushing to deploy recording equipment and conduct studies to better understand the effect the pandemic-related reduction in vessel traffic has on sound levels in our ocean. Meanwhile, the International Quiet Ocean Experiment—a research initiative started years before the pandemic on the idealized premise of a voluntary halting of marine activity to test its effects on ocean noise—is collating any recordings that may inform society about the outcome of this unforeseeable realization of that hypothesis. As the world adapts to a new normal, it will hopefully accommodate tangential lessons learned from the pandemic. This much larger accidental experiment, for all its devastating context in human, societal and economic terms, has the potential to reveal the impact we have on coral reef fauna and provide insights on how we might improve the environment in which these important species and critical habitats exist.

Reference:

The results will appear in an article co-authored among others by principal investigators Cynthia Pyć of JASCO Applied Sciences, Dr Jonathan Vallarta of PAMOS, and Dr Aaron Rice of the Center for Conservation Bioacoustics at Cornell University

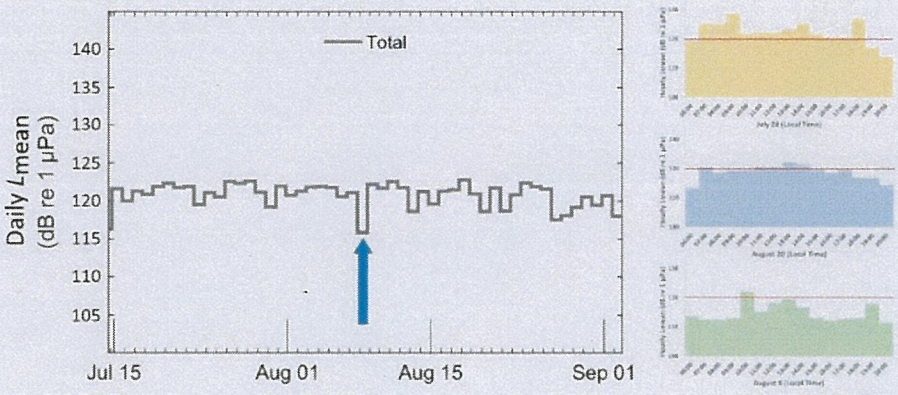


Figure 1: Left pane: daily average SPL for the study period, with the arrow denoting the day of virtually no vessel activity due to the passage of Tropical Storm Franklin. Right pane: hourly SPL profiles for daylight period on a "normal" (top) and "moderate" (centre) vessel activity day and on the day of no activity (bottom).

Corals and Coral Reef Futures

In this webinar hosted by Insider Divers, Dr Peter Houk, associate profession at the University of Guam Marine Laboratory explains the connections between corals and reef fish in our ocean before diving into the challenges of domestic and commercial fishing. He shares many interesting statistics and research findings and explains conservation efforts across the Pacific.

You can see more upcoming webinars by Insider Divers here: https://www.insiderdivers.com/academy

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COVID-19, Friend or Foe to Coral Reef Conservation?

The COVID-19 pandemic has affected all of us. In Malaysia, the government has enforced the Movement Control Order (MCO) as a mechanism to limit the spread of the disease. As a consequence, human activities are restricted, and reports of the environmental conditions have improved.

On 13 May 2020, Dr. James Tan from Universiti Malaysia Terengganu and Alvin Chelliah from Reef Check Malaysia featured in the "Ocean Hope Webinar 2020" organized by the Universiti Malaysia Terengganu Marina Club (Marine Biology Programme) in collaboration with Sustainable Ocean Alliance. Here, they discuss the potential impacts of COVID-19 (and the MCO) on coral reefs conservation and management-related issues.



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We have already lost 27% of the world's coral reefs. If present rates of destruction are allowed to continue, 60% of the world's coral reefs will be destroyed over the next 30 years

Source: WWF

Chapter 4: Protection

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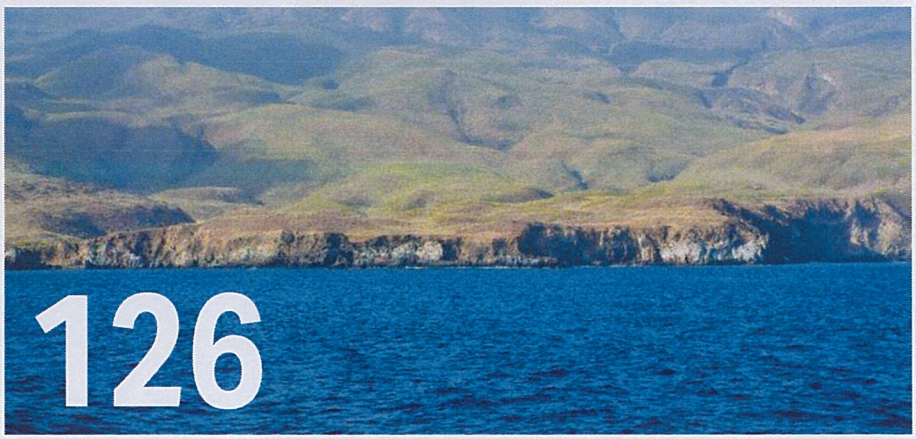

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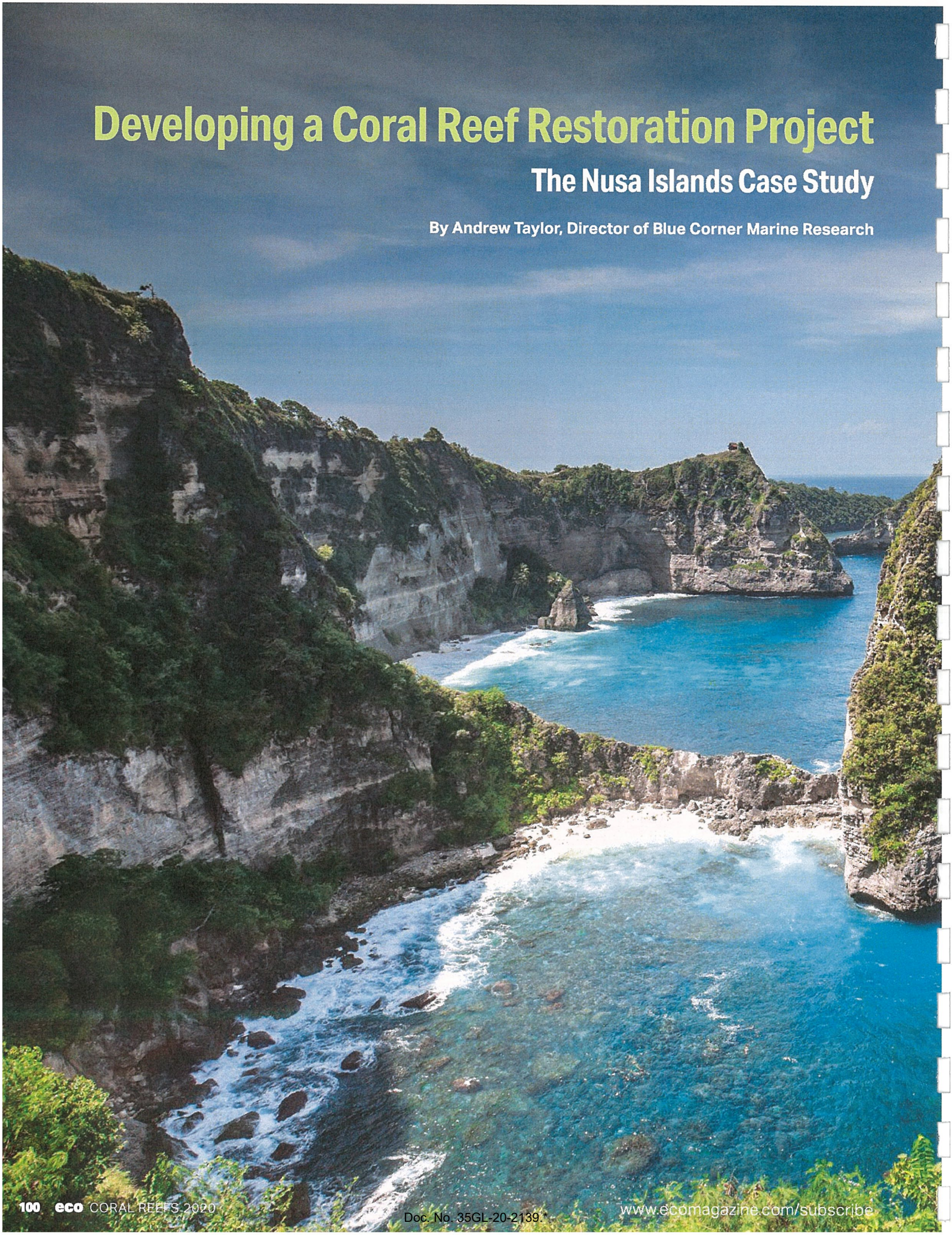

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Developing a Coral Reef Restoration Project

The Nusa Islands Case Study

By Andrew Taylor, Director of Blue Corner Marine Research



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On the Nusa Penida Island, Bali, coral reefs provide a vital source of income for the local community who rely on the tourism and fishery industries. Over the years, the coral reefs in this region have been subjected to several stressors which has seen areas transform from biodiverse coral ecosystems to unstable rubble sites.

Initial causes of coral rubble were due to:

- Anchors dragged from fishing boats, dive & snorkel boats, and tourism pontoons
- Clearing of coral from the reef flat for seaweed farming and building material, which removed the natural structure of the reef and changed onshore energy
- Clearing and shading areas of coral reef for tourism pontoons and sea-walking
- Historical dragging of fish traps and nets across reef flat

Similar to many areas of South East Asia, when functioning coral reefs turn to rubble it is rare for those sites to naturally recover. This was seen on Nusa Penida where there have been no signs of recovery in the last decade of observation. Conversely, rubble zones were actually growing in size due to erosion caused by currents and the smothering of adjacent and down-slope reef areas.

The community-led Lembongan Marine Association identified a need for reef restoration along the northern coastline of Nusa Penida Island. In partnership with Blue Corner Marine Research, a biologist-led restoration plan was implemented. Supported financially by tourism, the Nusa Islands Restoration Project seeks to reverse the degradation of reef in this area with the primary goal to increase ecosystem function and habitat complexity.

Assessing the Need for Restoration

Before beginning any restoration project, it is imperative to significantly reduce—or stop altogether—the activities that trigger degradation. Failure to curb their impact will render restoration efforts futile, and any incremental gains in ecosystem health will quickly be eliminated by cumulative impacts.

Management at the Nusa Penida marine park has since implemented a zoning system that limits certain activities to specific areas. The restoration site in question has been designated a protected site to ensure that impacts from boat anchoring and fishing are kept to a minimum.

Over the past decade, the region has seen a drastic increase in tourism. The promise of comparatively high wages and living standards from tourism-based jobs is curbing traditional extractive activities, such as fishing and seaweed farming. However, educational programs are needed to reduce existing threats to the ecosystem, which target the tourism industry and help manage potential impacts from tourist activities taking place near or at coral reef sites. An example, already implemented in the region, is the development of an educational program for local watersports operators on how to provide tourists with meaningful environmental briefings. The launch of several waste management initiatives on the island, including a recently established recycling center, should help reduce waste and pollution from entering the ocean.

For well managed reef sites, natural and unassisted recovery may be possible if there is suitable stable substrate remaining and sufficient input of new, young corals in the area. If natural recruitment is already high, then a restoration program may not be necessary. For a site comprising of mostly unstable rubble, such as that on Nusa Penida, natural recruitment is unlikely as any young corals which attempt to settle will be smothered by rubble and die off.



Fortunately for Nusa Penida's northern coastline, many of the initial impacts and activities degrading the reef have been reduced and, since there is little evidence of natural recovery, launching a coral restoration project is a viable option.

The Nusa Islands Restoration Project: A Two-Step Approach

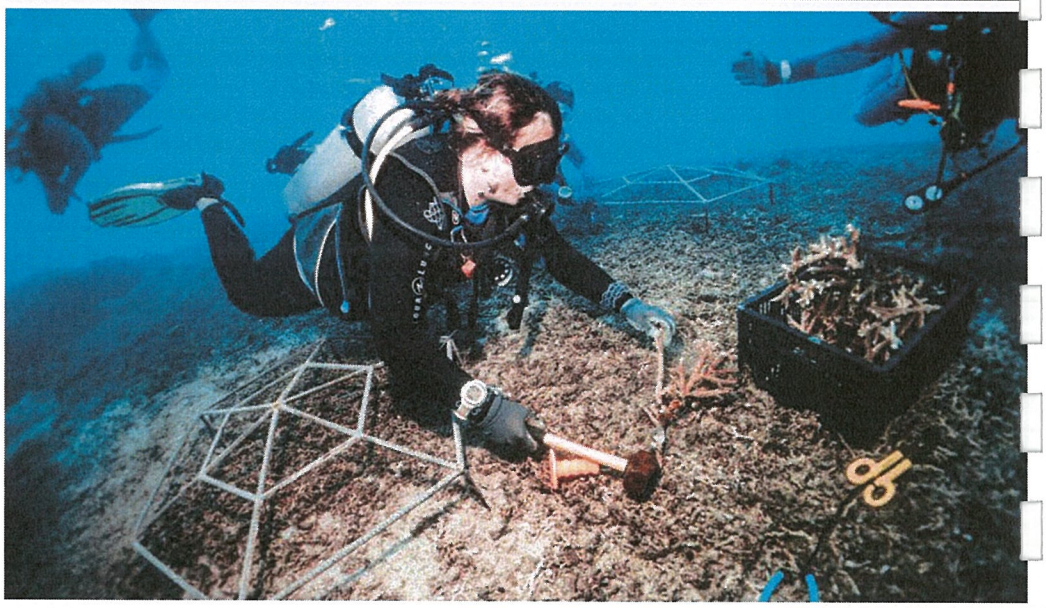
The first step in developing the restoration plan was to map the impacted area. Once mapped, we began by initiating a pilot project within a part of the reef deemed a high priority for restoration. The pilot project provided the opportunity to establish techniques before expanding to three adjacent areas. In 2020, the restoration site now covers an area of approximately 4,000 square meters.

The next stage was to define a target state of coral reef community, which acts as the restoration 'endpoint.' The creation of a site blueprint, which includes a description of the environment (species, structure and features) provides a clear restoration goal and helps support the planning of activities. The description is made by looking at historical reef health monitoring data and photos of the area, and analyzing the contents of the rubble, noting dead coral skeleton species. For reference, adjacent healthy areas of reef along the same shoreline and depth are compared by surveying reef substrates, as well as abundance and diversity of marine species present.

The goal of the Nusa Penida Restoration project is to transform the site from its current state—almost completely denuded of living coral and structure—into a healthy state of high coral cover and diversity. The plan relies on a two-step approach:

1. Recreate the physical structure of the reef to provide habitat and stabilize the rubble from erosion
2. Re-establish the primary habitat-forming organisms in an attempt to attract key marine species and re-instate the fundamental roles of the ecosystem





Structural Restoration

As the Nusa Penida restoration site consisted of unconsolidated rubble substrate, prone to erosion in ocean currents, structural restoration was needed prior to the restocking of biological communities. Structural restoration involves a variety of measures, including installing coated metal frames and mesh rubble fencing which offers marine life a stable substrate and habitat. The frames provide topographical structure to the reef and are used as building blocks for habitat formation. They also provide a stable substrate for coral transplantation.

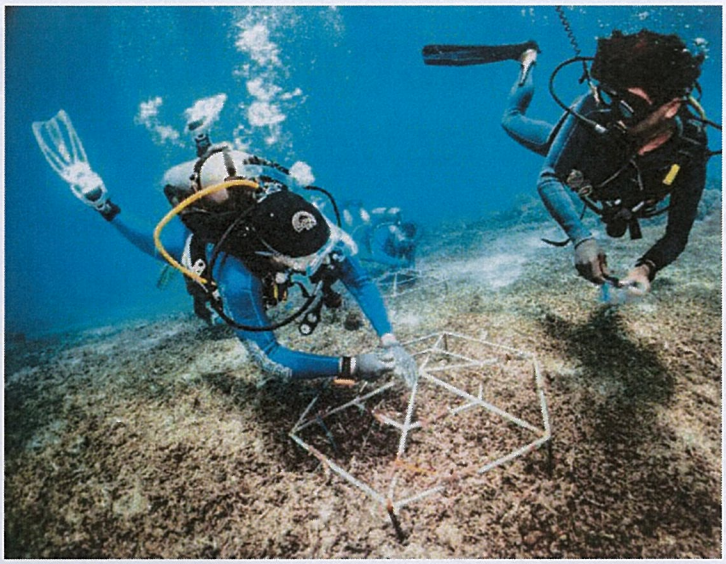
Structures were deployed onto the restoration site in a formation along the natural reef crest and clustered in other high erosion areas within the reef flat and slope. The purpose of this formation was to trap rubble, preventing it from shifting down the reef slope and eroding into healthy reef areas. Biological rationale to the design was to provide patch-reefs in which reef organisms such as fish and invertebrates could easily colonize by immigrating from adjacent reef areas.

In addition to the frames, wire mesh was rolled out across areas of rubble in an attempt to stabilize rubble movement. The mesh is able to hold the rubble for a long enough period of time for sponges and soft corals to settle and begin to naturally stabilize the area.

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Photos: Transplanting coral and assembling frames for restoration at the coral nursery. Credit: Blue Corner Marine Research.

Biological Restoration

With the structural elements in place, recovery of the reef's biological aspects could be stimulated by transplanting corals to increase the habitat for fish and invertebrates. The coral species most suitable for transplantation were defined by the restoration plan's target species composition based on surveys of adjacent healthy reefs. A list of target species was compiled in appropriate proportions according to water depth and reef zone. By conducting studies in naturally recovering areas, we were able to identify the initial habitat-forming foundation species to be used at the project site.

After structural restoration started, coral fragments were transplanted into the area. To avoid the introduction of new genetic stock or species, transplants were sourced from reefs within the same geographic region and environmental conditions. In an attempt to kick-start recovery, several species were transplanted to reflect the species composition of the target state, including three species of Acropora corals. Acropora are habitat-forming species known to grow quickly, aid in substrate stabilization, and provide refuge for natural settlement of coral larvae. Additional species included slow-growing Galaxea and Porites corals, foliose-shaped Echinophylia coral, and branching Montipora coral.

A coral nursery was established to reduce pressure on donor colonies from healthy reef areas. The nursery allows coral fragments to grow under optimal conditions with good water movement and away from benthic predators. Coral fragments are taken to the nursery and grown for several months until they are large enough to be transplanted onto the restoration frames.

Engagement with Tourism

The development of a tourism experience program helps to support the restoration project with financial and staffing assistance. Tourists are able to take part in the ongoing coral restoration project, alongside the professional biologists, by signing up for programs ranging from single day coral transplantation experiences to multiple week internship programs. The programs focus on delivering scientific knowledge to the public as well as providing hands-on experience for early career marine scientists and students.

Coral Restoration with Coral Guardian

Coral Guardian is on a mission to preserve coral reefs globally

By Ruxandra Toderasc and Coco Tamlyn, Coral Guardian



Local team working on coral transplantation.

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Reef-building corals are present in the intertropical zone, covering roughly 0.2 percent of the surface of the ocean, and home to over 25 percent of all marine species on the planet. Coral reefs provide a multitude of goods and services. They offer economic benefits, mostly through income from fishing, tourism, and aquarists, act as an essential resource for food, provide coastal protection, and contribute to public health. The global annual net profit of coral reefs is estimated to be $29.8 billion.



Entire reef systems are being impacted by overfishing, rising temperatures, and ocean acidification, among other factors, contributing to the destruction and bleaching of corals as well as reducing the benefits they bring to coastal populations. Various scientific reports on coral reefs are alarming: 40 percent of coral reefs have already disappeared, and extinction of 70 to 90 percent is expected by 2040. This would drastically affect the diversity of coral species, resulting in severe consequences. Entire ecosystems would be disturbed, and many people would be forced to radically change their way of life.

Based on this observation, a team of scientists and enthusiasts founded the NGO Coral Guardian.

Coral Guardian's story began in 2012 within the coral triangle in Indonesia, where marine ecosystems have been destroyed by destructive fishing techniques, including the use of dynamite or potassium cyanide. The main goal is to rebuild the seabed to revitalize ecosystems that are dependent on coral reefs, and thus benefit the populations that depend on them.

Coral Guardian restores damaged coral reefs through a technique called coral fragmentation, regular scientific monitoring, and the protection of restored areas.

Reef rehabilitation is not an end, but a means. Coral restoration provides local communities with a better understanding of the marine ecosystems on which they depend. By being aware of the importance of reefs, they become primary actors in their protection.

Through its awareness programs, Coral Guardian carries a message full of hope in its international outreach projects. By working with local communities, the NGO promotes the sustainable management of fishing stocks through the protection of their local marine ecosystem.

On an international level, they also raise awareness of the importance of coral reefs. In particular through its participatory conservation program called 'Adopt a coral.' After adopting one or more corals on Coral Guardian's website, the organization then transplants the adopted coral onto a previously damaged reef. In exchange, the donor receives a personalized adoption certificate for each coral.

By participating in scientific discoveries, Coral Guardian is involved in research related to the coral restoration and the dangers they face, such as global warming. The NGO's biological and social data could help develop research related to coral reef issues.



Local Coral Guardian team at the coral sanctuary on Hatamin Island.

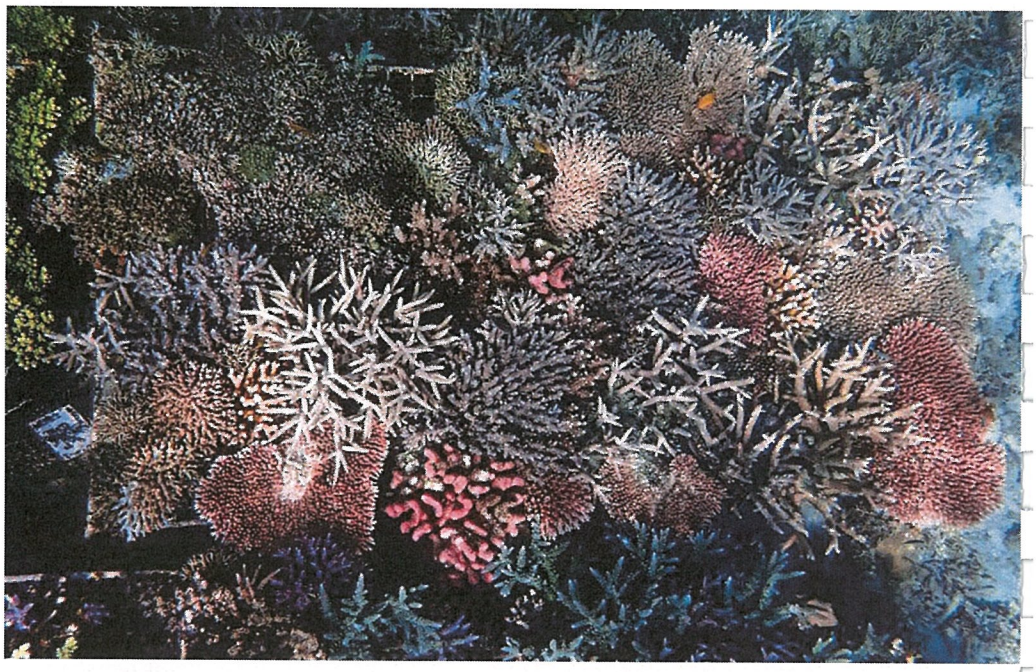
The Hatamin Island Case Study

Coral Guardian works on Hatamin Island in Nusa Tenggara Oriental. In 2015, the Coral Guardian team gained an in-depth understanding of the difficulties faced by coastal populations. By talking with the residents of a fishing village located in the region, the team learned that fishers had to travel at ever-increasing distances to meet their families' food and economic needs.

Based on this local community, Coral Guardian created a participatory marine conservation model. A pilot project was launched in the region on an island neighboring the village of Seraya Besar, Hatamin Island. The community now manages the project itself, further ensuring its sustainability and having a positive, long-lasting impact on the region.

Developing a stable team from within the community took several years. Today, a committed team of eight people, all aware of the importance of coral reefs, are working full time for the project. The local team is made up of former fishers, each of whom wants to protect the ecosystems on which they depend.

Each month is organized around a work routine that includes coral restoration, raising awareness, scientific monitoring, and the protection of Hatamin Island.



Coral Restoration

Restoration of damaged reefs is implemented by *coral fragmentation*. This technique involves fixing coral fragments onto a solid metal grid or structure. The coral then grows, bringing biodiversity back to the reef. Today, the oldest structures are composed of very healthy corals, currently reaching around 40 centimeters high. As a result, the team now uses these structures as nurseries to collect new fragments, instead of gathering them from the seabed as they did initially.

Restoration techniques are continually improving as the team tests them out, selecting the most suitable method for each case.

Each manipulation is a possible source of stress for the coral, which can then, in turn, cause it to bleach. Therefore, it is necessary to work in the best possible weather conditions and to interact very carefully with the fragments. However, this accumulation of stress also allows the coral to develop adaptive faculties, thus better reacting to changes in ocean temperatures.



Evolution of the restored area on Hatamin Island. In 2015, the reef destroyed by dynamite fishing. In 2019, healthy 4 year old restored reef.

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A healthy reef, transplanted 3 years ago.

Local team in the midst of scientific monitoring.

A protected and restored reef acts as a catalyst for marine biodiversity.

Social and Environmental Monitoring

To assist in the management of local marine resources, the team undertakes social monitoring. By questioning their fishing habits, the local population is made aware of the importance of marine biodiversity in terms of food and economics.

For one whole week in every month, the same ten fishermen from Seraya Besar are interviewed about their fishing practices. As it turns out, by protecting and restoring a specific area, we are witnessing a return of biodiversity, allowing fishermen to better provide for their families by fishing closer to their village.

The team regularly monitors the development of the transplanted reefs to ensure their success. The rate of growth, mortality, bleaching, and return of biodiversity is recorded on a selected sample on each structure. These indications of a restored reef's health are measured against meteorological conditions to fully understand certain biological phenomena.

This social and environmental monitoring will help Coral Guardian to demonstrate to local and international communities the effectiveness of the coral conservation program implemented on Hatamin island.

Protection and Raising Awareness

The Coral Guardian team has a permanent presence on Hatamin Island, providing unremitting protection and preventing illegal fishing in the conservation area. It is surrounded by buoys making it clear for boats coming to the island. Dealing with government authorities, in a country where the environmental cause is not a priority, requires great patience and full stakeholder involvement. However, thanks to competent government authorities, the project has been granted legitimacy by being designated a marine protected area (MPA). Raising awareness draws locals and tourists' attention to the best practices to adopt with regards to the marine world. Everyone who comes to the island is made aware of the participatory marine conservation project set up by Coral Guardian, as well as best practice for exploring the area. We also discuss the importance of coral reefs for marine biodiversity, as well as for people who depend on it.

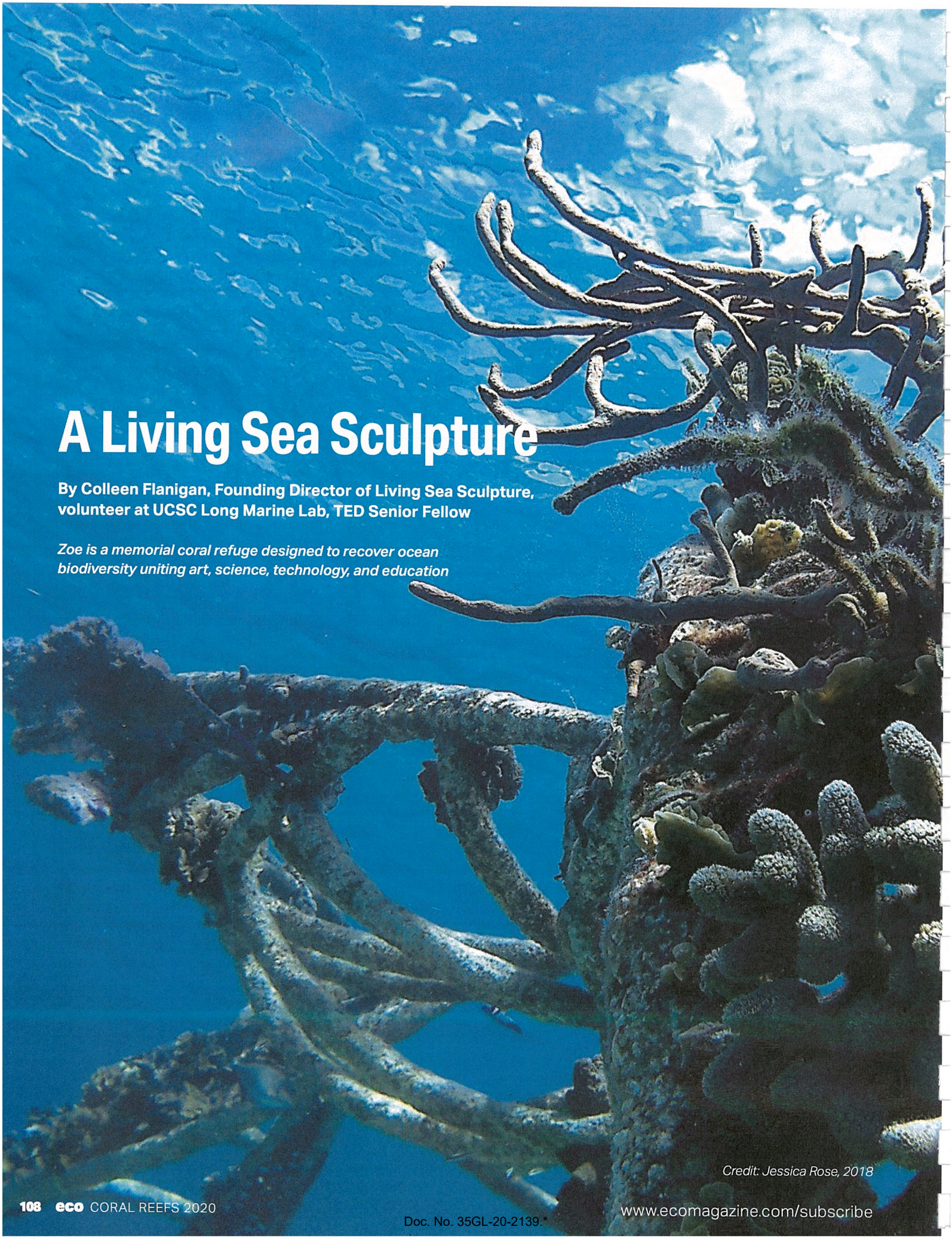
It is not too late to act. By protecting these ecosystems, 275 million people will continue to live with and from the benefits provided by coral reefs. Therefore, we urgently need to raise awareness of their importance and the concrete actions and solutions available for their protection. To effectively address the current ecological crisis in terms of social and environmental impact, Coral Guardian felt the urgent need to transmit the knowledge and experience it has gained over the years. This led to the creation of Blue Center. As the first training program of its kind, it targets project leaders interested in developing their own participatory marine conservation program, with the support of Coral Guardian.

The resilience of our future world depends on indigenous populations understanding the importance of their own marine ecosystems, based on scientific knowledge.

A Living Sea Sculpture

By Colleen Flanigan, Founding Director of Living Sea Sculpture, volunteer at UCSC Long Marine Lab, TED Senior Fellow

Zoe is a memorial coral refuge designed to recover ocean biodiversity uniting art, science, technology, and education



Credit: Jessica Rose, 2018

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Penn Schrader working on Zoe. Credit: Colleen Flanigan, 2019

For the past three and half years, *Zoe - A Living Sea Sculpture* has been anchored to the seafloor in Cozumel, Mexico. The DNA-inspired steel form is accreting limestone minerals through electrolysis to provide a fortifying marine substrate for corals to cement to and colonize. Corals build large natural reefs over thousands of years by secreting calcium carbonate, and with the urgency of the crisis facing coral reefs, this novel restoration method aims to give them a life-supporting pH boost and structural habitat, helping them adapt to environmental stressors such as climate change, ocean acidification, pollution, unsustainable fishing and development.

Zoe is a memorial coral refuge designed to recover ocean biodiversity uniting art, science, technology, and education. It is named in loving memory of Zoe Anderson, a young woman who wanted to help save corals and revive oceans but tragically died from a carbon monoxide leak. It's a sad irony that carbon monoxide's sister molecule, carbon dioxide, is threatening our entire planet. The project is disseminated worldwide through a virtual aquarium - the Zoecam – live streaming 12 hours a day. The daily recordings are accessible at the Living Sea Sculpture YouTube channel, where the database is growing and serves as a resource for scientific and cultural investigation and expression.

Located 60 meters from shore and four meters deep in front of Sand Dollar Sports Dive Shop, thousands of cruise tourists visit *Zoe* annually to snorkel, dive, and SNUBA. More and more, divers want to participate in coral restoration activities with our small team and volunteers. Various native coral species of Porites, Agaricia, Eusmilia, Gorgonians, and others have been transplanted - fragments of hope and a few test microfragments have been attached. In 2020, Penn Schrader and Lefke Kerr, while working on maintenance and monitoring of the project, observed larvae recruits of Agaricia and Eusmilia species. Just before the COVID-19 closures, we were discussing steps for further evaluation in preparation for more planting experiments in collaboration with local institutions. The restoration project is part of the larger local movement to transform the area devastated by hurricanes, pollution, diseases, and destructive human activities into a zone of ecological recovery and hands-on learning for the many divers and ocean lovers who want to participate. *Zoe* offers both an attraction and a practice, a catalyst for solutions and healthier relationships with the coastal ecosystem that everyone depends upon for sustenance and beauty. Living Sea Sculpture's small dedicated team, generous donors, and inspired volunteers have made this transdisciplinary project successful.

During the pandemic closures, though we miss diving and working on the project, we have the opportunity to watch and listen to the Livestream daily at the Living Sea Sculpture YouTube channel. This virtual aquarium provides an international portal into the sea during this pause, which is a valuable opportunity for discovery and research. While no cruise ships or motorboats are funneling into the zone, we are excited to observe the shifts in water quality and wildlife activity. Everyone of all ages is invited to join in our free "#iSpy With My Fishy Eye Virtual Scavenger Hunts" and participate in this coral restoration effort by capturing moments of ocean life action, identifying species, and sharing their curiosity and expertise. The details are here: https://livingseasculptures.com/%23ispy-contest-1

Low voltage electricity precipitates minerals to fortify the sculpture to become an evolving, life-supporting habitat for homeless corals and biodiversity in a region devastated by hurricanes, pollution, tourism, and climate change. As a memorial and coral refuge, this project uses the power of art, science, and technology to highlight life's fragility and its promise. Nothing happens in a vacuum. If the ocean teaches us anything, it's that everything is connected, and we belong to the same planet. It's our job to create the conditions for life to flourish.

In Honor of Zoe



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Why Are Our Reefs Collapsing?

Investigating coral reef degradation at the Perhentian Islands, Malaysia

By Melissa Versteeg, Dive & Volunteer Coordinator, Perhentian Marine Research Station

During a leisurely snorkel along a formerly healthy coral patch on a site called 'Seabell,' project manager Hidayah Halid noticed part of the reef now displayed clear signs of stress and coral degradation. Degradation is a term often used in conjunction with the Perhentian Islands when describing coral reef health. Seabell's recent deterioration reiterates the importance of a question central to the research and conservation activities of the Perhentian Marine Research Station (PMRS): *What causes reef collapse around the Perhentian Islands? And how do we manage these causes within a community completely reliant on the coral reefs?*

Formerly recognized as an important layover point for traders traversing between Bangkok and Malaysia, the Perhentian Islands are located in the South China Sea, East of peninsular state Terengganu. The Perhentian archipelago consists of a handful of islands within the Sunda Shelf Region. The two most well-known are Pulau Perhentian Kecil and Perhentian Besar. Their names underline a historical role in former trading industries as these names literally translate to 'little' and 'big stopping point'. Until the mid-'80s, the islands' waters had been increasingly exposed to unsustainable fishing practices: overfishing and the use of trawling nets.



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These uncontrolled practices led to the depletion of fish stocks with detrimental consequences for the Perhentian coral reefs.

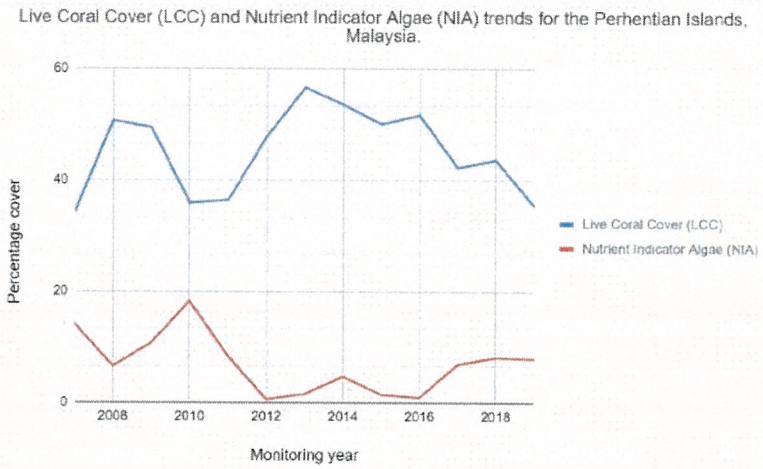
In 1994, in recognition of the reefs' fundamental role in food security, fish stock replenishment, and tourism potential, the islands were gazetted as a Marine Protected Area. Management of the park became the responsibility of Jabatan Taman Laut, under the direction and supervision of Malaysia's Department of Fisheries. Since the designation, only non-extractive activities are allowed within a two nautical mile radius from the low-shore tide line (Noh et al., 2018). What followed was a complete overhaul of the islands, where residents moved from a fishing lifestyle to one dominated by an ever-more profitable tourism industry.

The Perhentian Islands have become internationally renowned for their beautiful reefs, which boast a high diversity of species and high area coverage. The reefs host predominantly branching Acropora species on easily accessible fringing reefs and coral gardens that are perfect for recreational diving and snorkeling. In recent years, global exposure has fueled a dramatic increase in tourists flocking to the islands, igniting ambitious coastal developments. Between 1997 and 2014, the number of tourists visiting the Perhentian Islands increased by 41 percent, with a reported 80,000 tourists visiting in 2013 alone (Albattat et al., 2016; Rasoolimanesh et al., 2016).

The increased attraction of tourists to the Perhentians is proving a real double-edged sword. The growing influx of tourists is enhancing the quality of life for the local and adjacent communities, which, in turn, creates willingness and funds to conduct conservation-minded activities. However, ineffective monitoring and management are polluting, smothering, and killing the reefs at a concerning rate. More so, the Perhentians still lack centralized and effective sewage management, with wastewater loading nutrients into surrounding ocean waters. In fact, water quality testing confirmed the presence of fecal bacteria (Reef Check Malaysia, 2010) in our marine environments. The introduction of contaminants from wastewater, nutrients leaking from shoreline-based dump sites, and the continual rise in developments throughout the islands are all considered major contributors to a reported shift in nutrient indicator algae (NIA) on the reefs.



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Line graph displaying the percentage cover of Live Coral Cover (LCC) and Nutrient Indicator Algae (NIA) annually for the Perhentian Islands. Data source: Reef Check Malaysia

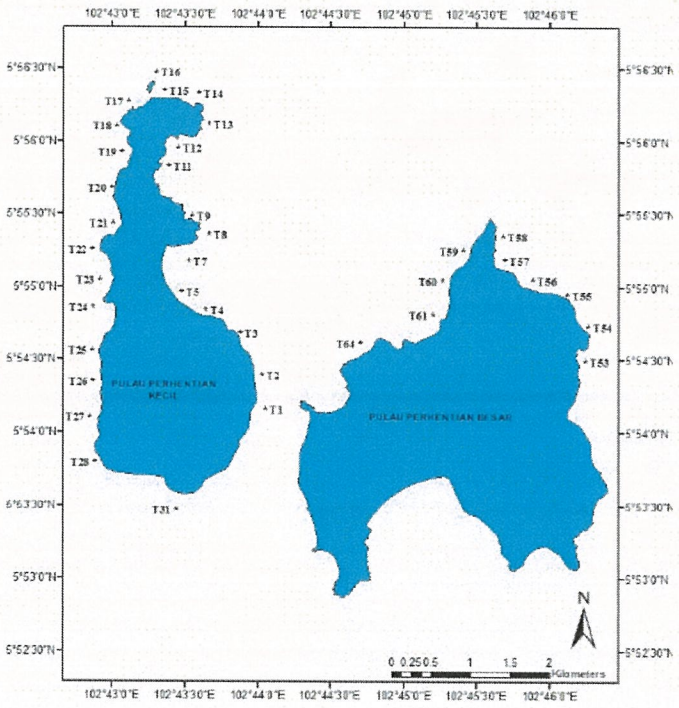
The Perhentian Marine Research Station

In 2016, the Perhentian Marine Research Station (PMRS) was established by the conservation-based social enterprise Fuze-Ecoteer. PMRS runs volunteer and group programs that create the funding necessary to finance the station's research. PMRS strives to combine scientific research with bottom-up biocultural conservation, and invites local and global communities to engage in reef conservation and coral research. Throughout the season (March until October), we head out with a small team of researchers and repeatedly monitor marine reef sites around the Perhentian Islands. Research includes rapid site assessments, identifying and, where possible, removing reef pollutants, and collaborating on coral propagation and coral reef restoration programs.

During its first years, PMRS set up a large-scale habitat mapping program to develop a detailed baseline overview of coral reef health along the Perhentian Islands, expanding the number of sites that had been monitored previously. PMRS recorded reef health indicators for a total of 41 unique sites. Hard and soft coral cover estimates were recorded in addition to NIA percentage cover, fish density and biomass levels, and coral rubble and crustose coralline algae parameters. Results were used to generate an index map of coral reef habitat states for the islands, which were subsequently compared to results from nation-wide coral surveys.

Our 2017 results show the reefs were in a worse state than was previously assumed from other data sources. The data shows a mean live coral cover (LCC) of 27 percent (sd=14). Reef Check Malaysia reported a higher average percentage for that year: 42.32 percent LCC. More so, when comparing NIA levels for PMRS data versus Reef Check Malaysia, Reef Check Malaysia reported an average NIA cover of 6.94 percent, where we found 13 percent (sd= 9). Differences in results can be related to different sample sizes and a differing survey methodology, as Reef Check Malaysia methodology stipulates assessments to be conducted at reef sites with the highest LCC estimates. Nonetheless, these results indicate that the health condition of the Perhentian reefs is far less favorable than was initially thought.

By identifying gaps in the current research, we aim to better understand local coral reef dynamics and their predicted degradation. At previously unmonitored sites we are now conducting baseline data collection to record coral distributions, site complexity, and abundance levels. Research permits have been granted for two such sites around the Perhentians, Village beach and Teluk Keke, and methodologies are currently undergoing refinement before progression into the data collection phase. In addition to a research focus on corals, we carry out parallel fish monitoring surveys. In doing so, we aim to uncover the species richness as well as the abundance and distribution patterns of fish species with high ecological importance, such as Scaridae and Labridae. These fish play a pivotal part in top-down control of algal growth, and clear substrate for coral planula recruitment. They are, therefore, important supporters of coral reefs and noting their presence on (artificial) reef sites provides an indication of ecosystem integrity. By better understanding the associated health parameters of the reefs, PMRS can inform new management measures as development, tourism, and the accompanied drivers of reef degradation continue to rise around the Perhentian Islands.



Survey sites of PMRS habitat mapping in 2017

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The Artificial Botte Reef

Last year PMRS was able to embark on a particularly wonderful project when we built our first artificial bottle reef, funded by American Express, as part of their Serve2gether corporate volunteering program in partnership with Points of Light and Tandemic. During the implementation phase of the program, 63 artificial reef blocks, constructed by setting recycled glass bottles in cement, were placed along a patch reef site at Perhentian Kecil. Live coral fragments were tied to the bottles and left to self-attach. After four months, 15 coral fragments already showed successful attachment, including *Acropora clathrata, Acropora digitifera* and *Acropora formosa*. Throughout the 2019 season, weekly dives were conducted to measure coral attachment and growth rates, and to maintain the artificial reef blocks. Initial data showed very promising signs with a 1400 percent increase in biodiversity as compared to the control area. Alongside high recruitment levels for crustose coralline algae, the bottle reef became populated with Labridae, Chaetodontidae, Epinephelinae, Actiniaria, Porifera, Pomacentridae and Nudibranchia species.

However, as is often the case during the initial stages of a new experiment, we experienced some hardships with the artificial bottle reef. The monsoon season that year included tropical storm 'Pabuk', which shifted several blocks that had been placed in a shallower part of the site. Post-monsoon surveying revealed many of the self-attached corals did not survive the event. On a brighter note, new juvenile recruits have attached and surviving corals show significant growth. Lessons taken from monsoon impacts on the artificial bottle reef have been used to refine deployment strategies for a second artificial reef site, set to be initiated at Teluk Keke on Perhentian Besar during the 2020 season. More so, at Teluk Keke we plan to initiate and trial a coralline nursery that will be maintained and monitored in partnership with local dive operators and volunteers.

Passive Reef Restoration Strategies

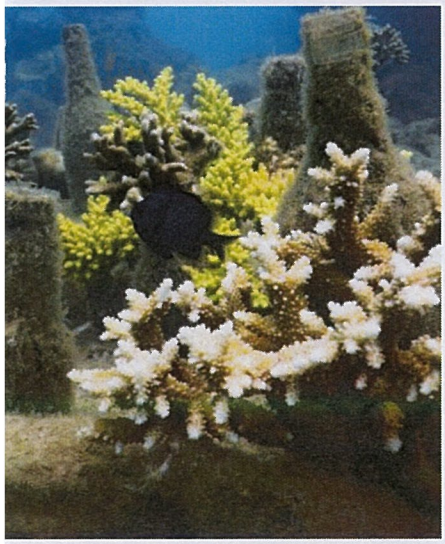
Besides efforts to increase coral conservation through preservation, we also advocate passive reef restoration strategies. The research station organizes weekly beach clean-ups, conservation and awareness talks, eco-snorkeling tours to stimulate conscientious snorkeling behavior, and dives against debris. Especially following monsoon season, there seems to be a peak in solid waste and ghost net presence on the reefs, so removal sessions are organized with the support of volunteer divers to help reef regeneration.

PMRS is perpetually on the lookout for enthusiasts and scientists who want to collaborate on coral research and conservation. By offering volunteer, student, and internship programs, we create an entry-level experience in the field of marine ecology and conservation, for those keen to protect the Perhentian reefs.

The coral reef research programs at PMRS focus on working side by side with local communities. We approach marine conservation with a perspective that promotes integral thinking and biocultural sensitivity. The future of the coral reefs intimately depends on collective understanding and the willingness of dependent communities. No conservation management strategy would be truly successful without a well-informed approach. At PMRS we hope that combining science with the right approach holds the key to an enduring and fruitful collaboration to protect the reefs of the Perhentian Islands.

References

More information can be found here: www.fuze-ecoteer.com/astra-portfolio/marine-conservation-volunteer-project/



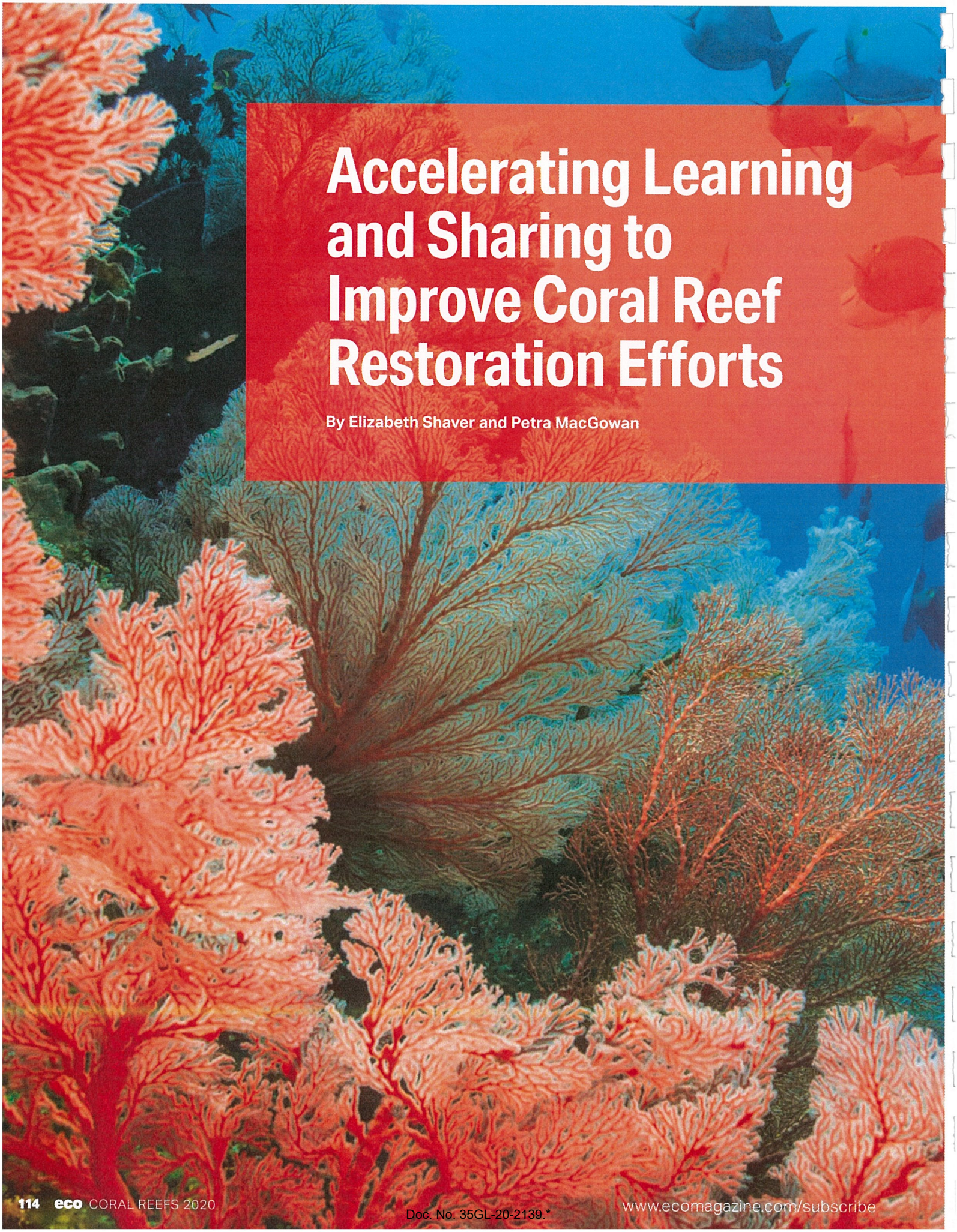
Successful attachments of Acropora species on the artificial bottle reef at Village Beach, Perhentian Kecil.



Hidayah recording the state of the artificial bottle reef following the 2019 monsoon season (which included tropical storm Pabuk). Only a handful of corals survived the monsoon.



Alanah and Melissa conducting coral transects for a new longitudinal research study which includes formerly unmonitored sites around the Perhentian Islands.

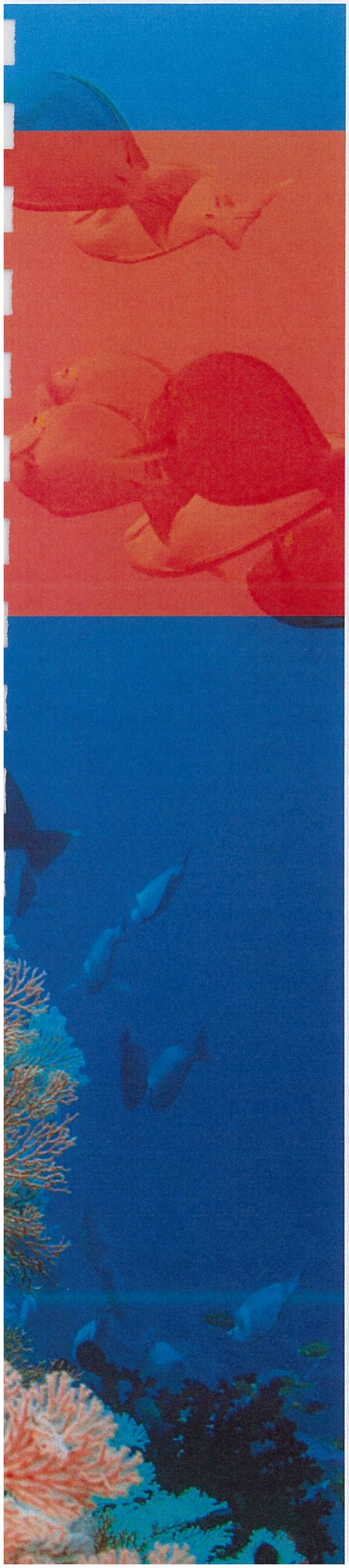


Accelerating Learning and Sharing to Improve Coral Reef Restoration Efforts

By Elizabeth Shaver and Petra MacGowan

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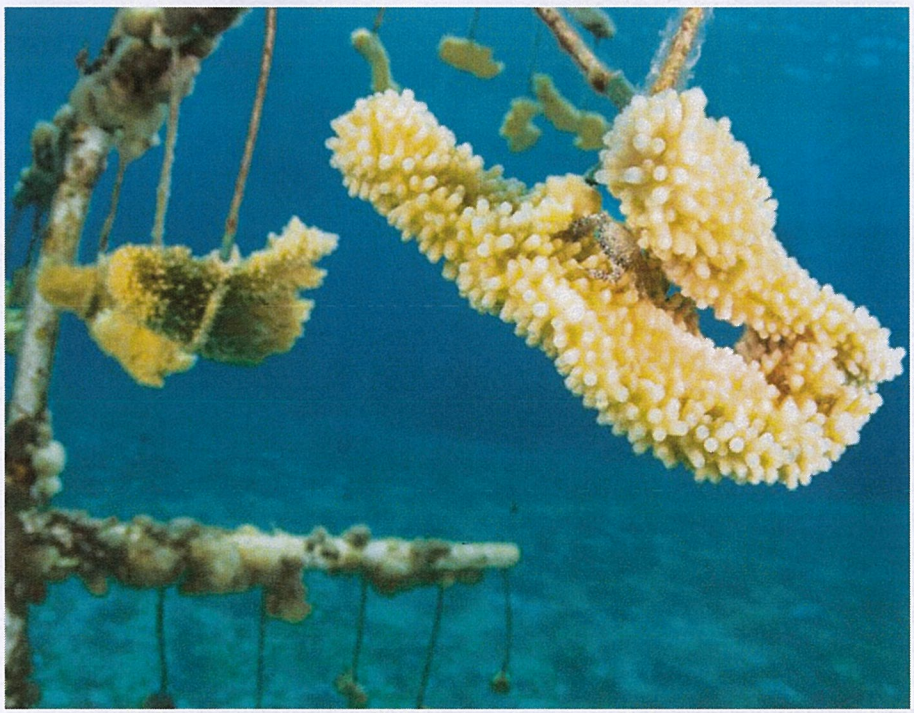


Coral reefs are among the most biologically diverse and economically valuable ecosystems on our planet. Yet, they are declining rapidly across the globe due to a combination of local threats and climate change. In response to the global loss of coral reefs and the ecosystem services they provide, restoration is increasingly applied to combat degradation and promote reef resilience. There is a growing consensus that comprehensive conservation strategies for coral reef ecosystems - like those for many terrestrial ecosystems - must incorporate active restoration interventions to address coral loss as climate conditions continue to change.

Interest and investment in restoration research and projects has grown rapidly over the past decade and will continue to grow as we enter the UN Decade on Ecosystem Restoration (2021-2030). Reef managers globally have recognized the need to include reef restoration as a key component of coral reef conservation efforts. It supports the maintenance of reef structure and vital ecosystem services and buys time for corals to persist and adapt to changing ocean conditions. Restoration interventions are a critical tool to complement more conventional management strategies like local threat reduction and protection.

Restoring Coral Reefs

Ecological restoration is defined as the "process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed" (Society for Ecological Restoration). The goal of restoration is to move an ecosystem towards recovery so the system can ultimately persist on its own without continued support. There are generally two types of restoration: passive and active interventions. In a coral reef context, passive interventions seek to remove factors causing reef degradation (e.g., macroalgae or coral predators) and allow natural regeneration processes to help the system recover. Active interventions are activities where humans intervene to support reef recovery and are particularly useful when natural recovery is unlikely to occur without assistance. Examples include the reintroduction or augmentation of key species or ecosystem attributes, as discussed in a paper by McDonald *et al.* (2016).



Elkhorn corals growing in a coral nursery. New Providence, Bahamas. Credit: Shane Gross

Early coral reef restoration activities began as an effort to repair coral reef habitats after acute disturbances such as ship groundings. Over time this changed to coral gardening techniques that address the loss of corals and ecological functioning of reefs. The field is evolving to include new techniques that support recovering coral populations and reef ecosystems. Increased research and on-the-ground discovery by practitioners have continuously improved the science and methodologies behind these efforts, with increasing low-cost and low-tech approaches, making restoration a viable approach for many managers and community practitioners.

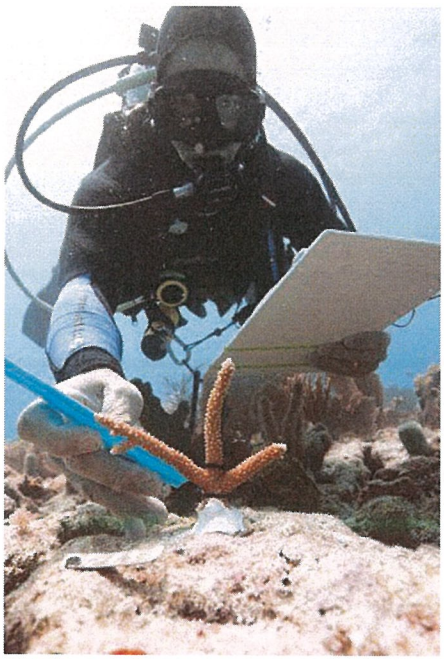
Successful reproduction and recruitment of new corals with diverse traits are essential for restoring coral populations. Coral reef recovery can be inhibited if coral populations are low, even with other management actions in place. Therefore, reef restoration projects often focus on the need to re-establish coral cover on degraded reefs by transplanting coral colonies that have been propagated in field-based or land-based nurseries, a process broadly known as coral gardening or 'asexual propagation'. Corals are also being produced through larval propagation techniques, also called 'sexual propagation', by collecting coral spawn, rearing larvae, and transplanting small coral colonies back onto the reef.

In addition to restoring healthy coral populations and cover on reefs, recovering reef substrate is another intervention that is applied when complex reef structure has been lost due to degradation or direct damage (see Boström-Einarsson *et al.* 2020). For example, the addition of manmade substrates or substrate stabilization techniques may be needed in damaged areas before coral colonies can be replanted. Coral reefs where macroalgae dominates the reef substrate may also need to have macroalgae removed to make the substrate suitable for coral transplantation and successful recruitment of new coral colonies.

With an ever-growing list of techniques applied in new restoration programs around the world, guidance on evidence-based best practices is more critical than ever. Ensuring that this guidance gets into the hands of marine managers and practitioners is essential. The Reef Resilience Network has emerged as a key vehicle to address these needs by connecting marine managers and practitioners with global experts, science, and resources to restore the world's coral reefs using the best available guidance.

Partnerships to Develop, Apply and Share Knowledge

To support managers globally in the design and implementation of effective coral reef restoration, the Reef Resilience Network (the Network) has partnered with the world's leading restoration experts and organizations to develop resources, create skill-building opportunities, and provide guidance and tools. For more than 15 years, the Network has served as a global leader in capacity building for marine resource managers and practitioners at the front lines of coral reef conservation. Led by



Monitoring newly outplanted coral at Big Pine Key, Florida. Photo credit © Tim Calver



A newly outplanted coral offshore of Ft. Lauderdale, Florida. Photo © Tim Calver

The Nature Conservancy, the Network is supported by dozens of partners, including the National Oceanic and Atmospheric Administration's (NOAA) Coral Reef Conservation Program. It includes more than 1,500 members and over 100 global experts in coral reef resilience, reef restoration, fisheries, climate change adaptation, and strategic communication.

The Coral Reef Restoration Module of the Network's online toolkit (www.reefresilience.org) compiles the latest science and tools to provide managers and practitioners with evidence-based guidance on best practices in reef restoration. The Restoration Module was created in partnership with experts from the Coral Restoration Consortium, Australia's Reef Restoration and Adaptation Program, and other global experts, and designed from a survey of over 110 Network managers from across the globe who provided their input on reef restoration needs. The Module offers synthesized science and resources to maximize the success of restoration efforts and the most efficient use of a manager's often limited resources, including guidance on the following topics:

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- **An Introduction to Restoration,** which provides background on ecological restoration, the role restoration plays in the management and conservation of reefs, and information on the Coral Restoration Consortium

- **Project Planning,** which helps managers determine whether to conduct restoration, set project objectives, select restoration sites, engage stakeholders and consider sustainable financing options

- **Restoring Coral Populations,** which provides guidance and instruction on coral gardening techniques, larval propagation techniques, and monitoring for coral outplants and the restored reef sites

- **Restoring Reef Substrate**, which describes key considerations for substrate addition with manmade structures and substrate enhancement methods such as algae removal

- **Rapid Response & Emergency Restoration,** which considers approaches to responding to disturbance events like hurricanes and summarizes new protocols being trialed in Mexico

- **Restoring the Reef Environment,** which provides information on restoring connected coastal habitats like seagrasses and mangroves

In addition, an open-access coral reef restoration online course is available that features activity sheets, videos, and assessments in both English and Spanish. The course can be accessed on ConservationTraining.org and includes six lessons: Restoration Planning; Coral Gardening; Larval Propagation; Restoring Reef Structure; Emergency Response; and Monitoring. Other tools include webinars and livestreamed recordings from coral reef conferences. As the field of restoration grows rapidly and new science, technologies, and resources become available, these tools will be updated and expanded.

The Network incorporates lessons learned from programs around the world that pilot cutting-edge restoration techniques, such as The Nature Conservancy's (TNC) Mexico, Caribbean and Florida programs, Coral Restoration Consortium member organizations, and Australia's Reef Restoration and Adaptation Program (RRAP). Successful strategies and methods are shared with managers and practitioners globally through a restoration focused webinar series cohosted by the Coral Restoration Consortium.

Addressing Gaps in Restoration Guidance for Managers

A fundamental gap facing coral reef restoration practitioners is the lack of guidance on strategic planning for restoration to address current needs and future climate change scenarios. In addition to careful planning, monitoring and evaluation and sharing of lessons learned are also essential.

In response, the Network has led the development of A *Manager's Guide to Coral Reef Restoration Planning and Design* (Shaver *et al.* 2020) with key partners such as NOAA's Coral Reef Conservation Program, US Environmental Protection Agency, and others. Using available information about the specific reefs in their locations, practitioners are guided through critical decisions about if, where, and how restoration should be conducted. Important resources informing the *Manager's Guide* include the Society of Ecological Restoration's (SER) *International Principles and Standards for the Practice of Ecological Restoration* (2nd Edition) and the Conservation Measures Partnership's *Open Standards for the Practice of Conservation* (CMP 2020).

The *Manager's Guide* describes a six-step adaptive process for planning and implementing coral reef restoration interventions through a climate-smart lens (modified from West *et al.* 2018). These steps help reef managers and planning teams develop a Restoration Action Plan. A hallmark of the process is the iterative nature of the cycle, where the availability of new information at any one step is used to refine other steps and continuously improve restoration through time. This guide aims to assist in the design of restoration projects to increase the likelihood of success and support learning throughout the implementation process.

Future Directions

In working with coral reef managers over the past 15 years, we know that knowledge is power. As restoration research, methodologies, and applications advance at an exponential pace around the globe, the Network is committed to evolving its resources to keep managers and practitioners in-the-know. Future projects include the development of guidance on land-based nurseries, micro-fragmentation methods, the use of aerial mapping to site coral outplanting locations, and substrate stabilization techniques.

We look forward to new partnerships and working with experts to get information into the hands of those managing and conserving coral reefs on the ground. Please contact resilience@tnc.org if you want to become a content expert, partner, or member of the Network.

For more information, check out:

Reef Resilience Network Restoration Module:
https://reefresilience.org/restoration/

Reef Resilience Network Restoration Online Course:
https://reefresilience.org/online/

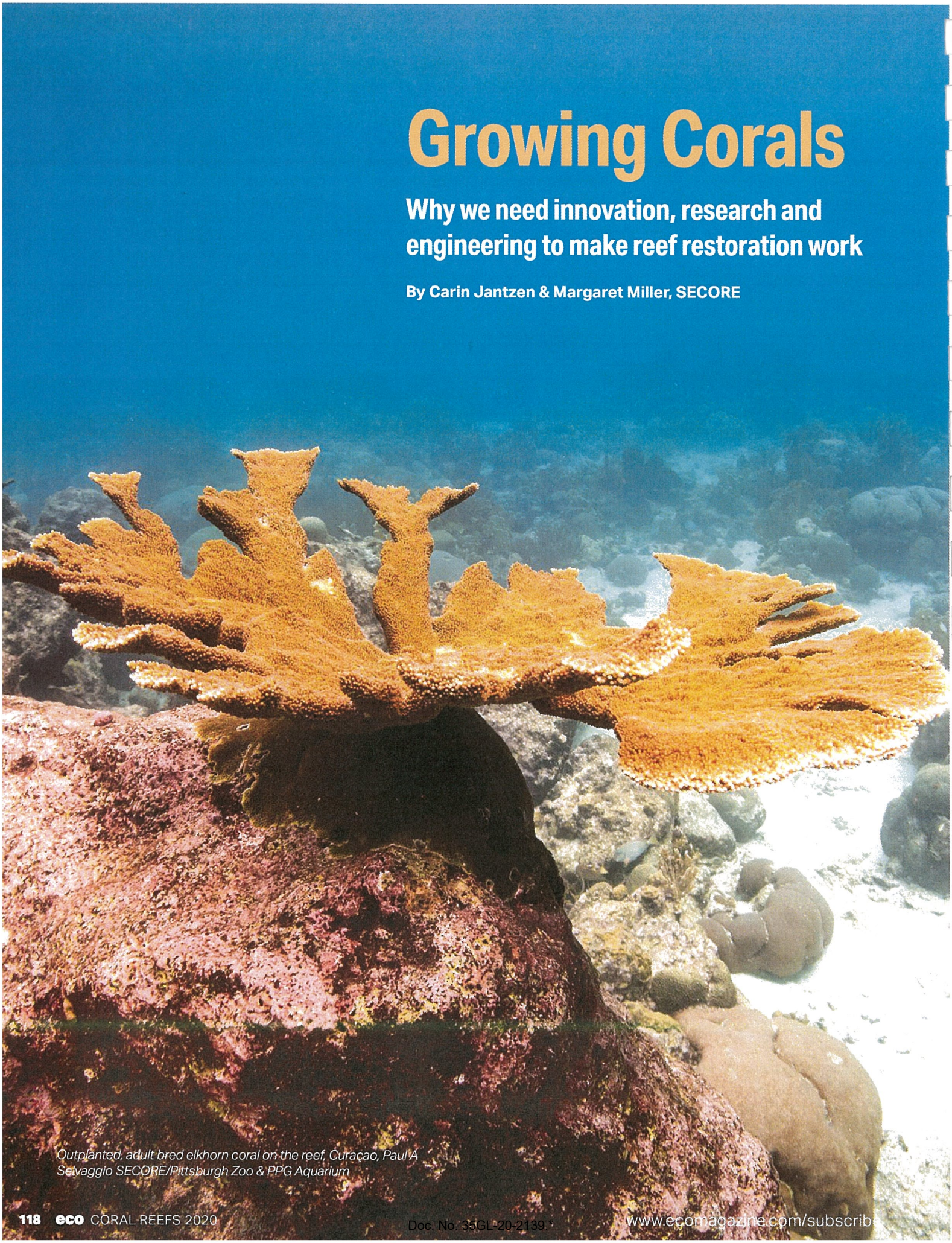
Coral Restoration Consortium:
http://crc.reefresilience.org

Coral Restoration Review, Visualization, and Database:
https://www.gbrcoralrestoration.org/restoration-database

Growing Corals

Why we need innovation, research and engineering to make reef restoration work

By Carin Jantzen & Margaret Miller, SECORE



Outplanted, adult bred elkhorn coral on the reef, Curaçao, Paul A Selvaggio SECORE/Pittsburgh Zoo & PPG Aquarium

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Coral Spawning Night

On a Caribbean Island, shortly after sunset, a team of scientists and volunteers is getting ready for their coral spawning dive. Along with their dive gear, they bring custom-made gauze nets, which they will place above spawning corals to collect their eggs and sperm. For the many coral species that take part in mass spawning events, there are one to few nights per year when they time their spawn almost to the minute to ensure highest chances of fertilization. Over several days, the team has been in the water waiting for this big event. When the divers head out, the water is already pitch-black. Putting heads under water, tonight seems different. The water is crackling and sizzling with activity, there is something going on in the reef—the nighttime reef creatures are taking up position for a rich feast on coral spawn. And there you can see the first corals preparing to spawn—small beads of eggs and sperm appear within the mouths of the coral polyps, like pale pearls spread over the colony. Now, it's time to place the nets above the coral. The net funnels the buoyant sperm-and-egg bundles into a sample vial on top, which, detached and lidded, is taken back to the surface by a diver.

Hard Times for Corals

Planet Earth no longer provides the same conditions as when many species—including us—evolved. Humans are causing dire and rapid changes to Earth's atmosphere that, in turn, alter ocean temperatures and chemistry. Combined in many places with severe environmental degradation from local human activities such as overfishing and pollution, this has caused tremendous and rapid population crashes in many reef corals.

When so many parents are lost, few babies are produced. The few coral larvae that do arrive at a reef where they might make their home, too often face so many obstacles that the chances of their survival to maturity are remote. Thus, it is no surprise that without enough new coral offspring, reef ecosystems cannot recover from increasingly frequent acute disasters. No corals, no reefs; and from such an ecological disaster, enormous socio-economic costs ensue.

There is an imperative need to fix the underlying causes, both climate change and local impacts. But the rapidity and severity of coral decline, along with the long-time lag that will be required for re-balancing the planetary climate system, demand rapid advance in both development and implementation of active coral restoration to give coral reefs a future.

SECORE's mission is to develop and share tools and technologies to sustainably restore coral reefs worldwide. One advantage of breeding corals from the very first day of their life, is that millions of coral embryos can be obtained during each spawning event. And the great challenge to implement coral restoration, is to do it on a meaningful scale.



Coral settlement substrates in CRIB, Dominican Republic, Paul A Selvaggio SECORE/Pittsburgh Zoo & PPG Aquarium

Coral Restoration Technology

Vital requirements to meet the goal of sustainably restoring coral reefs are feasibility, scale, and finally costs including the manpower needed for handling and outplanting. SECORE pursues a unique approach by combining ecological research to overcome early life-history bottlenecks, the development of innovative methods and tools that are translated into applicability by engineers, and an appropriate implementation strategy to meet the needs of each restoration site.

But let's start from the beginning. Corals have a somewhat unexpected life cycle. While they lead an almost entirely stationary life, building incredible calcareous structures that are the base of every reef, they have a short larval phase in which they can travel long distances, interconnecting reefs by a current-driven larvae flow. Coral larvae are capable of swimming on their own and are equipped with senses to seek and identify a suitable reef habitat at the end of their journey—where they must commit to reside as long as they may live. Most important reef-building species spawn their eggs and sperm synchronously into the water column to enable fertilization. If the remaining parent colonies are too far apart, they fail even this first step.

So, we start with collecting coral eggs and sperm with specifically designed nets to breed our new baby corals. The collected spawn is then fertilized 'in vitro', either on a boat, beach or in a lab nearby—time is a crucial factor here. We contain and protect the developing larvae in Coral Rearing In-situ Basins (CRIB), or, when these are not applicable, in land-based tanks. The CRIBs are anchored floating enclosures that provide natural ocean conditions during the development and later settling of the coral embryos into polyps. The CRIBs

were developed together with engineers, to make the design fit its purpose. An inflated pontoon floats the enclosure and prevents water from sloshing in or out.

Furthermore, we also developed ceramic 3-D structures that provide cues and designed microhabitats for the larvae to recognize as an appropriate choice for their permanent home. These settlement substrates can be manufactured in mass-production. After a pre-conditioning phase in reef-water, the substrates are introduced into the CRIBs prior to adding the coral larvae.

Later, the substrates with corals settled on them can be safely translocated to the reef. To deploy them to appropriate reef habitats, no further attachment is necessary. Their shape enables them to self-stabilize on the reef, reducing handling time and thus costs for outplanting by over 90 percent compared to former practices. In the near future, we envision engaging drones and other aspects of automation in breeding and outplanting more corals, more efficiently.

Salty Soup of Life

Enough spawn is collected for tonight and the divers hurry back with their precious catch to the lab to bring a new generation of corals to life. Still wet from the dive, the team pours the collected spawn of different parent colonies in containers with filtered sea water. While gently mixing this salty soup of life, the egg-and-sperm bundles break apart and fertilization takes place. Then the team continues to work with utmost concentration, rinsing away unneeded sperm that would otherwise contaminate the water while degrading. Immediately the microscopic small embryos start to grow and will develop into coral larvae over the following week.
A few days ago, the team set up two CRIBs, floating enclosures anchored at the seashore to keep the growing baby corals safe and healthy. It's already after midnight when the hundreds of thousands of coral embryos are introduced to the CRIBs by a small delegation of equally happy and exhausted scientists. In the torchlight, crates filled with settlement substrates are shimmering below the water surface. In the coming days, the team monitors larval development. Finally, the coral larvae are ready to settle. They are now taking advantage of the substrates provided to them as their new homes. The coral larvae will initially become single polyps and then start dividing to grow into colonies of many.





Spawning work—fertilization and rinsing coral embryos, at FUNDEMAR lab, Dominican Republic, Paul A Selvaggio SECORE/Pittsburgh Zoo & PPG Aquarium

Collecting coral spawn with specialized nets, Curaçao, Paul A Selvaggio SECORE/Pittsburgh Zoo & PPG Aquarium

Advantages of Breeding Corals

Apart from being able to get literally millions of coral embryos out of one spawning event, breeding serves the purpose of creating new genetic diversity, a fundamental premise for almost any healthy population. The changes corals face are rapid and extreme. Thus, we are pursuing strategies that can encourage this adaptive potential to proceed as quickly as possible. In the course of sexual reproduction, genetic recombination takes place—the reshuffling of the genetic pack. By placing many, genetically unique, baby corals back onto reefs at an early age, natural selection has the best chance to rapidly shape coral populations in a way to become suited to the current and changing reef environment.

Intensive research throughout the field is also focused on more extreme interventions to create coral genotypes that can be more resilient to warm temperatures or disease. Once evaluated worthwhile, considering all the risks of such an intervention, these more extensive genetic modifications will require large scale breeding and culture techniques—such as we are developing—to implement them at the scale needed.

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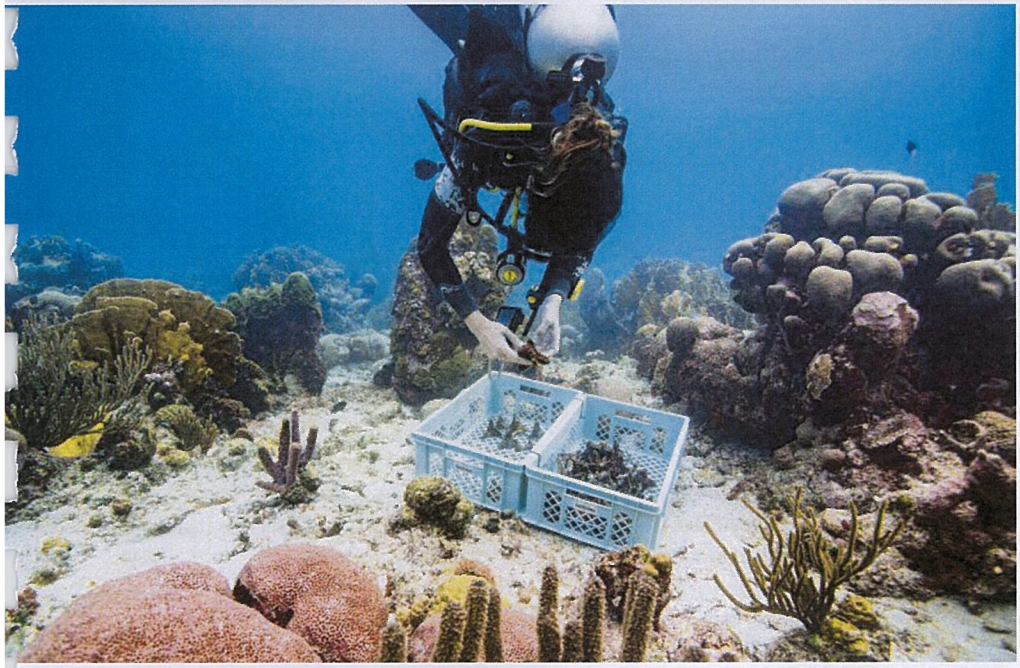
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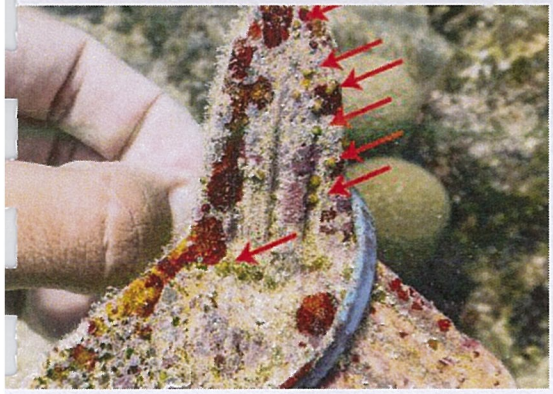


Sharing Our Knowledge for Implementation

As we develop these methods, tools and technologies, we test and evaluate them at our research sites. Next, we mentor local groups with interest and operational capacity, who often are already involved in coral restoration of some sort. We train these practitioners, visit them at their own location, providing mentorship and support where needed, and we supply the technology.

Given the rapid pace of coral decline, we have chosen to adopt a two-pronged strategy: sharing our current best practices with partners to get them started at their local reefs while concurrently pressing forward with the research, development and refinement of tools and techniques.





Adding coral embryos to CRIB, Bahamas, Paul A Selvaggio SECORE/Pittsburgh Zoo & PPG Aquarium

Outplanting corals on pilot site, Curaçao, Paul A Selvaggio SECORE/Pittsburgh Zoo & PPG Aquarium

Coral settlement substrate with two month old elkhorn corals, Curaçao, SECORE

Back Out on the Reef

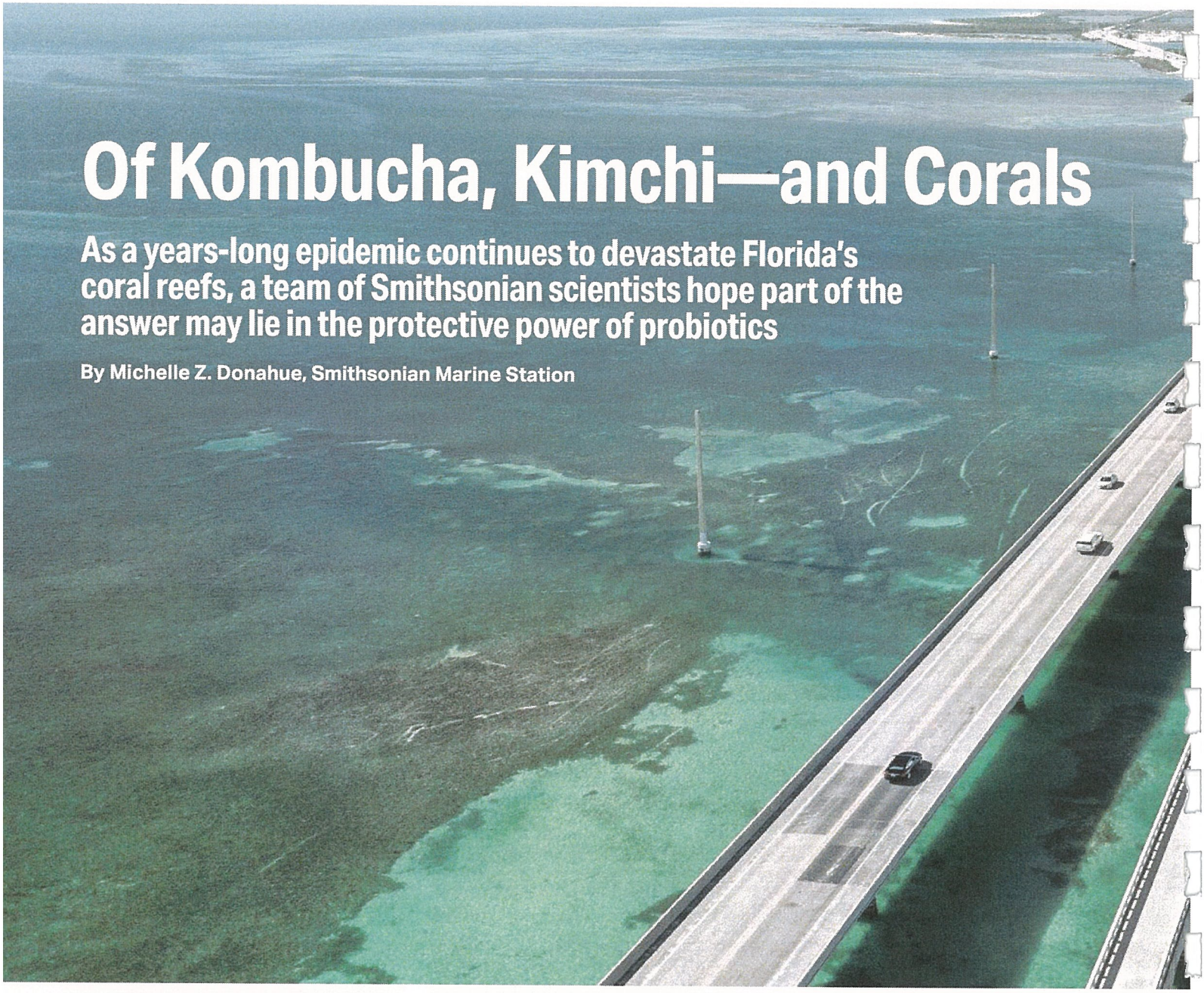
This time the divers are underway in sun-lit waters. A year has passed, and the baby corals have grown into little colonies. The outplanted substrates that bear the young corals camouflage perfectly into the reefscape and can be spotted only by the trained and alert eye. The divers photograph each substrate, so they can later measure growth and survival of this new coral cohort. They have been doing this periodically over the past year. Later onshore, the scientists will be satisfied with the results from this cohort as many of the substrates are home to at least one healthy young coral. While the divers proceed, they pass a couple of mature elkhorn corals that they had bred almost a decade ago. Since age four, they have been joining the annual spawning night with their wild neighbors.

Coral spawning and collecting of spawn, Mexico and Curaçao, filming and production Reef Patrol/SECORE



Footnote:

Read more about our work at www.secore.org and sign in for our Newsletter here (link to be imbedded: https://visitor.constantcontact.com/manage/optin?v=001LP7gO0WTvr3pUHAD8bgmULtv7mnWX5Yw)



Of Kombucha, Kimchi—and Corals

As a years-long epidemic continues to devastate Florida's coral reefs, a team of Smithsonian scientists hope part of the answer may lie in the protective power of probiotics

By Michelle Z. Donahue, Smithsonian Marine Station

Though the progression of any disease is never easy to watch, scientists who study corals in the Florida Reef Tract and in the Caribbean have witnessed colonies hundreds of years old melt away in weeks.

This is stony coral tissue loss disease (SCTLD). First evident as a thin band of dead tissue that can appear anywhere on a coral colony, the disease can destroy a specimen in days to weeks, spreading as lesions across the surface of the coral until all that's left is an ominous white skeleton.

And though there is not yet a cure for the disease, or even the exact identity of the culprit causing it, hopeful advances are being made—in the form of probiotics.

A Beneficial Relationship

If you've ever eaten yogurt or sauerkraut, or had a sip of kombucha, then you've had probiotics. And corals, just like the human gut, are home to complex communities of microorganisms including bacteria, fungi and protists; some members of these communities seem to boost their particular host's immune system. When harmful bacteria try to invade, the beneficial bacteria are able to repel or even kill the threats.

In the last year alone, a team of scientists at the Smithsonian Marine Station (SMS) in Fort Pierce, Florida have isolated and cataloged upward of 900 other potential probiotic candidates derived from healthy corals found in areas throughout the Florida Keys. Coral probiotics have been studied before, but never expressly for the purpose of developing an intervention for the ongoing disease outbreak.

SMS head scientist, Dr. Valerie Paul, and Dr. Blake Ushijima, a George Burch Fellow and microbiologist at SMS, have led efforts to isolate these bacterial compounds from healthy star corals (*Montastraea cavernosa* and *Orbicella faveolata*) from the Florida Keys. And although Paul and Ushijima are still working to tease out the full suite of beneficial effects of these probiotics, many advantages have already emerged.

A few particularly promising candidates seem to contribute resistance to the pathogen(s) causing SCTLD. Adding one of the strains to diseased corals in

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aquaria resulted in the disease slowing down or a complete halt of its progression.

Treated corals share their protective cultures with sickly neighbors. When diseased corals are put in close proximity to healthy corals treated with one of the probiotics, the beneficial effects seem to transfer to some diseased fragments, slowing or stopping disease progression there as well.

Healthy corals also seem to get an immune boost from treatment with probiotics, elevating their resistance to infection. This could prove advantageous for coral replanting efforts in areas where the disease has already ravaged Florida's reefs.

To dig deeper into what might be conferring the protective effects, SMS natural products chemist, Dr. Sarath Gunasekera, isolated and analyzed a chemical produced by one of the probiotics and determined it to be an antibiotic known as korormicin. This compound only affects other marine bacteria and is not a threat to humans or animals. Genetic work by Dr. Julie Meyer at the University of Florida, another collaborator on the effort, also revealed genes associated with the production of two other known antibacterial compounds: marinocine, a broad-spectrum antibacterial, and tetrabromopyrrole, which is also an important chemical cue for coral larval settlement.

At least one of the probiotics may also be useful for coral settlement studies, which has been a research focus of Smithsonian biologist Dr. Jennifer Sneed. Sneed has previously worked on tetrabromopyrrole and has also contributed to the ongoing probiotic development research.

Stopping the Spread

Since SCTLD was first documented near Miami in late 2014, the disease has now spread to affect more than 96,000 acres of coral reef, stretching 360 miles from Fort Lauderdale in the north to Eastern Dry Rocks in the lower Keys. As of early 2019, observers reported that the disease spread to the U.S. Virgin Islands and the Dominican Republic; as of last summer, the first signs were reported in Belize.

Of the 45 species of reef-building corals that occur on the Florida Reef Tract, 22 species have been particularly hard hit—some dying in days, such as maze coral (*Meandrina meandrites*), while others can languish for months to years, like giant star coral (*Montastraea cavernosa*). Some have survived an initial onslaught but are now succumbing to subsequent waves of the disease.

The Smithsonian's involvement in investigating the disease began in May 2017, when Paul received funding from the National Science Foundation to better understand the cause, development and progression of the disease, as well as examining whether beneficial bacterial communities—probiotics—might play a role in defense against SCTLD. Joining Paul, Meyer and Smithsonian collaborator Dr. Greta Aeby on the initial investigations were Dr. Claudia Häse, at Oregon State University, as well as Ushijima.

Many unknowns remain. One early mystery was how the disease spread from coral to coral. Aquarium studies by Aeby showed that the disease can transmit through direct contact with a diseased coral and through the water column; corals can also potentially become infected through contact with diseased materials, such as dive gear or animals that feed on corals.

Another major puzzle is the identity of the organism(s) causing the disease, and Paul and Ushijima are working with partners at USGS to rule out viruses as a cause. And with UF's Meyer, who is sequencing the DNA of all microorganisms present on diseased as well as healthy coral fragments, Paul and Ushijima hope to gain a clearer picture of the entire microbial community on corals, and learn if there is anything unique to sick corals that may provide clues to the disease's origins.

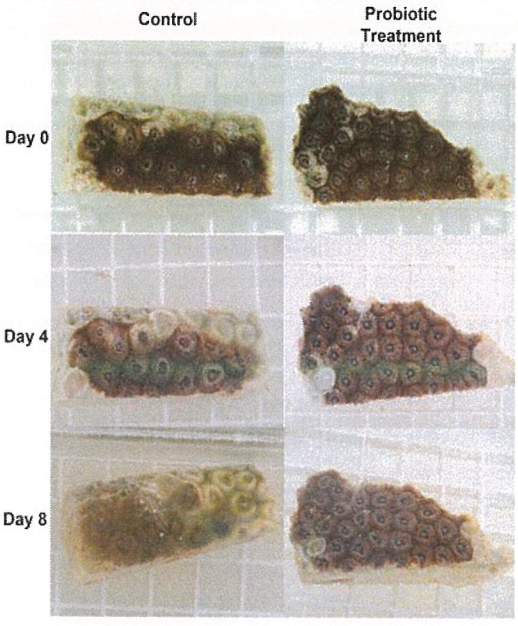
"Unfortunately, there are not many coral pathogens that have actually been identified," Ushijima said. "It's a very complex situation. And these reef builders—they are the reef. When they die, the reef will disappear."

"The scope and scale of this disease requires a large team effort and coor-









Top: A team of divers assemble an enclosure around a diseased coral colony for a field test of an experimental coral probiotic near Fort Lauderdale, Florida in early 2020. Credit:Kelly Pitts

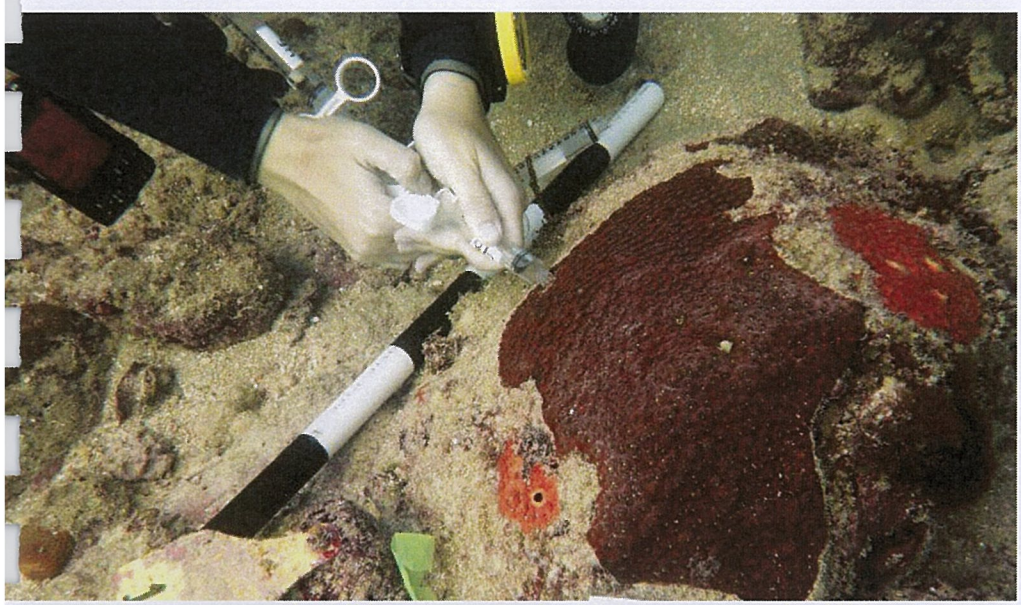
Center left: Researchers at the Smithsonian Marine Station developed an experimental treatment for stony coral tissue loss disease using protective, beneficial bacteria collected from healthy, disease-resistant corals. Here, a colony of great star coral afflicted with the disease sits inside an enclosure designed to keep the probiotic treatment in close proximity to the disease lesions. Credit: Dr. Valerie Paul

Center right: A research diver injects an experimental probiotic treatment into an enclosure surrounding a colony of coral infected with stony coral tissue loss disease. Credit: Kelly Pitts

Bottom: Compared with no treatment, samples of M. cavernosa treated with an experimental probiotic developed at SMS showed much greater resistance against disease. Credit: Blake Ushijima

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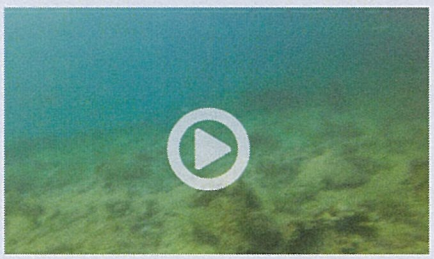




Above: Divers sample mucus from a colony of diseased corals near Fort Lauderdale, Florida in early 2020. Credit: Kelly Pitts

Left: At the Smithsonian Marine Station in Florida, microbiologist Blake Ushijima searches for the pathogenic causes of stony coral tissue loss disease. Credit: David Branson

VIDEO: Dr. Julie Meyer, a University of Florida researcher who collaborates with SMS on stony coral tissue loss disease research, measures lesions and healthy areas of tissue on a colony infected with the disease near Fort Lauderdale, Florida. (Video: Nicole Miller)



VIDEO: Looe Key was once one of the most pristine areas of reef on the Florida Reef Tract. Seen here in 2017, the reef was still healthy, but today has been devastated by stony coral tissue loss disease. (Video: Julie Meyer)



dination with other coral biologists in Florida," said Paul. "It is a devastating problem already impacting the entire Florida Reef Tract, and there has been tremendous cooperation among state agencies, universities and research organizations in response."

Earlier in 2020, Paul, SMS researcher Kelly Pitts and other SMS research divers finally began the first field trials of one probiotic with the help of Dr. Brian Walker at Nova Southeastern University—when the global spread of COVID-19 scuttled travel and scientific fieldwork. But once fieldwork is able to resume, the field testing will expand to reefs in the Florida Keys.

Saving Corals for the Future

While treating diseased colonies on the open reef tract is a priority, an additional and equally important goal is to protect healthy wild corals. According to Ushijima, "any disease outbreak requires combined efforts from managing disease transmission, treatment of sick individuals, as well as protecting healthy populations from infection or re-infection."

Maurizio Martinelli, the coordinator for state and federal coral disease response efforts with Florida Sea Grant, said this work is one of the first promising advances that may eventually result in a treatment option for whole colonies in the reef tract. One of the main approaches being tested involves labor-intensive spot treatments of individual coral colony lesions.

"It's one of the most wexciting developments recently," Martinelli said. "We think it's a great opportunity to treat colonies more holistically, which has been the goal from the beginning."

Martinelli noted that another possible benefit may be that as probiotic-inoculated corals are replanted on the reef, their beneficial bacterial communities can spread to other corals, combining the effort of reef restoration with disease intervention.

"Even if we are unable to save the currently infected corals, there is a chance we can protect future generations," Ushijima added.

Opportunities for Coral Reef Refugia

A Case Study at The Revillagigedo Archipelago

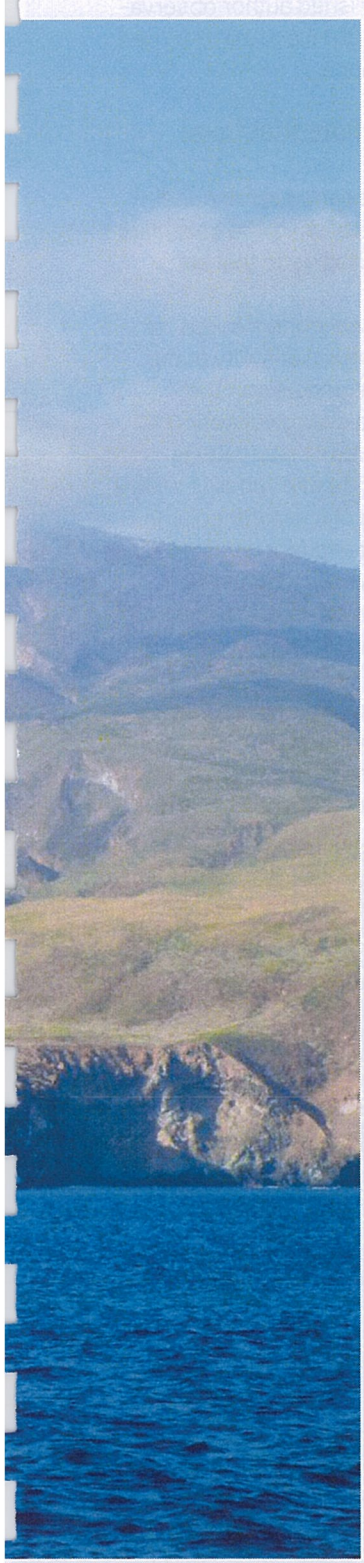
By Amber Carter, University of Edinburgh



Socorro, the largest of the Revillagigedo Archipelago islands. Image: Amber Carter

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Across the globe, the rapid degradation of coral reefs calls for urgent action to enhance reef conservation. The limitation on resources available to tackle the coral reef crisis means that protective measures need to be prioritized, and scientists are increasingly turning to reefs that exist outside traditional coral conditions in search of hope.

Unusual reef habitats that offer the potential to be safe havens for coral species in future climate change conditions are also known as 'climate change refugia.' For terrestrial environments, identifying and incorporating climate change refugia in conservation planning has been widely adopted. Yet, despite an increasing body of evidence and scientific literature defining the conditions of climate refugia for coral reefs, the concept has not yet been widely used in the ocean.

The eastern tropical Pacific is of particular interest to scientists studying coral refugia. Here, corals exist in exceptionally dynamic conditions caused by complex currents, a strong and shallow thermocline, and regular upwelling of cool, nutrient-rich waters. Coral populations across the region thrive despite widespread warming events caused by the El Niño Southern Oscillation.

In the Revillagigedo Archipelago, a coral population is thriving in unlikely conditions, attracting the attention of scientists from the University of Edinburgh. In this little-studied location, researchers sought to characterize the oceanographic conditions and reef coral community. With their findings, we discuss the potential for the site to act as a climate refugia for corals, and consider potential management and learning opportunities for the identification of refugia worldwide.

The Revillagigedo Archipelago

Located 450 kilometers southwest of Cabo San Lucas, Mexico, the Revillagigedo Archipelago is a group of four volcanic islands in the eastern tropical Pacific (ETP). The islands: Socorro, Clarion, San Benedicto and Roca Partida do not have civilian inhabitants, and the only permanent human presence is a small contingent of the Mexican navy. In 2017, an ocean region of 150,000 square kilometers surrounding the archipelago was designated a no-take marine protected area.

Revillagigedo lies at the convergence of the California and Equatorial currents, generating an oceanographically complex and productive transition zone. These rich waters have led it to become an iconic dive destination, home to at least 28 species of shark, internationally significant aggregations of manta rays, and a calving ground for humpback whales.

The islands also host a significant coral ecosystem with the highest number of coral species in the Mexican Pacific, supporting 366 species of reef fish, including 26 species found nowhere else in the world.

What Makes a Coral Refugia?

There are three environmental processes that control the formation of coral refugia: (1) the long-term absence or reduction of stressful conditions, (2) conditions that promote resistance of corals to disturbance, and (3) conditions that support recovery of a coral population.

When a coral becomes stressed, it expels the symbiotic algae living in its tissues, leading to coral bleaching and increased chance of coral mortality. Today, the most significant cause of mass coral



Reef fish at the Revillagigedo Archipelago. Image: Raimundo Valenzuela Urgelles

bleaching is exposure to prolonged periods of above-average sea surface temperature. Because of the importance, the team chose thermal refugia as the research focus. In the future, however, refugia may need to function against multiple stressors, including ocean acidification and depleted oxygen.

Simultaneously to the absence or reduction of heat stress, thermal refugia will be reliant on conditions that promote coral resistance. Resistance can occur through the acclimation of corals to survive in unfavorable temperature conditions. For example, corals are more likely to acclimatize to short periods of thermal stress in reef environments that experience temperature fluctuations on a daily basis. Over time, these corals become more resistant to higher mean water temperatures. Natural selection following a disturbance event, can also boost the resilience of a coral population.

After a disturbance event, the coral population's recovery will be reliant on the level of coral survival and the settlement of coral larvae. Larvae settlement can occur through self-recruitment (the settlement of larvae in the population where it was produced), or larval connectivity (larvae arriving from other coral populations transported by ocean currents).

A location may possess all the environmental components of refugia, but impacts from direct human pressures such as pollution or overfishing can reduce reef resilience. Therefore, the ability for a location to fulfil its potential as a refugia is strongly influenced by human pressures on the ecosystem.

How Do You Identify Refugia?

The identification of refugia at a location requires detailed understanding of the oceanographic conditions and characteristics of the coral community.

While studying the Revillagigedo Archipelago, scientists used remotely sensed sea surface temperature to investigate regional scale oceanographic processes, and data from underwater temperature loggers was used to investigate localized oceanographic conditions.

The team was able to characterize the coral community by synthesizing information from studies spanning over twenty years, published in English and Spanish. Research on the resistance of corals at The Revillagigedo Archipelago is complex; the most severe bleaching occurs during the warmest period of sea surface temperature, when the islands are inaccessible due to tropical cyclones. As such, unpublished author observations following the large El Niño event of 2015 and 2016 helped make predictions about bleaching resilience.

Is the Revillagigedo Archipelago a Potential Coral Refugia?

Once a good understanding of the oceanographic conditions and coral community had been established, the scientists could investigate the features of the Revillagigedo that are indicative of a potential coral refugia.

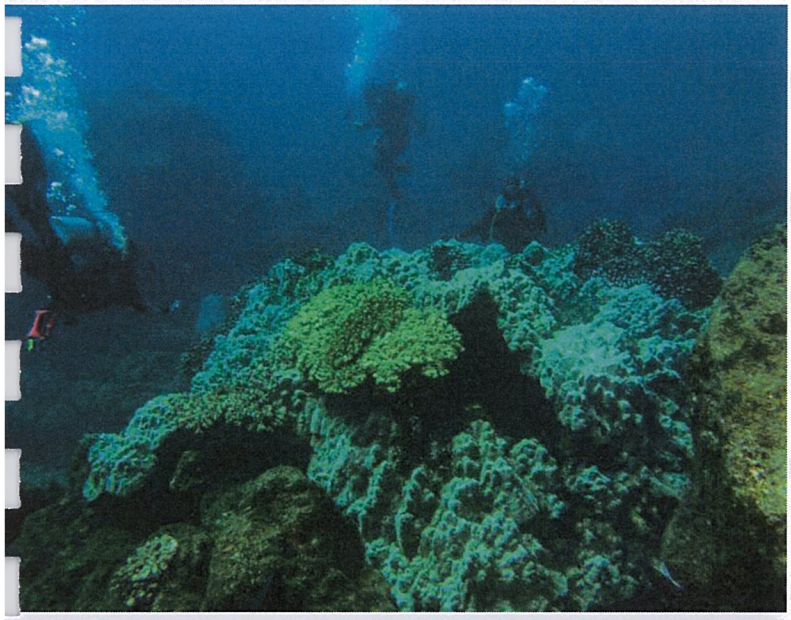
Analysis of the underwater temperature loggers suggests the presence of high-frequency temperature variability at the islands. Daily temperature variations were generally in the range of 2°C to 3°C, but some days saw a change of up to 7°C. Through time-series analysis, the temperature fluctuations could be linked to vertical movements of the thermocline associated with the tidal cycle, and the mixing of the water column during tropical cyclones which occur three to four times a year. Past studies have shown that temperature fluctuations similar to those occurring at Revillagigedo can improve the resistance of corals to thermal stress and reduce the likelihood of severe bleaching and mortality.

Remotely sensed sea surface temperature records from 1982 to 2017 registered a maximum regional increase of 2.4°C associated with an El Niño event. This is significantly lower than temperature anomalies experienced in coral regions towards



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Left: Porites colony on volcanic rock at Punta Tosca. Image: Raimundo Valenzuela Urgelles

Top: Coral at the Punta Tosca dive site. Image: Raimundo Valenzuela Urgelles

Above: A white-tip reef shark amongst volcanic boulders. Image: Raimundo Valenzuela Urgelles

the equator in the eastern tropical Pacific, which experienced anomalies up to 6°C. Importantly, it was much lower than the 7°C temperature fluctuations observed by the underwater temperature loggers. Therefore, the region is likely to have greater resistance to the level of temperature stress caused by El Niño.

The characteristics of the coral community can indicate its resistance to environmental change. The coral community at the Revillagigedo Archipelago hosts one of the most species-rich coral ecosystems in the ETP; half of these species are endemic to eastern tropical Pacific and one-third endemic to the Revillagigedo. If migrating larvae from other coral populations decrease, self-recruitment will become an increasingly important component of refugia. Fortunately, high levels of endemism at the Archipelago suggest significant self-recruitment.

On the other hand, the presence of the same coral species could indicate larval connectivity with the Central Pacific, other oceanic islands in the ETP, and with the coastal regions of mainland North and Central America. In the short-term, maintenance of a coral population through long-distance connectivity is unlikely. However, on a centennial to millennial time-frame, long-distance connectivity may assist with the migration and expansion of persistent coral species from the Revillagigedo Archipelago to other regions.

Coral bleaching events at the Revillagigedo Archipelago have not been well documented and, therefore, it is difficult to assess the resilience of the community to bleaching. However, during the 2015 to 2016 El Niño, divers observed bleaching ranging from zero to 70 percent around the islands. On dives the following year, no bleaching was observed and there was little evidence of coral mortality, suggesting the corals had recovered from the bleaching event.

Management and Learning Opportunities

The Revillagigedo Archipelago has many features indicative of refugia. The remote setting, large size and current management measures of the Revillagigedo Archipelago marine protected area minimizes human threats to the coral ecosystem. As such, the Archipelago is in a fortunate position where no further restrictive management interventions are needed to maintain the health and thus the capacity of refugia of the coral ecosystem.

Although the concept of climate refugia for coral reefs has been discussed for over two decades, there is still a paucity of direct evidence of which environmental and ecological conditions are optimal. There is an opportunity to recognize the Revillagigedo Archipelago as a globally significant research site, in which the conditions of refugia can be empirically investigated. By using this biogeographically important location, removed from direct human impacts such as land-derived pollution, over-fishing or other forms of disturbance and extraction, climate-specific impacts on the coral ecosystem may be more confidently isolated. This anticipatory and hands-on learning approach to defining climate refugia may then help inform the designation of coral-relevant marine protected areas elsewhere, and help guide management decisions on where reducing direct human impacts may pay the greatest long-term conservation dividends.

While it is important to acknowledge the uncertainties of future climate change and its impact on the processes and biological responses underlying coral reef refugia, identification of refugia sites will highlight conservation priorities that may support the persistence of coral ecosystems in the future.

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Properly managed coral reefs can yield an average of 15 tonnes of fish and other seafood per square kilometer each year.

Source: WWF

Chapter 5: Methods

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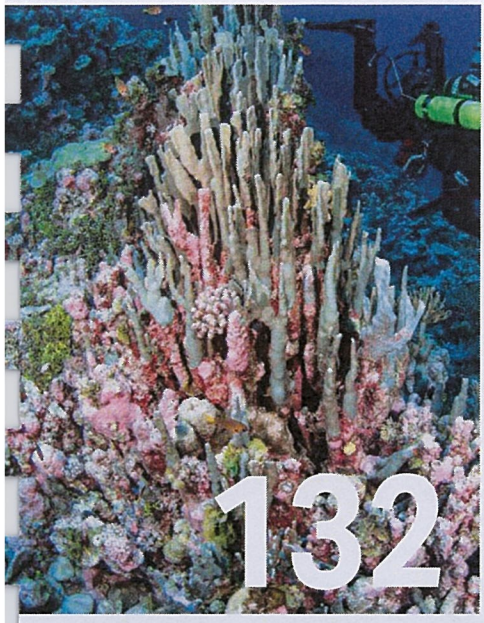
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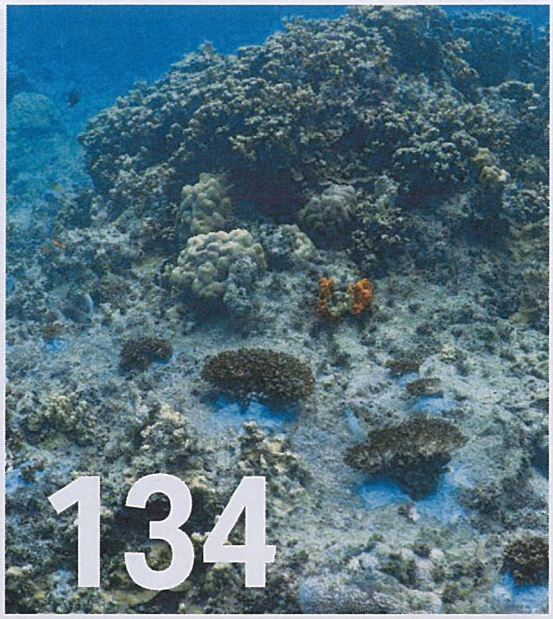
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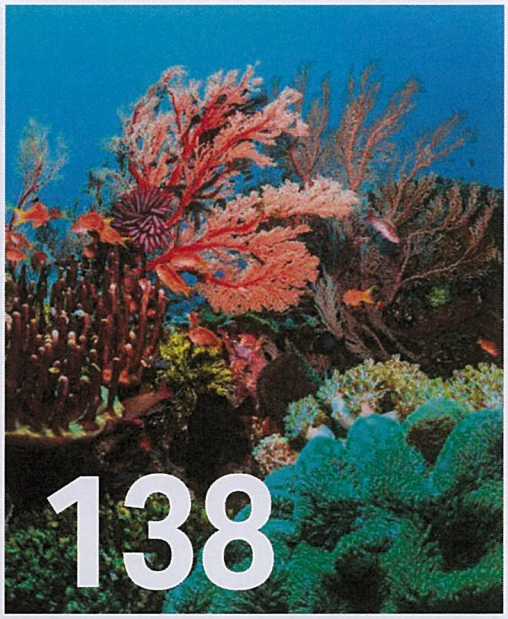
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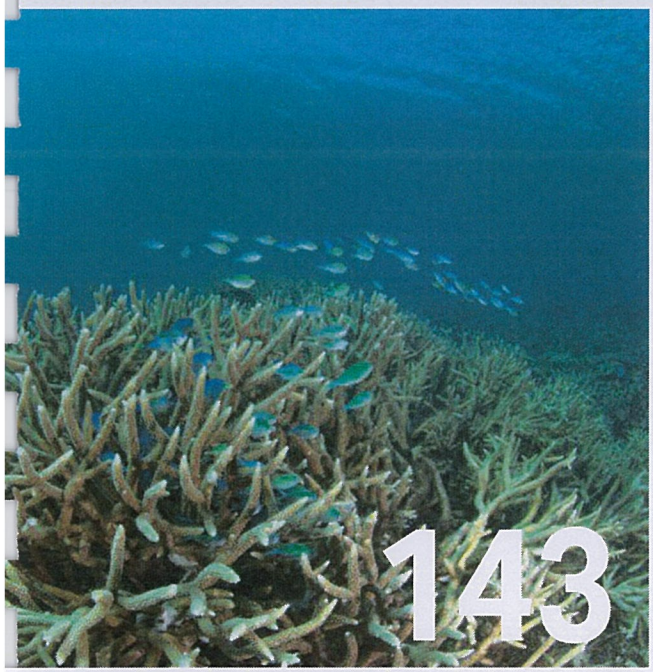
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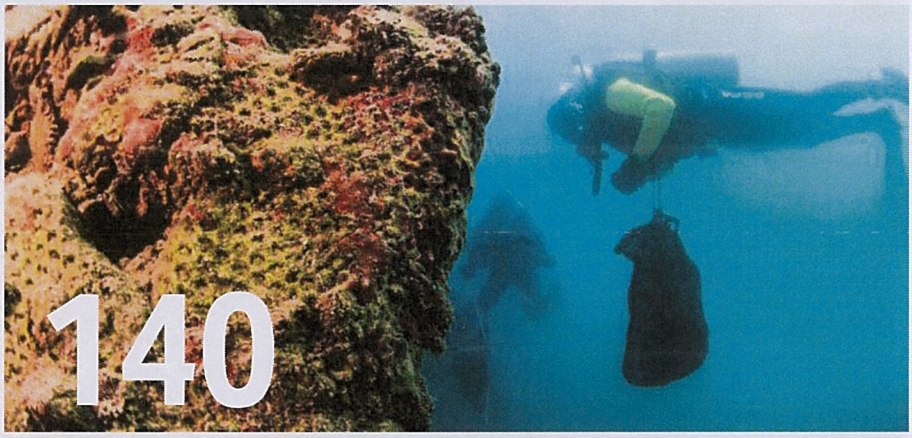
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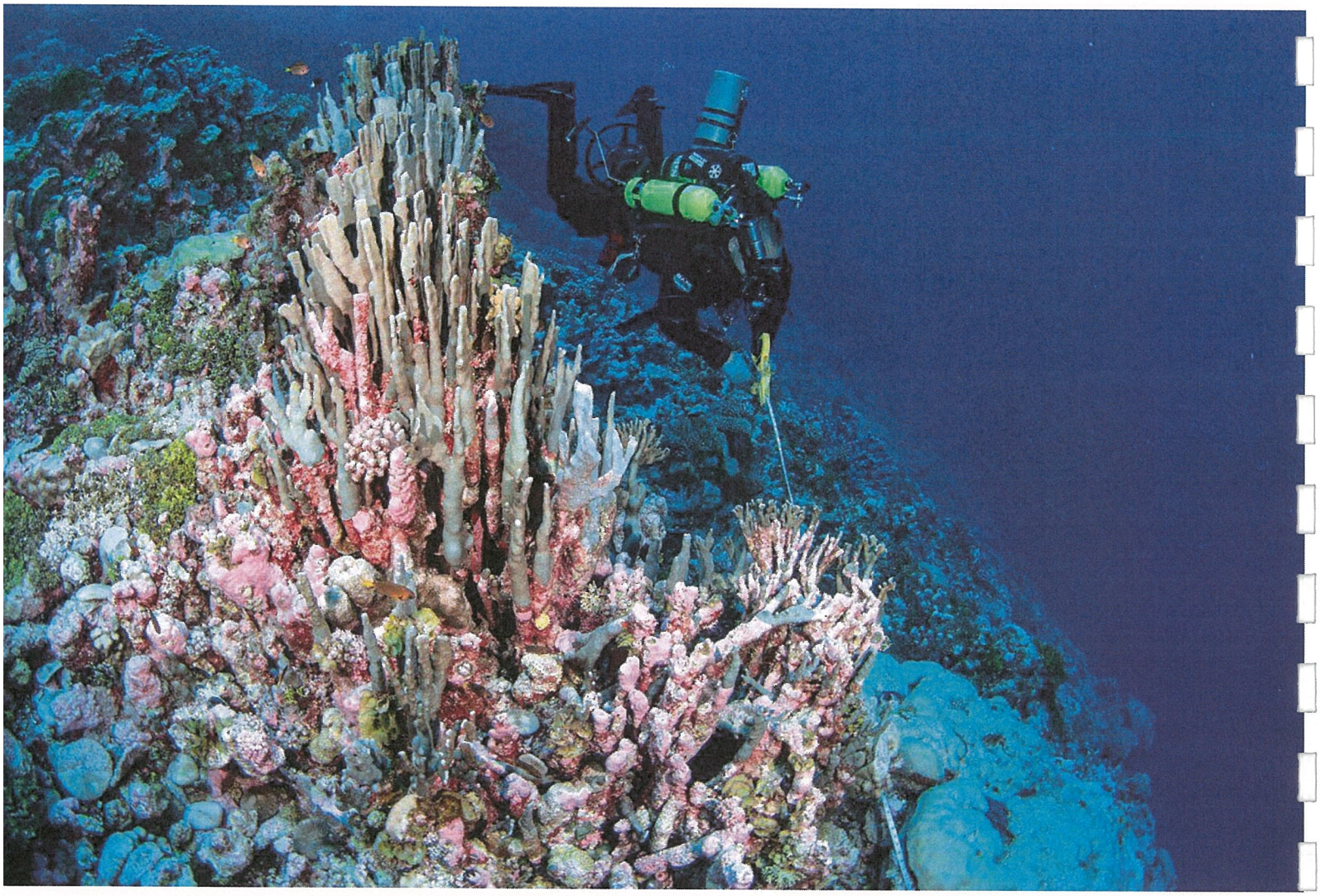

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All photos: Luiz Rocha © 2019 California Academy of Sciences

Surveying the Coral Reef Twilight Zone

By Tyler Phelps, AAUS Member

Fifteen minutes. That's all the time we have to collect our data at 500 feet (150 meters). Dressed like "aquanauts," we are some of the first divers to visit these deep coral reefs. With every breath, millions of inert gas molecules rush into our body's tissues. After documenting the habitat, conducting fish surveys, and collecting potential new species, we begin our ascent. It will take six hours of decompression before we are able to surface. Our team at the California Academy of Sciences is just one out of a handful of institutions in the world that uses scientific diving to conduct research in the "twilight zone."

Mesophotic coral ecosystems are sometimes referred to as the coral reef "twilight zone" that exists between 100 feet (30 meters) and 400 feet (120 meters). This mesophotic range is determined by the amount of intermediate ambient light, "meso" meaning middle and "photic" referring to light. Generally, coral reefs occupy only a 0.1 percent area in the ocean, yet they support 25 percent of all marine species on the planet. Since the mesophotic has only been explored by science in the last 25 years, many new species are still being discovered. Cameras, remotely operated vehicles (ROVs), and submersibles are capable of reaching these depths but are void of the human element. In many cases, human eyes can detect and identify species that cannot be seen through a pixelated screen or behind a viewing window. ROVs and submersibles can be costly to operate and may be loud or have bright lights that can deter marine life. Current robotics technology also does not have the dexterity and agility to effectively collect live fishes. If you are a fish biologist interested in studying these ecosystems, the best way is to dive there yourself.

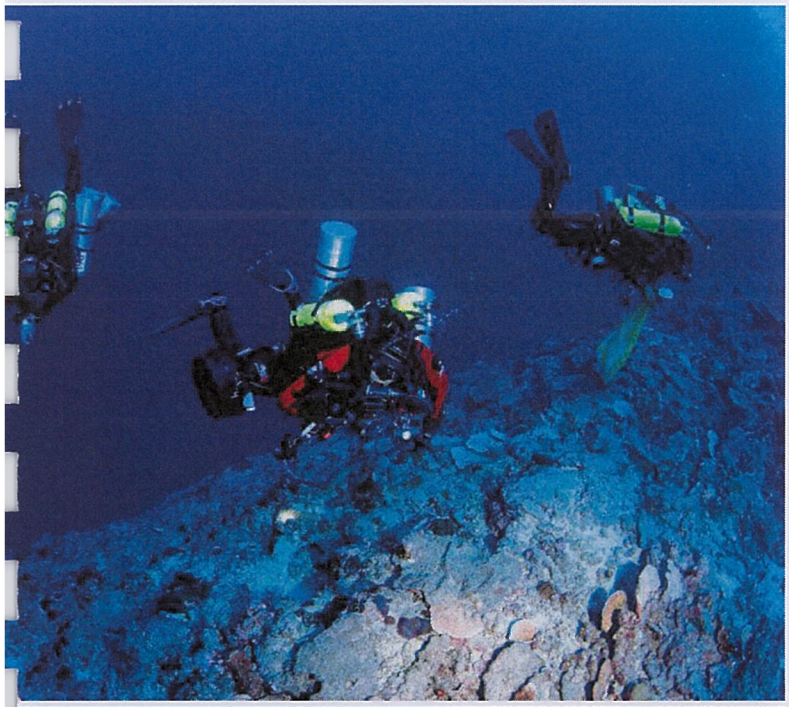
Diving to over 400 feet (120 meters) takes years of training and mental discipline since you are no longer able to swim directly to the surface if something goes wrong. It begins with strong fundamentals of traditional SCUBA diving practices. Our

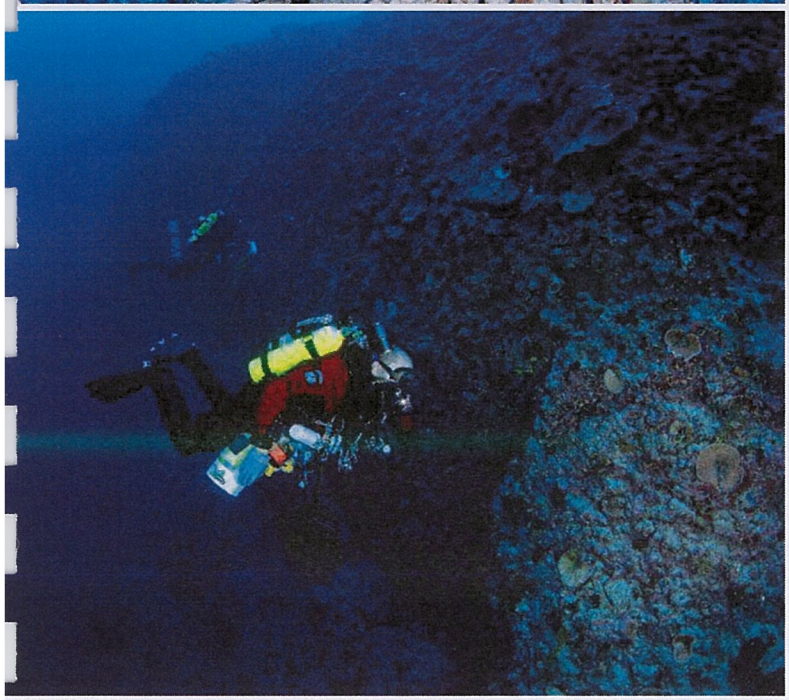
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team employs surveying methods with transect lines that are very similar to shallow scientific dives. By deploying a transect tape secured to bare substrate, we can count and size fishes directly in front of us to three feet (one meter) either side of the line until reaching a fixed distance, usually 65 feet (20 meters). After hundreds of dives practicing these techniques, scientists can pursue technical diver training to explore deeper than recreational limits (130 feet/40 meters).

There are two main branches of technical diving: open-circuit, think traditional SCUBA in which exhaled gas is lost as bubbles, and closed-circuit, which captures exhaled gas and recycles it through a carbon dioxide scrubber in the form of a rebreather. While modern rebreathers were being developed, they were considered "death machines" due to the number of fatalities, similar to when SCUBA was first pioneered. Nowadays, the technology has improved significantly and a rebreather diver's biggest threat is complacency, impatience and inattention. Due to their complexity, rebreathers require checklists to assemble and need heightened awareness while diving with them. To dive deep, high purity helium is needed to prevent an impaired "buzzed" feeling (or "narcosis") that is commonly associated with nitrogen from the normal air we breathe. A rebreather can be an expensive investment, but they use considerably less of the expensive helium than in open-circuit technical diving. In the long term, they can save money! Rebreathers offer additional physiological advantages such as having increased energy from higher oxygen pressure exposure and added safety by doing your decompression on the rebreather instead of switching gasses, which remains one of the deadliest parts of deep diving. These machines are also much quieter than open-circuit SCUBA and allow divers to get much closer to marine life.





Hundreds of hours are needed to build proficiency on a rebreather to progress to deeper depths and more advanced helium gas mixtures. Only then should additional task loading, such as collections and surveys, be attempted. Since few scientists can collect from these depths, many new species are still being found. Our team, led by Dr. Luiz Rocha (Curator of Ichthyology) at the Cal Academy, discovers an average of two new species for every hour of bottom time in the mesophotic. Using a "fish decompression chamber" that the Academy invented, some of these new species can be found on display at the Steinhart Aquarium's Twilight Zone exhibit in San Francisco, CA. After collecting or conducting surveys, we leave the bottom and continue to run transects while decompressing along our slow incremental ascent. The data we collect can offer insight to the community composition and ecology of fishes along depth gradients.

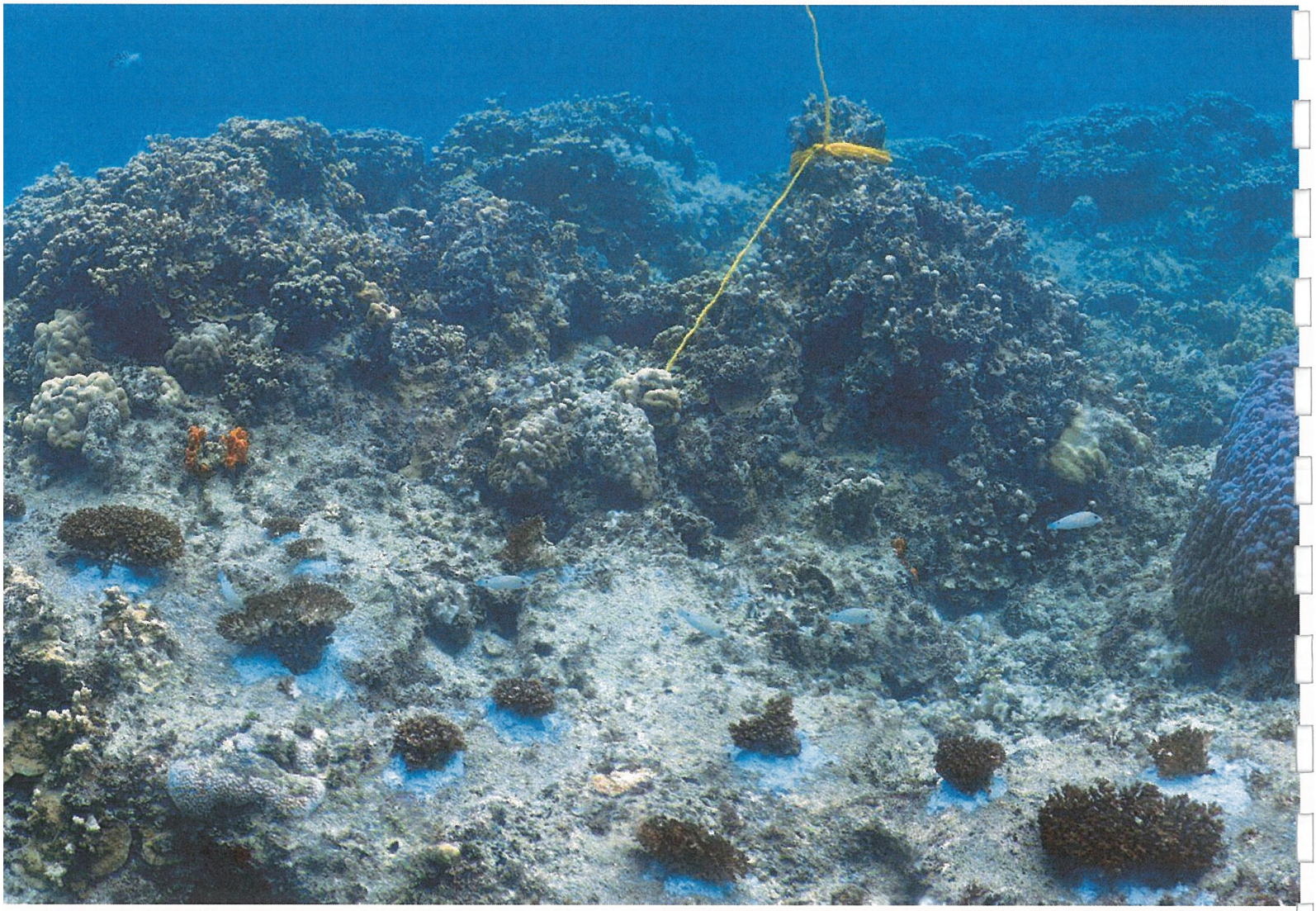
Within the scientific community, it has been hypothesized that mesophotic reefs may offer refuge to impacted shallow species. Assessing the hypothesis has mostly been done with baited camera stations, which can introduce bias due to bait attracting certain fishes from various depths. Arduous training and experience needed to survey mesophotic depths is selected by very few diving scientists in the world. In a 2018 paper published in *Science*, Dr. Rocha and our colleagues found virtually no overlap in species from shallow reefs to mesophotic depths, indicating a low potential for refugia. Furthermore, we have found evidence of human and natural impacts such as various forms of trash and sedimentation from storm events covering deep reefs. Although we cannot easily see these mesophotic reefs, they are not without impact and deserve protection.

For more information about our research, please visit: https://www.calacademy.org/exhibits/twilight-zone

Relocating Corals in Guam

A team of experts successfully complete an important coral relocation effort in Guam prior to the COVID-19 outbreak

By Keith Spring, CSA Ocean Sciences Inc.



Coral relocation and physical reef rehabilitation programs have been undertaken at various locations around the world over the past 30 years, and with varying levels of success. These projects have been associated with both large and small vessel groundings on coral reefs; ship channel and harbor dredging activities; pipeline corridor dredging related to oil and gas operations, electric power plants, and desalination facilities; seawall and bulkhead repairs; resort developments; and other nearshore construction projects. Early coral relocation and reef rehabilitation projects were conducted primarily as mitigation for direct reef damages caused by vessel groundings or marine construction and dredging impacts. These intervention measures involved the stabilization of fractured reef substrate along with the salvage and reattachment of detached and often heavily damaged coral colonies.

In many cases, the salvaged corals were heavily abraded, fractured, or partially dead, resulting in low colony survival after project completion. As with any new procedure, techniques were gradually improved and protocols were developed

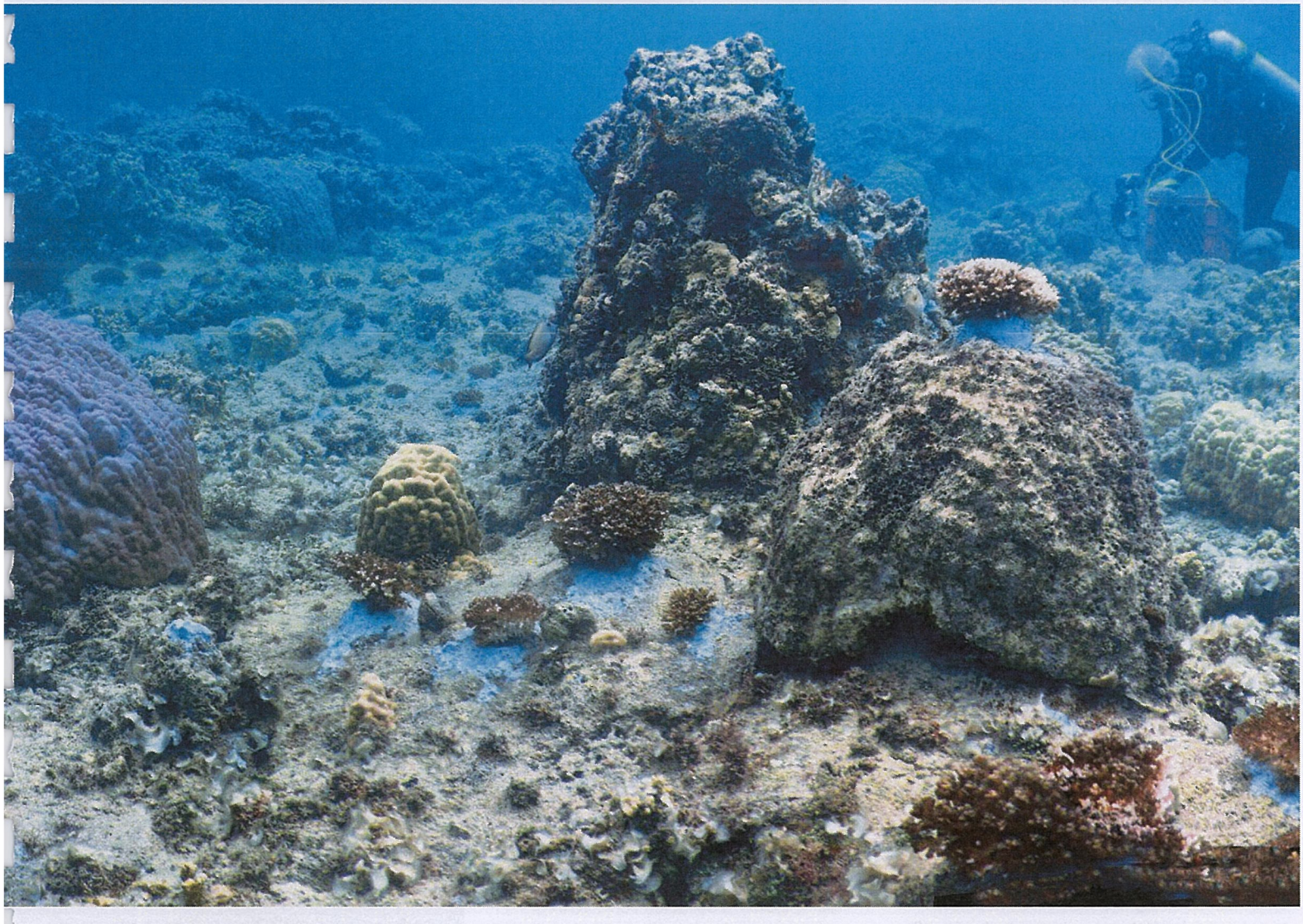
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A 3D rendering of one of the deeper water reattachment sites.

Panoramic view of the shallow coral reattachment area with reattached colonies of Pocillopora damicornis scattered across the foreground. For scale, the large lavender colony of Porites lutea is about 1 meter in diameter.



to standardize the process and improve coral survival rates.

Coral relocation success depends upon several factors including the species and specimen selection process, initial health and condition of the donor coral colonies, collection and attachment techniques and handling of the colonies before and during reattachment, skill of field personnel, and the overall water quality and physical site conditions at the recipient areas. In all situations, careful advance planning is necessary to optimize project success. This has resulted in coral survival rates of greater than 90 percent on many of the more recent properly designed and implemented projects.

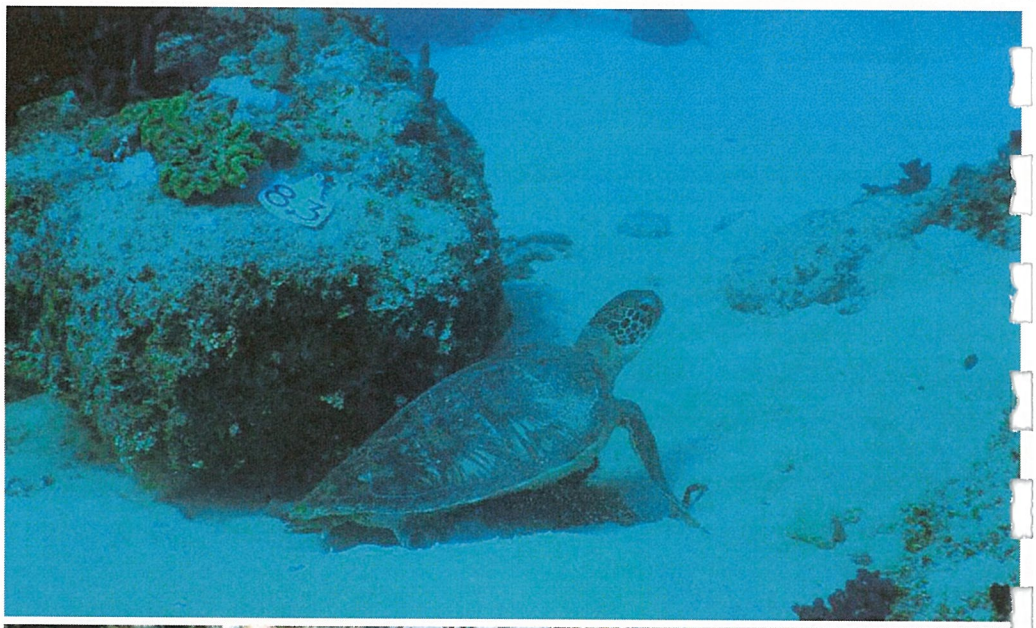
CSA Ocean Sciences Inc. (CSA) marine scientists have long been directly involved in marine habitat mitigation, completing more than 200 marine habitat restoration projects over 40 years. These include more than 65 specific coral relocation and reef rehabilitation projects worldwide over the past 26 years in Florida, Hawaii, Puerto Rico, Guam, Rota, Tinian, Saipan, the Bahamas, Turks and Caicos Islands, Qatar, Kingdom of Saudi Arabia, and Oman. During these

projects, tens of thousands of corals have been relocated and reattached, including 111 species of hard corals and 25 species of soft corals and octocorals. During these efforts, CSA staff have developed and field tested coral relocation and reattachment techniques on projects ranging in size from just a few corals to more than 12,000 colonies.

CSA scientists recently completed a coral relocation project for the Port Authority of Guam (PAG). Funded by the USDOT Maritime Administration (MARAD), this critical component of the PAG's Hotel Wharf Rehabilitation and Access Roadway Repair Project was completed immediately before the COVID-19 pandemic brought most of the world to a screeching halt in March of this year. Mitigation activities had to be completed before the initiation of significant repairs to Hotel Wharf in Apra Harbor, scheduled for the summer of 2020. The repairs to the wharf, which is located along the northern side of the harbor, include the construction of a new sheet pile retaining wall outside of the existing bulkhead that would cover existing corals and other marine biota colonizing the structure. As part of the mitigation for the project, CSA was retained by WSP USA Inc. (WSP) to conduct an initial assessment of the wharf face and seafloor adjacent to the wharf. This involved locating potential reattachment sites for corals that were removed from the wharf face and adjacent seafloor. Once a suitable site was found, the team could detach all healthy coral colonies from areas likely to be impacted by the project, reattaching them at the identified recipient sites.

Three weeks before the Hotel Wharf project start date, COVID-19 was threatening to postpone the project entirely. With an experienced scientific diving team already on the ground—and ready to mobilize—the CSA field team approached the Port Authority with a solution that could prevent an indeterminate delay to their construction schedule. With the COVID-19 pandemic looming, but yet to directly impact Guam, we were able to accelerate the coral relocation project schedule. This required the immediate coordination between the PAG and WSP with their environmental subconsultant Duenas, Camacho and Associates, Inc. (DCA), and CSA staff. Concurrent with the PAG and WSP expedited review and acceptance of plans, CSA mobilized additional equipment and supplies, coordinated with their dive support subcontractor, and initiated the project two weeks earlier than planned.

The CSA team included experienced





A small hawksbill sea turtle (Eretmochelys imbricata) *alongside one of the deeper coral reattachment sites. Tagged coral #83 is a colony of* Lobophyllia hemprichii.

A reattached colony of the relatively uncommon species Lobophyllia hataii.

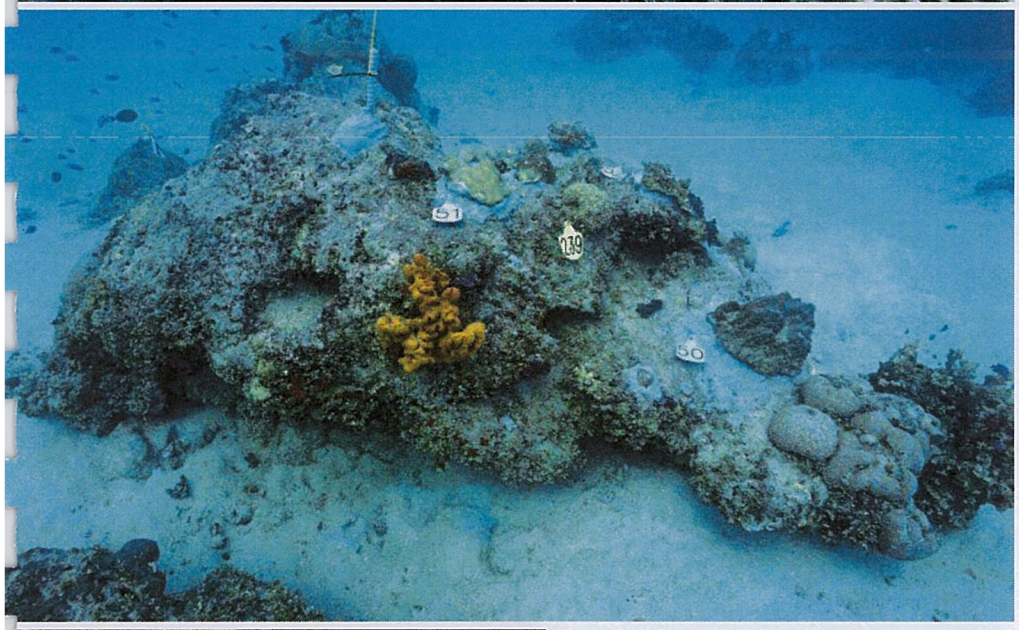
Raising crates of collected corals to the surface for transport to the reattachment site.

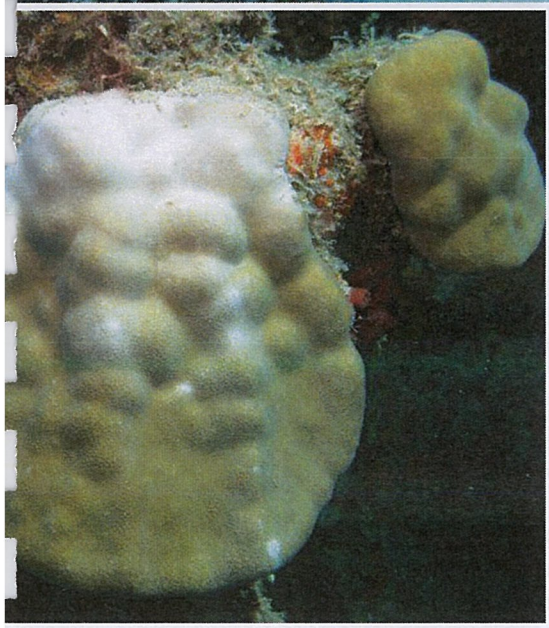


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A pair of nudibranchs (Hypselodoris tryoni) *at the coral reattachment site.*

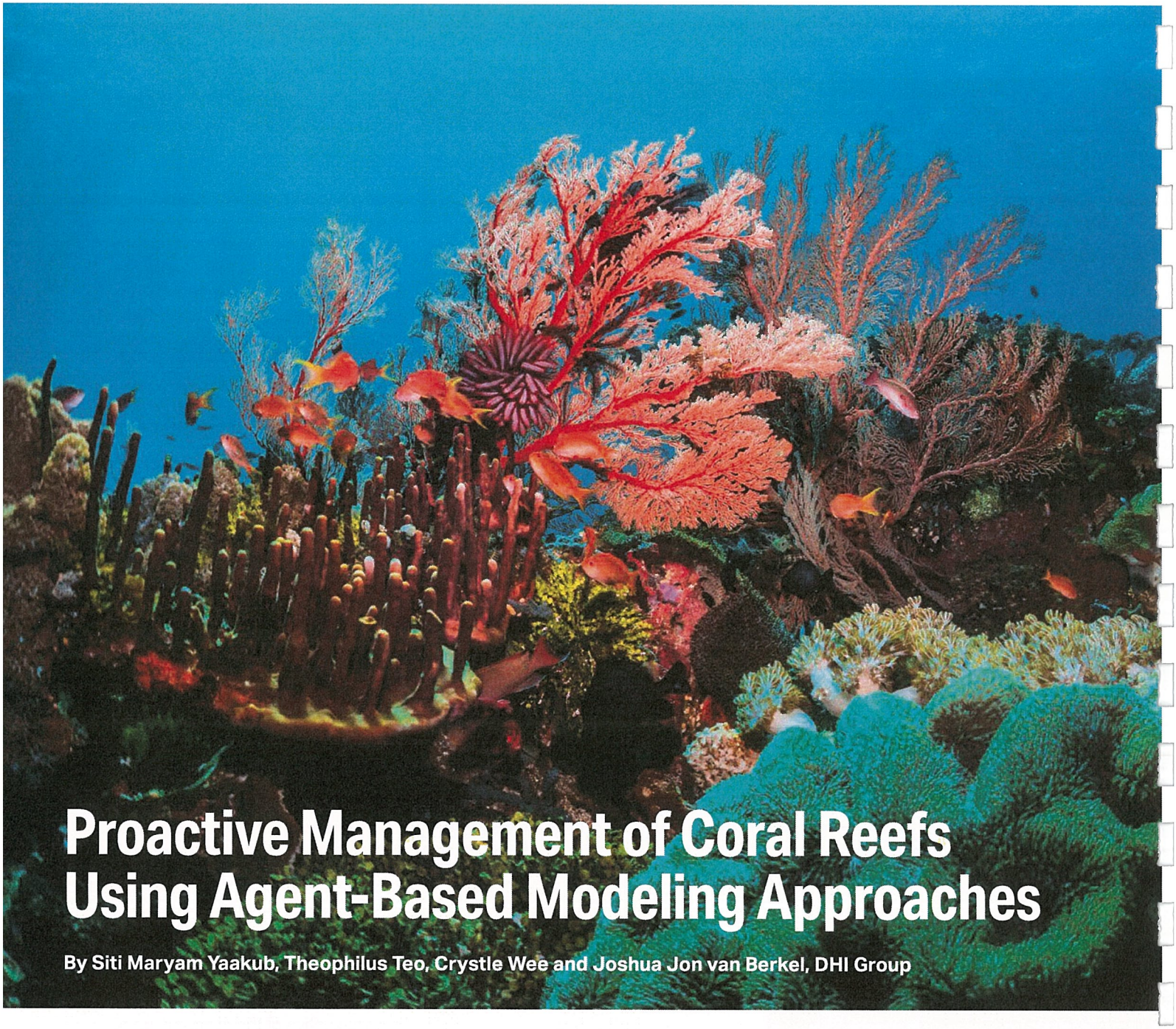
One of the deeper water coral reattachment sites with tagged reattached (light blue tags) and reference corals (yellow tags).

Two colonies of the coral species Porites lobata *prior to being detached from the face of Hotel Wharf.*

marine scientists Keith Spring, David Snyder, Jeffery Landgraf, and Chip Baumberger, along with Victor Bonito, a coral expert and the director of Reef Explorer, Fiji. During the first day of operations, the team completed the initial wharf assessment and identified several slightly degraded reef areas to the west of the wharf that was expansive enough to contain the relocated coral colonies. Nearly 600 relatively healthy stony corals ranging in size from ten centimeters up to 75 centimeters diameter, and comprising at least 30 species, were carefully removed from the wharf face and from adjacent man-made debris at the base of the wharf. They were placed in plastic crates and transported to the reattachment areas over three days. The relocated corals included six individuals of the species *Lobophyllia hataii*, relatively rare within Apra Harbor, as well as several octocoral sea whips and elephant ear sponges (*Ianthella basta*). Water depths at the reattachment areas ranged from approximately two meters near the reef crest down to 12 meters at the base of the reef slope, similar to the coral collection depth range on the wharf.

CSA staff reattached the corals to areas of exposed reef substrate using a hydraulic cement and sand mixture, avoiding damage to adjacent healthy coral colonies and mimicking the densities and orientations of naturally occurring corals. Following the completion of the coral reattachment, CSA scientists tagged and mapped the specific locations of a representative subset of the corals for subsequent survival monitoring and completed a baseline health assessment survey. Monitored coral colonies included an experimental group of 132 relocated corals and 101 reference corals. Reference corals were selected based on health conditions, proximity to the reattachment site, and representative of the relocated coral species. As part of the permit conditions for the mitigation effort, CSA staff will return to conduct additional coral health and survival monitoring at 6 months, 18 months, and 36 months post-relocation.

Due to the rapid coordination and cooperation between PAG, WSP, DCA, and CSA, the team was able to transform what could have been a major delay to the Port's refurbishment schedule into a successfully completed coral relocation project. This will allow commencement of the Hotel Wharf refurbishment without delay. After completing the project, all CSA staff were able to return safely home and undertook quarantine with no adverse health effects.



Proactive Management of Coral Reefs Using Agent-Based Modeling Approaches

By Siti Maryam Yaakub, Theophilus Teo, Crystle Wee and Joshua Jon van Berkel, DHI Group

Globally, coral reefs are at widespread risk from anthropogenic disturbances at local and regional scales. As coastal construction increases and global temperatures rise, an estimated 33 percent of coral reefs are now in danger of extinction (Source: Natural History Museum). Coral reefs in nearshore coastal waters are particularly susceptible to degradation due to local pressures and stressors from coastal development and maritime activities.

Such unacceptable impacts can, however, be managed via processes such as integrated coastal management and Environmental Impact Assessments (EIA). In these processes, it is important to not only identify direct impacts (e.g. from habitat loss), but also indirect and cumulative impacts. For example, a waterfront development that involves reclaiming a small part of an adjacent fringing reef directly results in the loss of reef habitat. This construction can then alter local hydrodynamics and morphology (e.g. erosion and sedimentation). The resulting change in hydrodynamics can further disrupt connectivity between the impacted reef and neighboring reefs, ultimately affecting ecological processes such as recruitment and genetic exchange.

To better understand these dynamics, DHI developed a numerical agent-based model (ABM), capable of realistically simulating the movement and dispersal of coral larvae. ABM is an alternative bottom-up population model where the focus is on the individual, referred to as an agent. ABM allows fundamental traits of the agents to be modeled at random, which allows room for trait variance between individuals. When coupled with a hydrodynamic model, the agents within the model domain can respond to input such as water temperature or flow velocities. This makes it possible to analyze the potential effects of hydraulic and environmental cues on the movement of aquatic organisms on a complex spatial scale over time.

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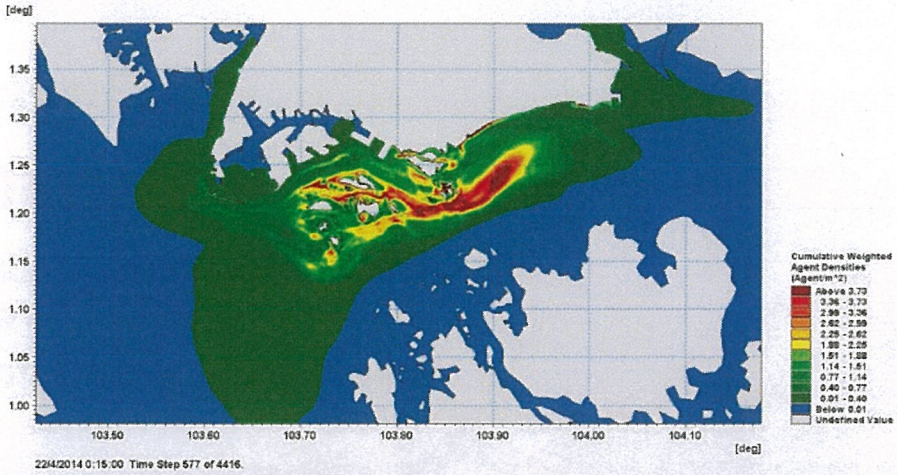
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DHI's coral larvae ABM developed in the MIKE ECO Lab module and coupled with MIKE 21/3, describes how these larvae interact with the surrounding hydrodynamic environment as well as mortality, competency, settling behavior and movement in the water column for both the zygote and larval stages of hard corals. The parameters that drive these processes are based on biological and experimental evidence from peer-reviewed studies (Gleason and Hofmann, 2011; Slattery et al., 2011; Tay et al., 2011) which increases the robustness and ability of the model to simulate real life situations.

The coral larvae ABM can be used in various situations ranging from simulating impacts from coastal developments to the management and planning of marine parks and reserves. These ABM simulations are also capable of numerically predicting the source-sink dynamics between coral reefs to aid in restoration initiatives such as site selection and optimizing the placement of artificial reef structures. When used in tandem with other restoration practices, ABM simulations can greatly enhance the likelihood of success in selecting sites prime for receiving these coral recruits (see Box).

Similar ABMs have been developed in MIKE ECO Lab for other marine habitats such as mangroves and seagrass meadows, making the software an ideal solution for understanding connectivity within and between different habitats. Ultimately, its use supports a proactive and total marine ecosystem approach to managing marine protected areas and reserves.

For more information on the coral larvae ABM or MIKE ECO Lab, please visit www.dhigroup.com.

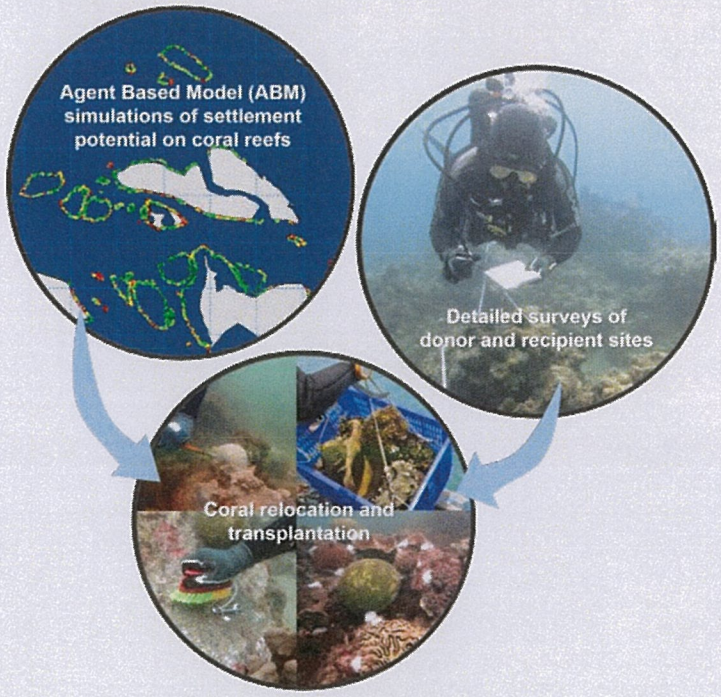


A snapshot from an agent-based model (ABM) of coral larvae transport simulated using the MIKE ECO Lab module in MIKE 3, a hydrodynamic software by DHI. © DHI

Quantifying Changes in Settlement Diversity

Changes to the transport and dispersal of coral larvae as a result of development can be simulated using ABM. These models allow the quantification of changes in settlement density at source and sink reefs, highlighting any major negative trends in overall connectivity. Analyses of source sink dynamics for individual reefs provides an indication of the impact the loss of a single reef can have on the recruitment dynamics for the area.

Another useful output is the generation of a settlement density map which highlights areas that receive a high density of coral recruits. These maps can then be coupled with detailed surveys along coral reefs to quantify benthic composition including live coral cover and diversity. This information can be used to determine which sites are most suitable for coral transplantation to maximize the survivability and success rates of transplanted colonies and new coral recruits. A multi-disciplinary approach such as this also promotes maintenance of dispersal and transport pathways for continued genetic connectivity and diversity.



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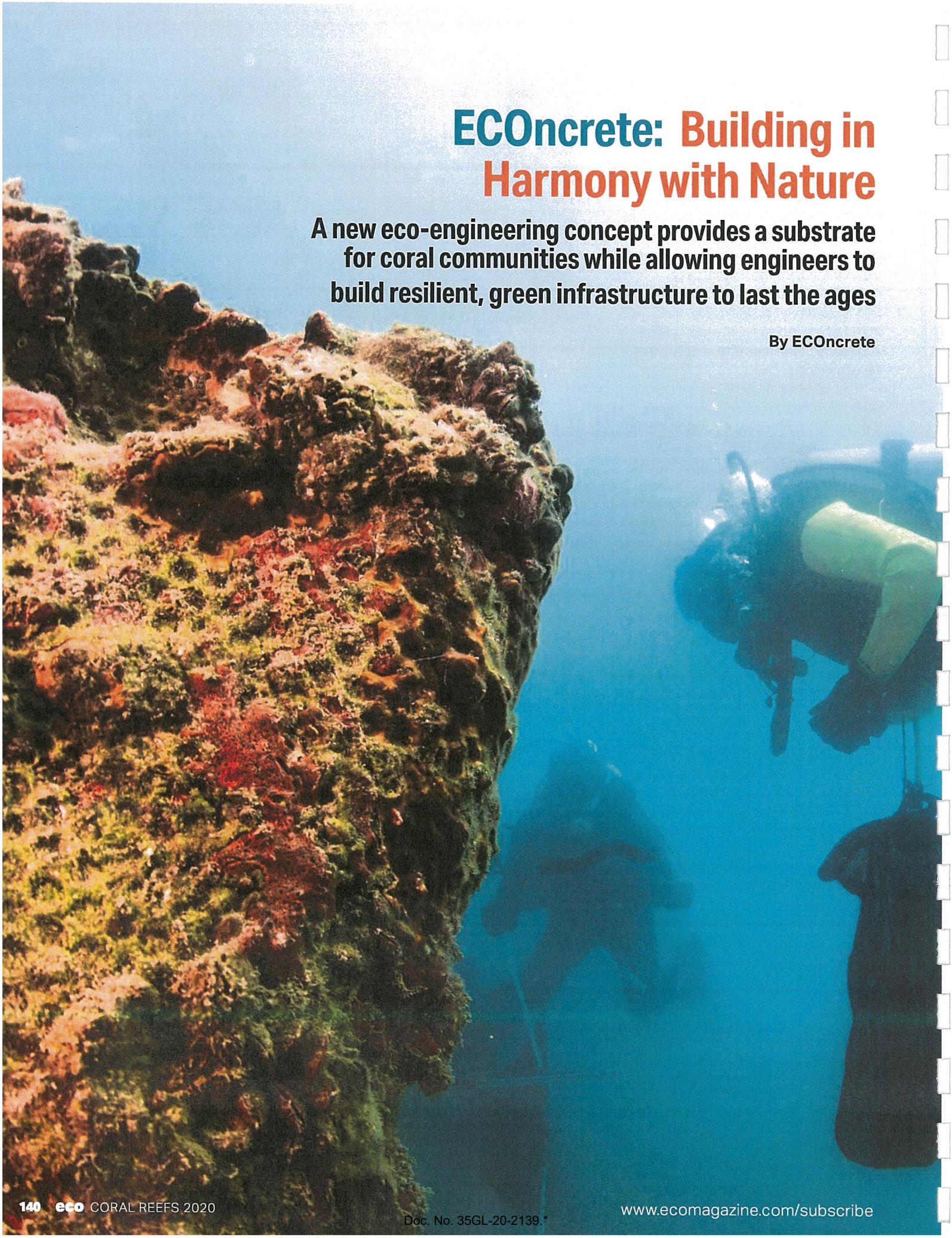
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ECOncrete: Building in Harmony with Nature

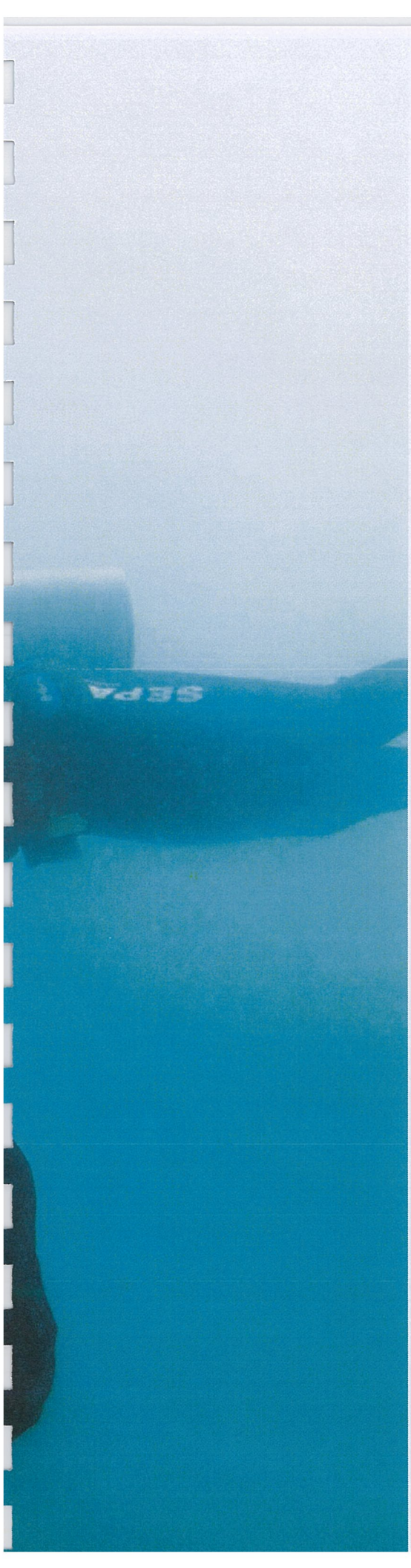
A new eco-engineering concept provides a substrate for coral communities while allowing engineers to build resilient, green infrastructure to last the ages

By ECOncrete



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By harnessing natural processes, ECOncrete is leading the world in high performance, environmentally sensitive concrete products for coastal and marine infrastructure. Benefiting both the environment and marine structures, our bio-enhancing solutions reduce the ecological footprint of ports, coastal defense schemes, urban waterfronts, mooring systems and offshore energy facilities. The integration of innovative eco-engineering technologies allows decision-makers, engineers, contractors and landscape architects to build in harmony with nature.

ECOncrete's products are manufactured using patented bio-enhancing concrete admixtures with tailormade forms and form liners. By encouraging natural colonization of marine communities, such as the growth of oysters, corals and tube worms, ECOncrete technologies help structures become stronger, have a longer service life and better cope with extreme weather events and rising seas. These organisms also act as an active carbon sink, offsetting some of the large carbon footprint associated with the concrete industry.

ECOncrete's unique multidisciplinary team of marine ecologists, biologists, geologists, concrete experts, engineers, and designers are working to bridge development and sustainability to increase ocean health and resilience.

Through these innovative solutions, ECOncrete is changing the way our future coastlines look and function by harnessing natural processes for the benefit of the local ecosystem, and for the benefit of coastal and marine infrastructure. Our ECO Armor units, Enhanced Seawalls, Tide Pool Armor designs, Marine Mattresses and ECO Pile Encasement technologies, replace the barren "grey" urban coastlines and waterfronts with high performance, resilient, and blue-green infrastructure. In 2018, our Tide Pool Armor won the "Global Biomimicry Design Challenge." In 2019, ECOncrete was selected as one of "TIME Magazine" 100 best inventions.

Our mission is to keep innovating and provide our clients with cutting edge solutions tailored for their structural needs, and for the needs of the local ecosystems.

Especially in these difficult times of the COVID-19 pandemic, we all need to take concrete action and reset nature. It's time to make a change and set new environmental standards for coastal and marine construction that allows marine life to thrive, using nature-based solutions and ecological engineering.

Let's work with nature, for humanity and the environment.



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Putting the 'Great' Back into the Great Barrier Reef

By Mary Jo Wagner

Long thought to be "too big to fail," the Great Barrier Reef (GBR) is under serious threat and its outlook is dire.

One of the latest victims of global warming, a published study in April 2019 revealed that baby coral in Australia's GBR have declined by 89 percent due to deadly ocean heat waves and mass bleaching in 2016 and 2017. And the ability for adult coral in the northern regions of the GBR to recover from bleaching events dropped by 93 percent—dead coral can't make new baby coral.

Further loudening the climate crisis alarm, the Australian government last August officially downgraded the health of the GBR's ecosystem from poor to very poor, publicly affirming what marine scientists already know: parts of the GBR, which has supported marine life for centuries, is now itself on life support.

"The reef is definitely not as healthy as it was 20 years ago and the mass bleaching effects, particularly in the last five years, have had severe impacts," says Dr. Chris Roelfsema, a researcher and lecturer in the Remote Sensing Research Centre, School of Earth and Environmental Sciences at Brisbane's Queensland University. "We've been witnessing this decline from our research and fieldwork and there is no doubt that climate change is the culprit. There is still a lot of life along the GBR so I won't declare that it's dead but it is absolutely threatened and the coral, which is the support system for thousands of species, is under serious stress."

The Need for Maps

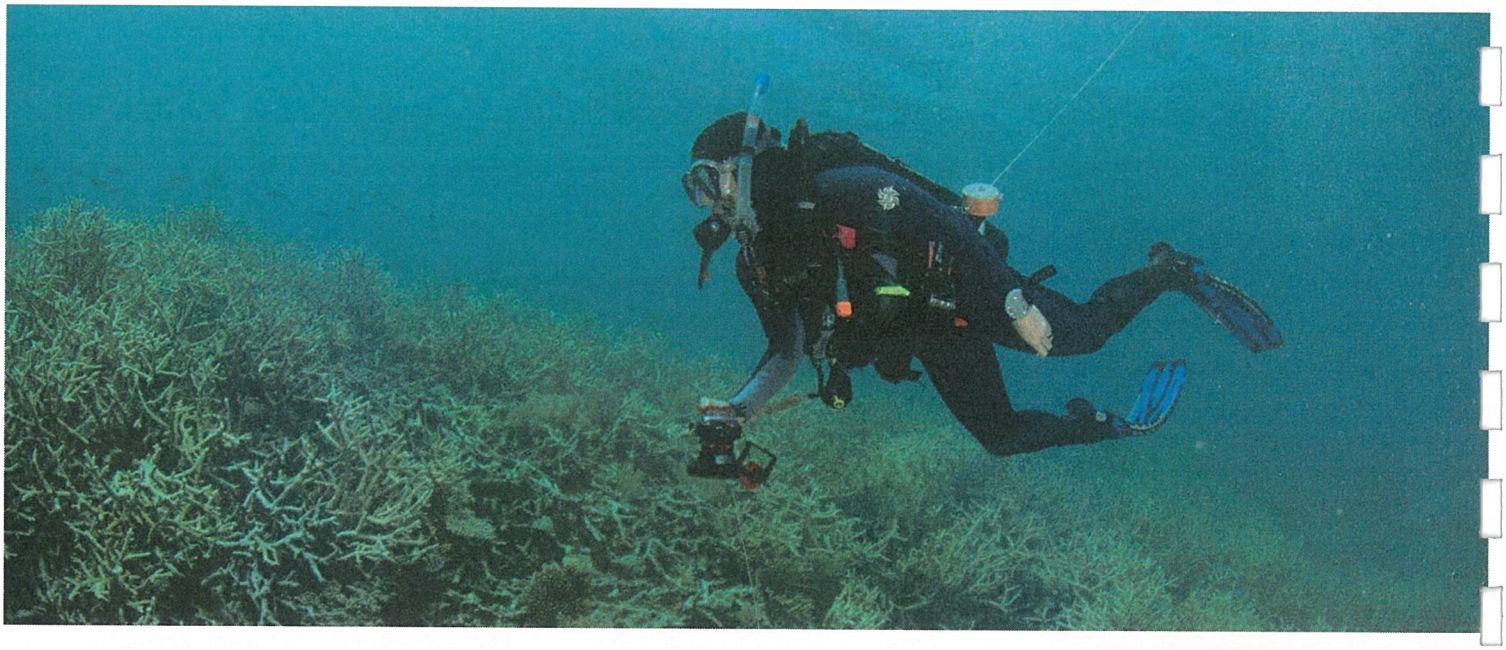
The challenge to help conserve the world's largest coral reef has been due in part to the lack of a complete map of the GBR's topography, its habitat communities and different coral types. Without the big picture of a comprehensive map of the entire ecosystem, it has been difficult to dive under the surface to better understand the GBR's life, monitor it and develop protective strategies.

A new mapping technique, however, may help scientists turn the tide. A project team led by Roelfsema combined satellite imagery, object-based image analysis (OBIA) software, coral knowledge and field data to successfully produce the world's first-ever topographic map of the GBR's 2,900 reefs. With this new mapping approach, scientists can now not only better understand where coral and specific habitat types are likely living, they'll have the tools to start charting a path towards rescue, restoration and resilience.

Mapping Issues

Roughly the same area as Italy, the GBR stretches approximately 2,300 kilometers along the coast of Queensland in northeastern Australia. That's about the same length as the west coast of North America, from Vancouver, Canada to the Mexican border. A World Heritage Site, the GBR composes 2,900 individual coral reefs, 600 continental islands, 300 coral cays and about 150 inshore mangrove islands. Its intricate architecture provides a home for thousands of different species including jellyfish, mollusks,

Acropora species, or branching coral, growing 12 cm per year on Heron, Southern Great Barrier Reef (source: C.Roelfsema 2019)



fish, sharks, rays, whales, dolphins and microorganisms. According to the Great Barrier Reef Foundation, the GBR is valued at A$56 billion, contributes more than A$6.4 billion each year to the Australian economy and supports around 70,000 jobs.

Despite its significance, no systematic mapping program exists for the GBR. There is no current and comprehensive map of the individual GBR's geomorphology (topography) or benthic composition (reef bottom flora and fauna), and the full extent of its coral habitat is not well mapped. To date, the highest quality overview map of the GBR is a 10-year-old coral reef map produced from Landsat imagery showing the outline of each reef. Although that map shows the locations of the GBR's reefs, it doesn't provide the thematic detail, accuracy or ecosystem depth scientists need for their work.

Underwater surveys provide meticulous records of the health and biodiversity of coral reefs, but they are costly, time intensive and only provide a narrow extent—characterizing a coral habitat of 500 square meters (about the area of two tennis courts) takes a 30-minute dive. With that method, mapping the GBR's 28-square-kilometer Heron Island would take three years of continuous diving.

What scientists have needed is a map that marries detail and large-area coverage.

Mapping Solution

With the help of higher resolution satellites, the availability of ancillary water data, the sophistication of intelligent OBIA tools, the improvements in machine learning and advancements in computing power, Roelfsema has been able to produce exactly that. Fulfilling a 20-year-long vision, he's combined these tools to develop a semi-automated approach to mapping the geomorphology of shallow GBR reefs and their benthic communities over a large scale. It's a crucial first step in helping scientists and conservationists to answer a multitude of questions about the world's largest coral reef ecosystem.

"Mapping the geomorphic zones and reef habitats helps us understand how the GBR as a whole is functioning," says Roelfsema. "We can see how it's growing, where it's growing and when it stops growing. We can see the composition of the reef structure and begin to assess benthic types. That foundational understanding can help identify at-risk zones and lead to better management of the GBR. It's insight we've never had before."

A Development in Waves

Since 2007, Roelfsema has been experimenting with satellite data and Trimble eCognition OBIA software to develop a scalable, coral reef mapping approach.

In 2016, he led a pilot project using eCognition technology to produce geomorphic zonation and benthic composition maps of 20 reefs covering a 250-square-kilometer area in the southernmost section of the GBR.

The success and promise of that study led to funding in 2017 to expand the technique across 237 reefs in Cairns/Cooktown (CC), a group of northern GBR reefs about 10 to 50 kilometers offshore that are in dire condition. Similar to the pilot, their aim was to classify and map the geomorphology, benthic types and coral types of these shallow reefs using similar data sources and the previously established eCognition rules. Although this would push the technique into uncharted territory, Roelfsema was confident in the software's ability.

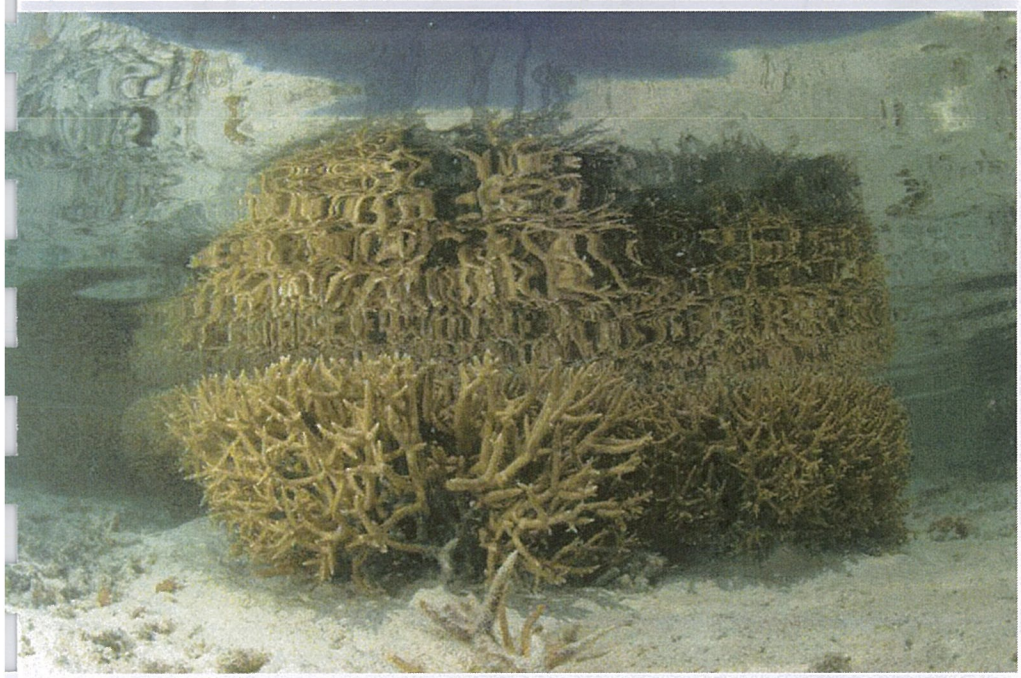
"The power of the software is that you can turn your knowledge into rules that it'll strictly follow," he says. "We can tell it all that we know about coral, reefs, slopes, waves and benthic communities and it uses those biophysical properties, pixel characteristics and spatial relationships together to classify features. Unique and special to eCognition is its 'cognitive analysis.' Similar to how our brain identifies objects, when the software classifies an object it not only considers its color or texture but also its spatial relationship to neighboring objects. Adding that relationship analysis layer greatly strengthens the classification."

Unlike in the pilot, Roelfsema's team had little first-hand knowledge of the

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From Left Clockwise:

Dr. Eva Kovacs collects a photo validation data survey within a 1m2 footprint along the GBR. At the surface, she tows a GPS unit to track her position. (source: C.Roelfsema 2019).

Encrusting and table corals on reef slope Heron Reef, Southern Great Barrier Reef(source: C.Roelfsema 2019)

Branching coral just underwater surface captured on the reef flat of Heron Reef, Southern Great Barrier Reef Australia (source: C.Roelfsema 2019)

237 CC reefs. To collect field data, they performed dive surveys of 23 individual reefs. They recorded the topography, benthic and substrate compositions, and took thousands of geolocated photos at regular intervals while towing a GPS device at the surface. The georeferenced photos were processed into meaningful information about each reef's benthic communities.

They acquired three, 30-meter-resolution Landsat 8 Operational Land Imager (OLI) images to cover the 3,000-square-kilometer area of interest (AOI). A third party used pan-sharpening techniques to create a 15-meter seamless mosaic of the images. Using a physics-based algorithm they derived water depth, slope and wave values. Roelfsema also supplemented his own field survey data with attribute data gathered from other citizen science projects.

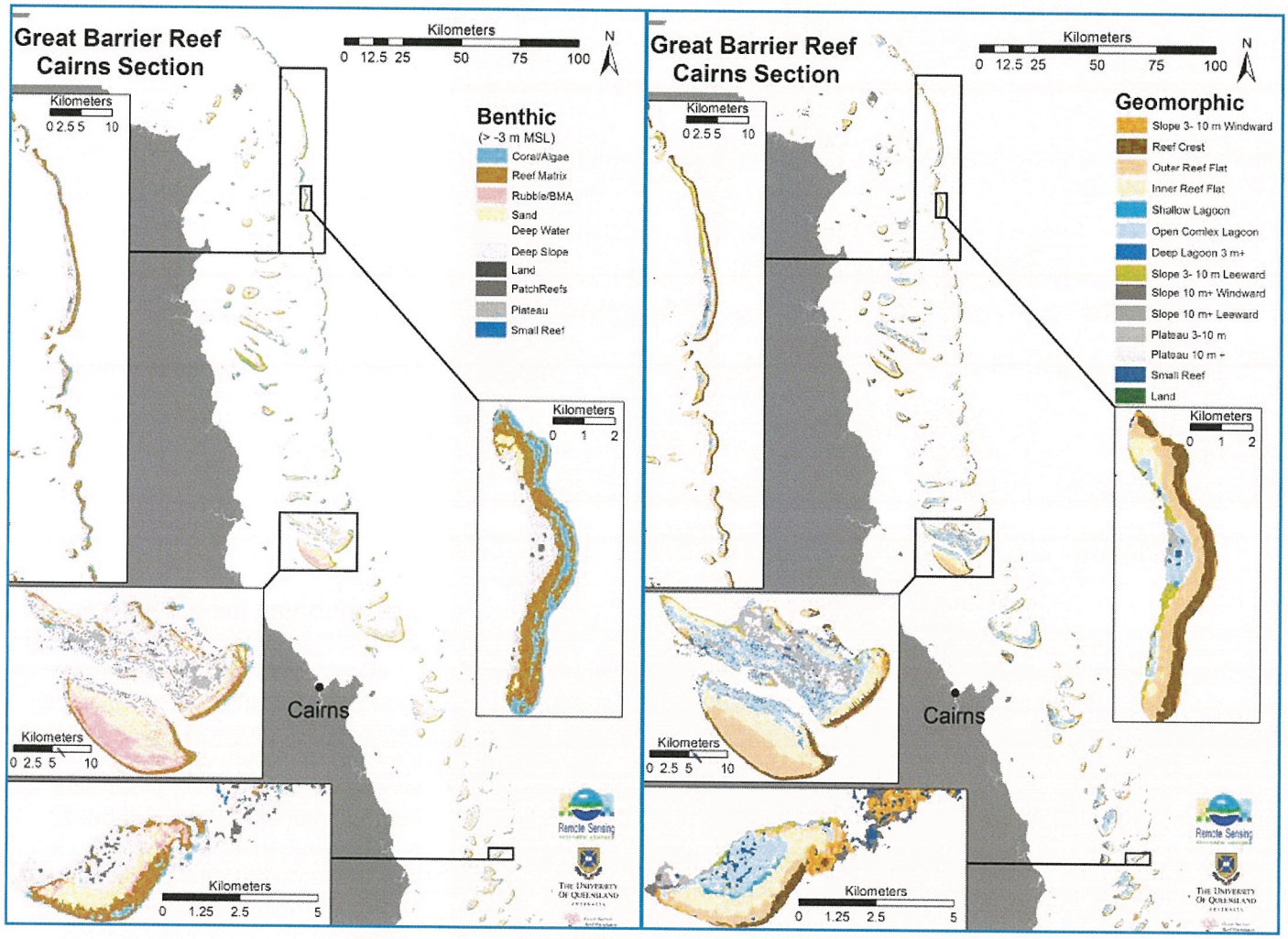
With the input data sources prepared, Roelfsema readied the OBIA technology, customizing the previously developed eCognition rule sets for the 237 specific CC reefs.

"Once you have master rule sets, adjusting them is a simple exercise," says Roelfsema. "It's another advantage of OBIA. It's flexible, it's easily scaled and it's easily repeatable."

Distinguishing the Underwater Jungle

eCognition first concentrates on classifying geomorphic zones. Methodically moving from one reef to the next, it analyzes the depth values of the image mosaic and distinguishes reefs from non-reefs—any feature above 20 meters is reef—to create a reef map. It then differentiates between the shallow reef top (above three meters) and not reef top. Within the identified reef top, it classifies shallow geomorphic zones such as reef crest, inner reef flat, outer reef flat and lagoon. Then for the deeper, not-reef zones it uses depth, wave and wind information to distinguish exposed and sheltered slopes—objects with a gradient of more than 10 degrees are slopes—and plateaus (less than five degrees). Once all the geomorphic zones are classified, the software uses field data and depth characteristics to differentiate benthic habitats such as coral/algae, seagrass, rock, rubble and sand.

In an additional step, eCognition divides the classified slopes into hard substrate and soft substrate (sand) and exports it as a vector layer in ArcGIS. Referencing detailed field data on coral types, along with wave, depth and slope data, a team uses an ecological model to create a predictive map of dominant coral types—branching, massive, and plate—for each reef.



The eCognition-based classification and map of the benthic habitats and geomorphic zones across the 237 Cairns/Cooktown (CC) reefs, a group of northern GBR reefs about 10 to 50 km offshore that are in dire condition. ©Roelfsema et al 2020.

In total it took eCognition 45 minutes to produce geomorphic and benthic habitat maps for all 237 of the CC reefs.

"That's mind blowing," says Roelfsema. "We have never been able to map so many reefs with such little field data to that level of detail. And in such little time."

At the end of 2017, Roelfsema presented the mapping results to GBR Marine Park Authority (GBRMPA) officials to not only validate the approach but to illustrate what this kind of information could mean for the whole GBR. Impressed by the maps, the GBRMPA invited Roelfsema to submit a proposal for mapping the entire ecosystem, and in early 2019, he was granted permission and funding to scale the methodology to all 2,900 reefs of the GBR.

The G, B and C of the GBR

A three-year initiative, the Great Barrier Reef Habitat Mapping Project (GBRHM) aims to develop a comprehensive, seamless map of the GBR that details the Reef's geomorphology, its benthic habitats and specific coral types. And last October it already bore its first significant fruit: Australia's, and the world's, first-ever map of the GBR's geomorphology, its slopes, plateaus and ridges along each individual reef.

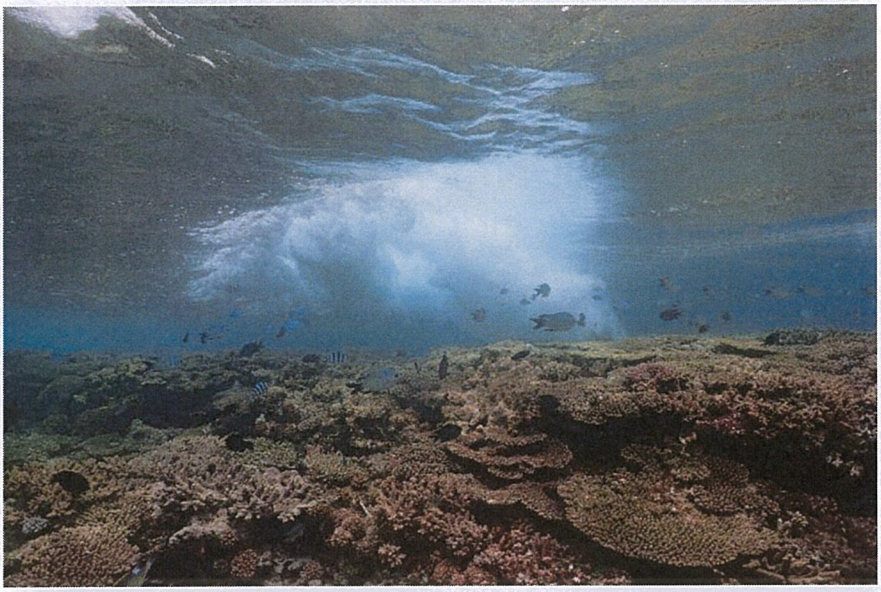
Roelfsema and his team created the map based on his eCognition mapping technique, with a few modifications.

Instead of Landsat, they acquired 129 Sentinel-2 images, which have a swath width of 290 kilometers and a 10-meter spatial resolution (four visible bands). Those scenes were processed into seamless mosaics and water depth, slope and wave values were derived using the same previously established algorithm. They also collected any and all field survey data they could find on the GBR to incorporate into the classification process.

To create a larger reference dataset, they applied the same eCognition rules from the initial set of 237 geomorphic reef maps to an additional 63 GBR reefs, producing geomorphic and benthic habitat maps for a total of 300 reefs.

Given the enormity of the GBR and the terabytes of data to be analyzed, the team switched the classification and mapping process to Google Earth Engine (GEE). Using the eCognition-

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Dense healthy coral just under the water surface close to the reef crest at Heron, Southern Great Barrier Reef(source: C.Roelfsema 2019)

based reference dataset of 300 reefs, they created a set of training and validation points. Those points were fed into GEE's machine-learning classifier to systematically classify and produce a geomorphic map of the whole GBR. They then applied OBIA neighborhood rules to strengthen the map results.

In late October, they presented the premiere GBR geomorphic map to the GBRMPA, and although officials "loved it," Roelfsema's team made improvements before delivering the finalized map last December. In 2020, the team will refine the map to classify and map the GBR's benthic communities, and in 2021, they will layer in specific coral types. All maps will be publicly available through the GBRMPA.

"This map has been a dream come true," says Roelfsema. "We're providing more detail than scientists have ever had before. Now they'll be able to make spatial, ecological and biophysical connections that they haven't been able to before. And, it's only going to get better."

That sounds like just the medicine the GBR needs.

Next Stop—The World

Having proved that they can map the GBR, Roelfsema and his team have been a lead mapping partner in the Allen Coral Atlas (ACA), a massive project to produce geomorphic and benthic-type maps of the world's 231,000 coral reefs.

Using 3.7-meter-resolution imagery from Planet Dove satellites, field data and geo-ecological models, Roelfsema's team create eCognition-based training maps that are input into Google's Earth Engine for classification and mapping. Once completed, the reef maps are post-ed to the ACA's online atlas. (https://allencoralatlas.org/)

To date, they have mapped several individual reefs around Hawaii, Indonesia, Belize, Tahitii and Sri Lanka; large reef systems in the GBR Cairns region, Fiji, Tonga and Vanuata have also been done. Some of the most recent reefs mapped are the complex reefs in the South West Pacific, and reefs around western Micronesia, east Africa and the northern Caribbean.

Funded by the late Paul Allen's philanthropic organization Vulcan, the ACA expects to have the world's coral reefs mapped by fall 2021.

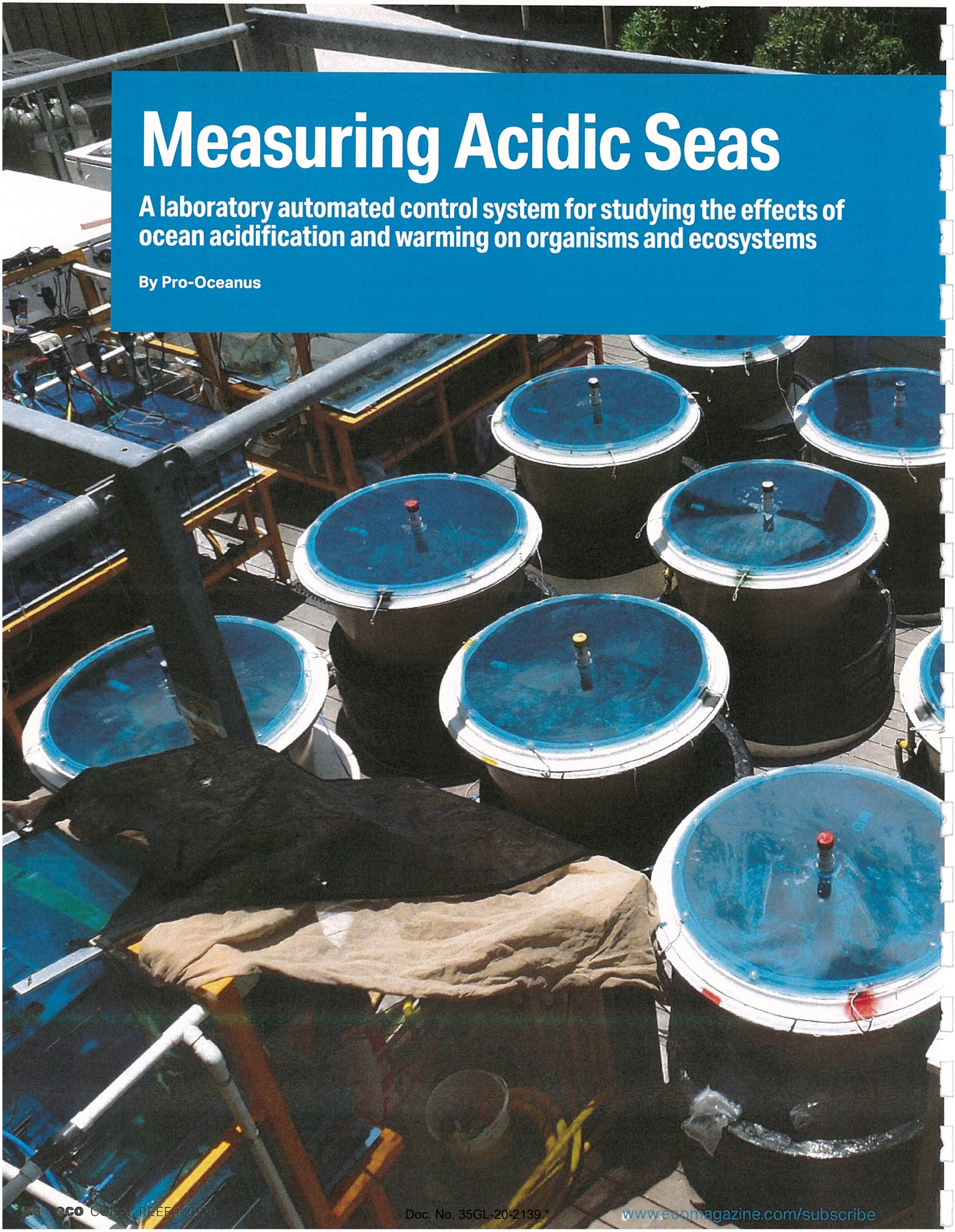
The mv Kalinda sits anchored at Ellison Reef in the Central Great Barrier Reef. Two smaller boats launch from here to drop divers and snorkelers off to collect georeferenced photo quadrate data along and on top of the reef to calibrate and validate habitat maps. (source: K. Joyce 2019).



Measuring Acidic Seas

A laboratory automated control system for studying the effects of ocean acidification and warming on organisms and ecosystems

By Pro-Oceanus



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As anthropogenic carbon dioxide (CO_2) builds in the atmosphere, the ocean is becoming more acidic. This change in pH not only affects the ocean's capacity to absorb CO_2, but the resulting reduction in carbonate (CO_3^{2-}) reduces the capability of organisms such as corals, foraminifera and shellfish to precipitate hard parts.

As the global ocean continues to absorb CO_2 from the atmosphere, changes in ocean chemistry can profoundly affect the organisms that call the ocean home. Organisms that precipitate hard parts such as corals, foraminifera and shellfish are especially susceptible to changes in ocean pH from increasing dissolved carbon dioxide levels (pCO_2). The effects of ocean acidification on organisms can be studied using a system that elevates naturally fluctuating CO_2 in water by offsets that represent various predicted future levels.

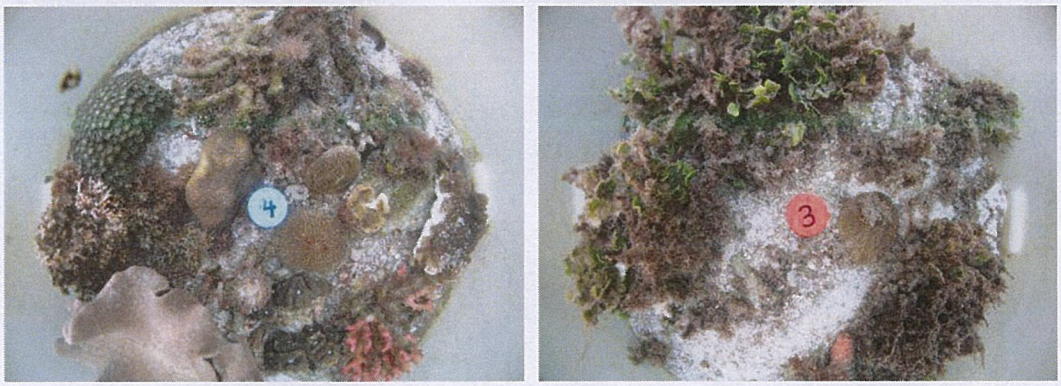
One laboratory that is taking the lead on research studies into the effects of these changes on coral reef ecosystems is the Coral Reef Ecosystems (CRE) Laboratory, School of Biological Sciences, located at the University of Queensland, Australia. Under the guidance of Associate Professor Sophie Dove and Professor Ove Hoegh-Guldberg, the lab is conducting research into a variety of topics related to coral reef ecosystems. The laboratory is part of the Australian Research Council (ARC) Centre of Excellence for Coral Reef Studies. This facility enables water temperature and CO_2 concentrations to mimic future scenarios having received funding from the ARC, the US NOAA, and the Great Barrier Reef Foundation. The facility is located on Heron Island in the Southern Great Barrier Reef of Australia.

Working with the researchers and technical staff at the CRE laboratory, Pro-Oceanus scientists and engineers developed a pCO_2-control system that simulates acidification conditions typical of current, and future levels expected in the next 50 to 100 years. The pCO_2-control system stabilizes CO_2 levels in high-turnover 8,000 liter flow-through tanks (known as sumps) of seawater that are used to feed numerous downstream experimental tanks. In this respect, the sumps mirror an acidified ocean washing over a reef with the organisms within the experimental tanks able to alter seawater chemistry through processes such as photosynthesis and respiration. The system also uses industrial heater-chillers to alter sump temperatures, so that desired temperatures are achieved in downstream experimental tanks.

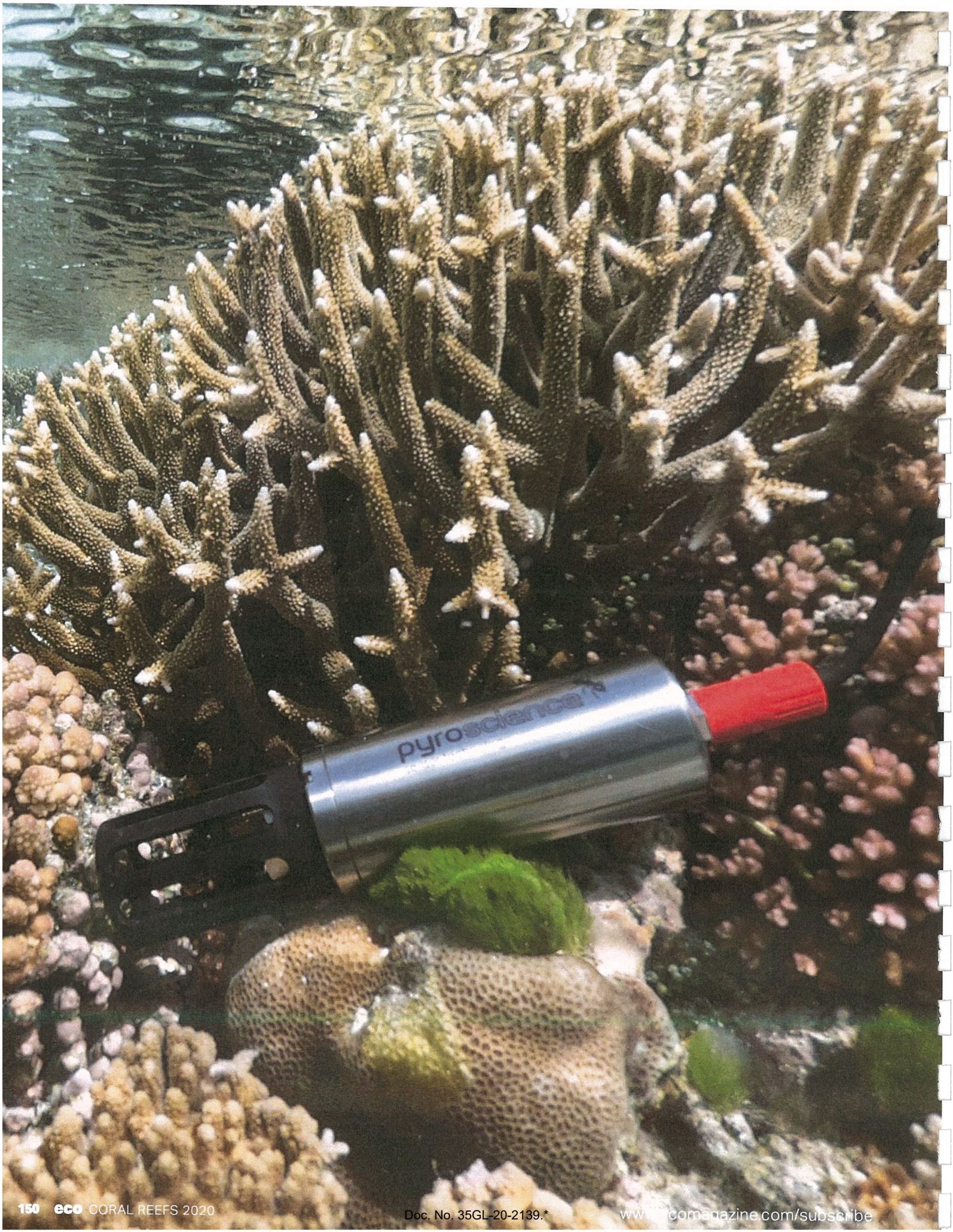
The pCO_2 control system uses one central CO_2-Pro sensor that receives seawater from the four experimental sumps in series. The pCO_2 levels are logged by a central computer system and are used to control the injection of an enriched CO_2 gas stream or CO_2-free air supply to regulate the pCO_2 concentrations in each of the experimental pCO_2/T treatments as required by their respective look-up table. The appropriate mix of enriched CO_2 or CO_2-free air is delivered to the 8,000 liter sump via a fine curtain of bubbles. These bubble streams are injected in a distributed manner to maximize bubble residence times. CO_2 is mixed to 30 percent using an inline gas mixer fed by bottled CO_2 and compressed air. CO_2-free air is produced by passing compressed air through two absorbent columns filled with soda lime to scrub CO_2. Experimental CO_2 and temperature follow look-up tables with the assistance of a custom-made software program. Each look-up table follows bi-hourly and seasonal variations recorded for 2012 and 2013 at a field reference site (Harry's Bommie) with distinctive treatments applying different offsets to this baseline. The 8,000 liter sumps (2.23 meters × 2.23 meters × 1.63 meters) are constructed from fiberglass around a stainless steel frame with fiberglass lids. Water drawn from the sumps to feed the satellite tanks is re-filled continuously with water pumped from the inner reef flat on the Great Barrier Reef. This water is filtered through a sand bed filter to remove particles larger than 10 microns that have the potential to lodge in the pCO_2 sensor.

The CRE laboratory has conducted research on many species of corals, algae, sponges and reconstructed ecosystems over the past 10 years, working to understand their responses to changes in ocean chemistry. Experiments in the controlled environments created by the large-scale system described herein, provide a better understanding of changes in growth rates and metabolic processes as ocean acidification and warming continue in areas such as the Great Barrier Reef.

The ability to understand changes at the ecosystem level requires a solid and repeatable laboratory design that allows for control of multiple parameters for studying change on time scales that are required for growth of organisms. The collaborative efforts of University of Queensland researchers and Pro-Oceanus scientists and engineers have led to the development of this pCO_2 control system for large tanks of seawater, enabling the study of how past, current and future levels of CO_2 in the atmosphere will affect coral reef ecosystem health.



T4 is a present-day conditions tank; T3 is a business-as-usual (RCP8.5) conditions tank with temperature and acidification effect combined. Photos courtesy of Dr. S. Dove, Coral Reef Ecosystems Laboratory.



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AquapHOx: A Cutting-Edge Optical Sensor for Ocean and Coastal Monitoring

The AquapHOx is a new flexible optical sensor platform for measuring O_2, pH and temperature

By Andrea Wieland, Maria Mosshammer, Erik Trampe and Michael Kühl , PryoScience GmbH

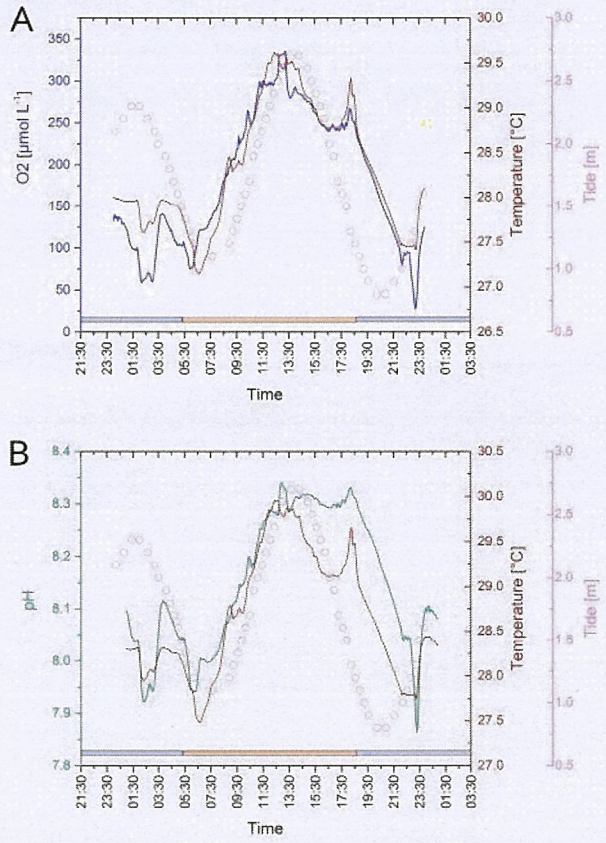
PyroScience was founded in 1998 by scientists and engineers originating from leading sensor research groups at the Max Planck Institute (MPI) for Marine Microbiology (Bremen, Germany), University of Copenhagen (Denmark), the Technical University of Graz (Austria), and RWTH Aachen (Germany). These research groups have a long history of pioneering new sensor techniques with optical measurement principles.

Today, the Germany-based sensor manufacturer supports researchers, NGOs, governmental organizations and industry by developing highly innovative and reliable sensor concepts. PyroScience recently launched a new flexible optical sensor platform for monitoring critical parameters and their dynamics in our ocean, such as current changes in water temperature and oxygen decline. The AquapHOx is a new compact and easy-to-operate underwater sensor platform and answers the call for a robust device for monitoring oxygen, temperature and pH levels in open ocean, the deep sea and coastal ecosystems, including coral reefs.

Based on the AquapHOx technology, the company provides flexible underwater solutions that can be tailored to measurement requirements within different ocean habitats. PyroScience offers long-term loggers for oxygen, pH and temperature as single analyte shallow water versions, complemented by the flexible multi-analyte logger AquapHOx-LX for stand-alone operation down to 4,000 meters water depth. The AquapHOx technology delivers industry leading accuracy for pH measurements and unmatched flexibility for standard oxygen monitoring, ultra-fast oxygen and temperature monitoring, or trace oxygen detection.

The new AquapHOx long-term logger has proved successful in diverse coastal habitats, including also the Great Barrier Reef of Australia (Mosshammer, Trampe & Kühl, MBL, University of Copenhagen, Denmark). Here, the AquapHOx Loggers were deployed within a patch of branching Acroporid corals on the reef flat of Heron Island to record O_2 (graph A), pH (graph B) and temperature (graph A+B) over a diurnal cycle. With this approach, a pronounced *in-situ* dynamic could be observed, as well as diel variations of important environmental variables driven by irradiance and tidal changes. The data also revealed hypoxic conditions in the investigated coral patch during night-time, demonstrating that the AquapHOx underwater loggers are ideal tools to follow chemical dynamics on coral reefs.

With the new versatile underwater devices based on the AquapHOx technology, PyroScience has expanded and complemented the product line of customer-friendly, cutting-edge optical sensor solutions for crucial parameters.



AquapHOx-LX Long-term Logger. Photo Credit: Trampe, Mosshammer & Kühl, MBL, U Copenhagen (DK)

Data from Mosshammer, Trampe & Kühl, MBL, University of Copenhagen (DK)



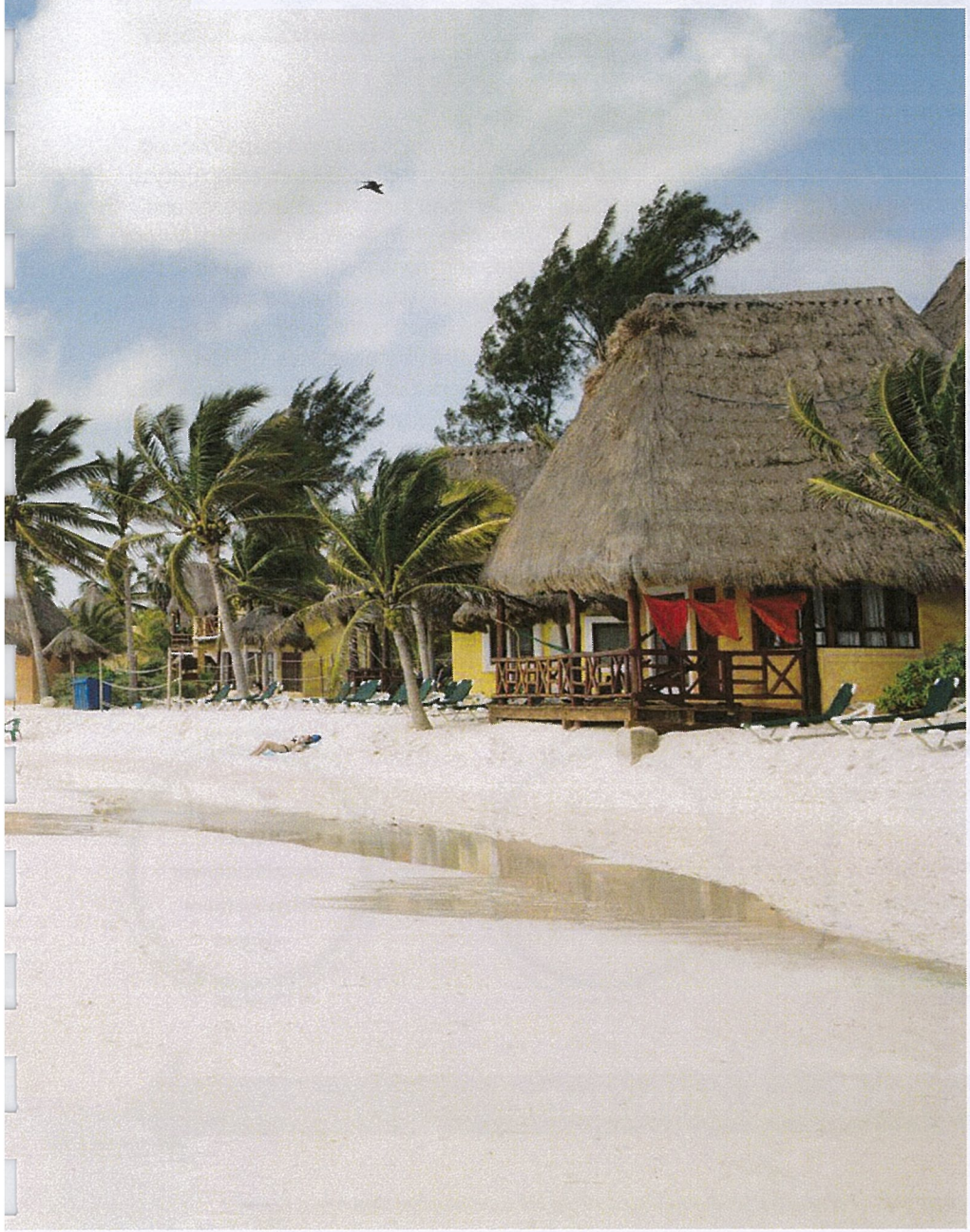
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Ecosystem-Based Management for Mexico's Coral Reefs

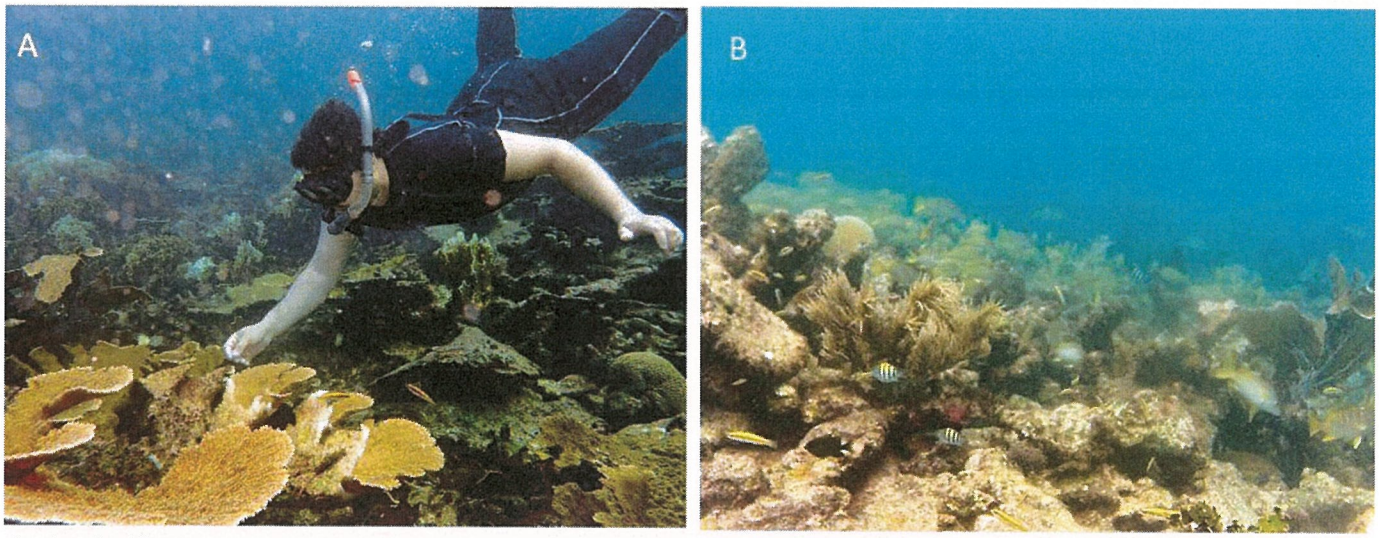
A novel proposal of ecosystem-based management for the protection of marine ecosystem services

By Silas Principe, University of São Paulo *



Puerto Morelos is a small fishery town between the tourist destinations of Playa del Carmen and Cancun, Mexico. It hosts incredible biodiversity, as well as rich mangroves and coral reefs ecosystems along its coast. Over the last decade, this small town has become increasingly overpopulated, and threats to these ecosystems have multiplied, not only affecting the essential ecosystem services they provide, but also human well-being. This reality is also true for many other coastal regions around the world where ecosystems are increasingly under threat due to population growth and tourism.

Using Puerto Morelos as a case study, our team focused on the coral reefs and mangrove ecosystems. We suggested different strategies for overcoming the continuous degradation, including improvements to management actions for the conservation of these ecosystems and the ecosystem services. An Ecosystem-Based Management (EBM) approach is a valuable strategy since it focuses on ecosystem services. It can reflect social goals, values, desires, and benefits. Incorporating ecosystem services into holistic management strategies allows managers to better capture the diversity of positive and negative human-nature interactions. This is crucial when it comes to translating the message about the importance of natural resources, and subsequently transmitting this message



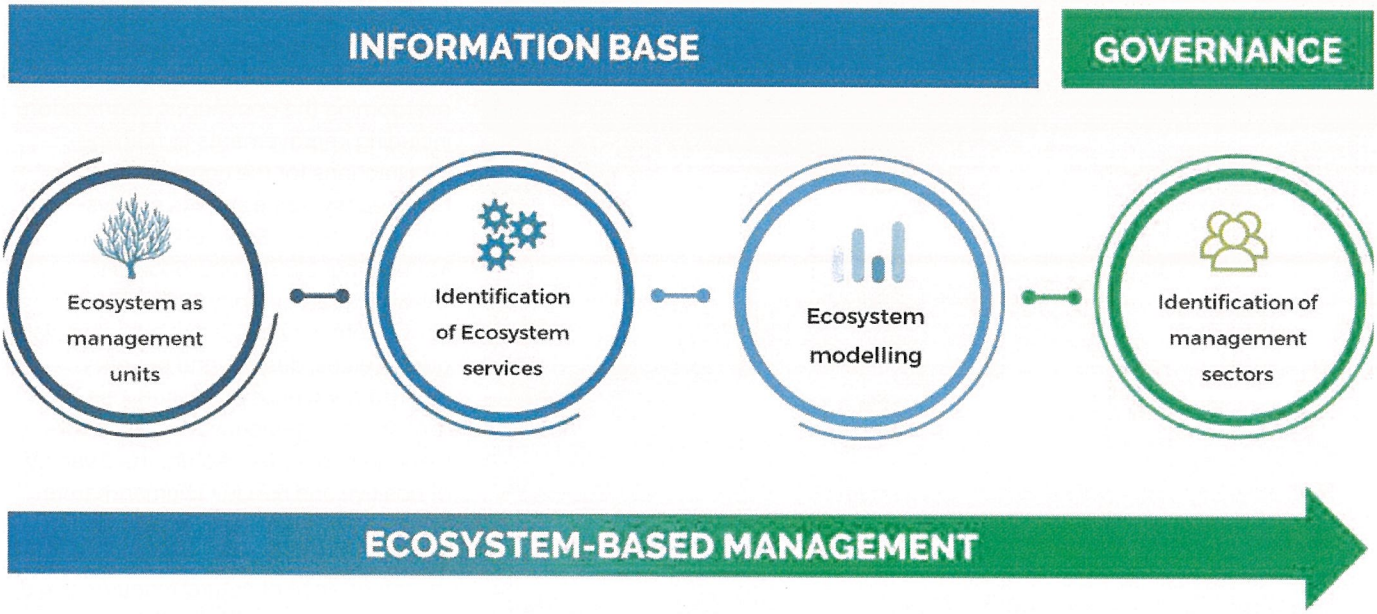
Coral reefs of Puerto Morelos. A) a well-preserved reef and B) a highly degraded reef. / Photos by Andrés Sánchez.

from the scientific community to broader society.

To help managers, policymakers, and practitioners implement EBM strategies, we developed a conceptual framework based on two key points: "Information base" and "Governance". Specifically, our approach includes four steps: 1) the identification of ecosystems as management units; 2) the identification of the ecosystem services (Ecosystem Services Matrix); 3) the ecosystem modeling (Conceptual model and Global Biodiversity model); and 4) the identification of the management sectors (DPSIR and Policy assessment).

Identifying the ecosystem as a management unit (first step) is fundamental. Many management strategies focus on separate aspects of an ecosystem and overlook the interplay of multiple processes occurring in such a complex environment. Taking a more holistic view is imperative given that anthropogenic threats resulting from numerous human activities are particularly harmful to coastal ecosystems, and affect several aspects of the ecosystem at the same time.

The second and third steps involved decoupling the ecosystem complexity to understand the multiple processes and the ecosystem services provided by coral reefs and mangroves ecosystems. In this sense, we selected the coastal protection service, which is an ecosystem service provided by both systems. We identified the drivers that affect it, generating a loss of this important service. Thus, in the third step, we moved forward and analyzed what would happen to the ecosystems under varying future scenarios, hence



The proposed framework for Ecosystem-Based Management of coastal ecosystems. / Icons from Freepik (Creative Commons license).

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helping to identify which management pathway to follow.

The identification of current and available public policies and management tools was an important step in our research workflow. According to Dr. Francisco Veiga, who was involved in the research, "the assessment of the legal and management framework is essential to provide responses regarding the anthropogenic (urbanization, ports, tourism, sewage, among others) and natural (i.e., climate change/Global warming) drivers of change". Therefore, the legal framework must support decision making towards sustainable development and conservation of key ecosystems.

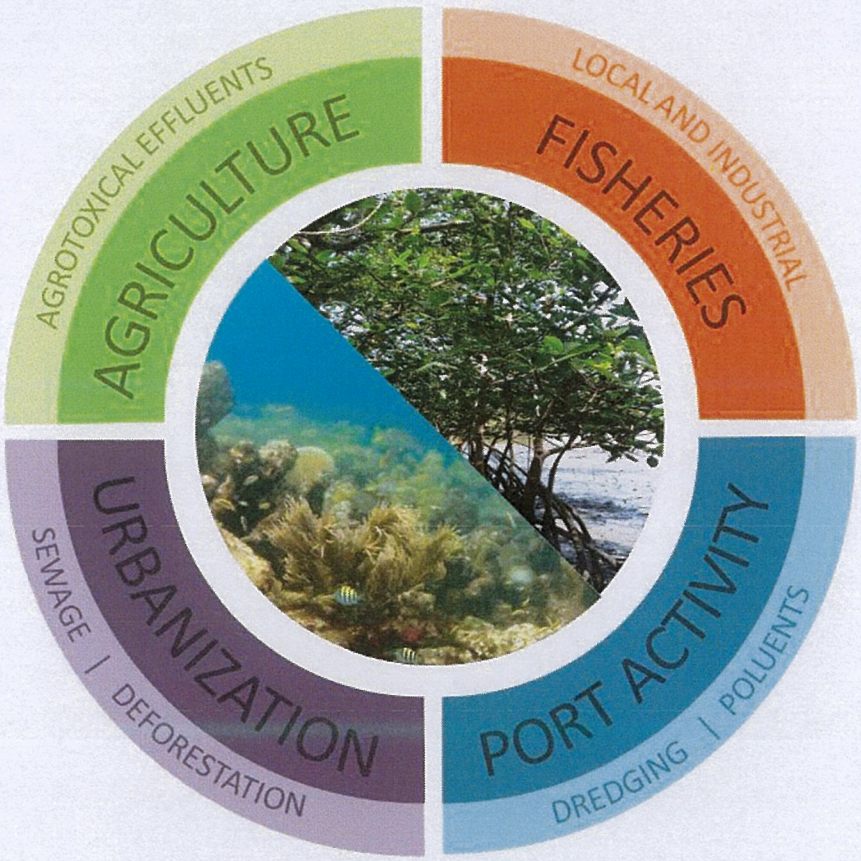
By applying this framework to Puerto Morelos, we were able to identify the pressure exerted by urbanization (especially by tourism) on coral reefs and mangroves, which will affect important ecosystem services such as coastal protection. Our framework also showed that integration among laws—at federal, state and local levels—concerning land use and ecosystem conservation is another critical step to managing sustainable development in Puerto Morelos. It is essential to highlight, within the marine ecosystem context, the importance of the policies focused on land, since they are integrated systems. What happens in coastal areas, directly and indirectly, affects the marine system. Therefore, the EBM's objective is to integrate all the components to better understand, manage and conserve the biodiversity and the ecosystems.

This research emerged from a workshop (SPSAS Scenarios) held in Brazil in 2019. During the workshop, researchers with different backgrounds and nationalities explored the use of scenarios to protect biodiversity and human well-being. This cross-disciplinary approach was important to amplify the view of the problem and the alternatives for protecting coral reefs and other coastal ecosystems.

"Having the opportunity to discuss scientific matters of this nature with people from different backgrounds always reveals fresh perspectives," said Dr. Andrés Sánchez, who led the research. "Each member contributed with knowledge and points of view that allowed us to form ideas that we wouldn't have imagined otherwise. Being able to reflect on experiences and opinions from around the globe was invaluable".

We discovered that many of the most pressing problems are common in different countries, so this multicultural approach allows us to find common solutions. Dr. Evangelina Viotto, who also contributed to this work, shares the same opinion: "Many of us work in other areas of research, such as animal ecology or grassland communities. This work posed an irresistible challenge for us to tackle a complex and multi-faceted problem".

A healthy ocean depends on the implementation of a comprehensive management framework, not the usual sectoral approach to management. Coastal ecosystems are complex, and tools like the one presented here can help stakeholders better manage these environments, guaranteeing the conservation of biodiversity and the supply of important ecosystem services that maintain human populations. As we approach the United Nations Decade of Ocean Science for Sustainable Development (2021-2030), we are reminded once more that coral reefs and associated ecosystems are in danger, and a better management is crucial for their protection.



Some of the anthropogenic activities affecting coastal ecosystems in Puerto Morelos / Photos by Andrés Sanchez and Jaqueline Borges.

*** Reference:**

The original research article is has been accepted for publication in Biota Neotropica. Authors include: Andrés Sánchez-Quinto, Julliet Correa da Costa, Nadia S. Zamboni, Fábio H. C. Sanches, Silas C. Principe, Evangelina V. Viotto, Elvira Casagranda, Francisco A. da Veiga Lima, Bianca Possamai, and Larisse Faroni-Perez.

Could Fish Social Networks Help Us Save Coral Reefs?

Mike Gil spies on fish: using novel multi-camera systems and computer vision technology, the TED Fellow and his colleagues explore how coral reef fish behave, socialize and affect their ecosystems. Learn more about how fish of different species communicate via social networks -- and what disrupting these networks might mean to the delicate ecology of reefs, which help feed millions of us and support the global economy.

This talk was presented at an official TED conference, and was featured on the TED home page.



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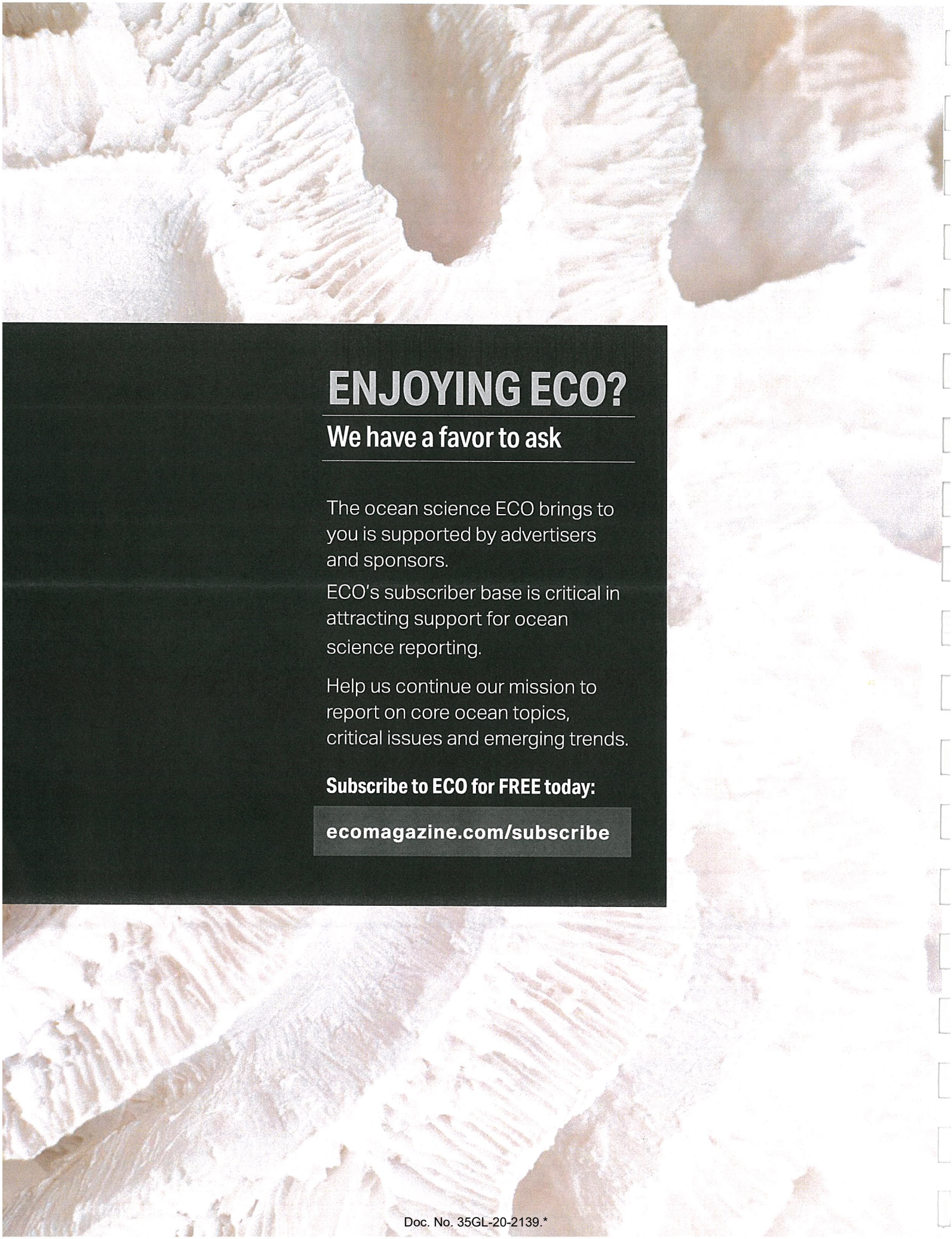
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