Ecosystem Reboot

How scientists are building an inside-out Noah's Ark for Florida's vanished coral reefs

by

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ABSTRACT

In Florida, a deadly marine plague called stony coral tissue loss disease has inspired an unprecedented conservation plan: to rescue affected corals from the wild, and keep them alive in captivity, indefinitely. The idea was to make a Noah's Ark turned inside out, evacuating corals from an inhospitable ocean, and raising, breeding and propagating them on land, with the quixotic hope that the reef can one day be rebooted from its backup copy. To do so, Florida's coral community would need to collect thousands of corals, find places to warehouse their charges, and figure out ways to grow big, genetically diverse captive populations. And with stony coral tissue loss spreading swiftly up and down the state's coast, they needed to act fast.

This may be the most audacious conservation plan ever attempted — not just to save a species here and there, but to rescue the basis of an entire ecosystem, and to keep it alive through everything the future has in store. And where Florida's beleaguered reefs go, the rest of the world will follow. Sooner or later, but most likely sooner, corals everywhere will be in need of their own inside-out arks, ferrying them towards some hoped-for future. Improbable as it seems, it just might work.

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Only three days remained before Hurricane Ian was due to slam into Florida's west coast, and there wasn't a single box truck in Tampa to be found.

It was late September, in 2022. After knocking out power to all of Cuba, Ian was now whipping itself into a Category 4 storm over the Gulf of Mexico, siphoning heat and moisture from an ocean as hot as bath water. At the time, predictions put Tampa dead-center in the hurricane's projected path. A 15-foot storm surge and roof-peeling winds threatened a metro area home to 3 million people — and a small collection of some of the rarest corals on earth.

"It's a pretty intense feeling when you literally have the majority of the rest of a species in your care, and there's a hurricane headed your way," says Keri O'Neil, the senior coral scientist at the Florida Aquarium in Tampa. At the aquarium's conservation campus — a serene place of lawns, ponds and buildings perched on stilts — O'Neil and her colleagues rushed to evacuate their twenty-odd pillar corals, *Dendrogyra cylindricus,* before the storm was set to strike. These corals, rescued from the ocean in the wake of a devastating marine plague, are among the last of their kind left in Florida.

The aquarium enlisted the Reef Institute in West Palm Beach, 200 miles away and on the opposite coast, to rent a box truck and drive it to Tampa, slipping in and out before Ian drew closer and traffic snarled highways. The pillar corals, wrapped in wet newspaper and packed in styrofoam coolers, were safe for now. As for the hundreds of other corals in O'Neil's care, they got lucky: A last-minute shift sent the storm veering south, bringing only gusts and showers to Tampa.

Others, however, were not as fortunate. The hurricane would claim 155 lives and wreak $113 billion in damages, making it the deadliest storm to hit Florida in nearly a century, and the third costliest storm in U.S. history. The same thing that helped make Ian so ruinous is also what laid the groundwork for the near-extinction of Florida's pillar corals: an ocean that's too hot, and is getting hotter.

For decades, scientists have predicted that the majority of the world's coral reefs will be functionally dead by 2050, no longer able to offer their countless vital services, ranging from food and income for coastal communities, to habitat for a quarter of all marine wildlife. However, when a 2022 study from the University of Hawaii looked at every threat reefs face — not just from heat, but from acidification, storms, pollution and overfishing — that timeline got pushed up even sooner, to 2035. A different 2022 study, this one from the University of Leeds in the U.K., indicated that at 1.5 degrees Celsius of warming, 98% of reefs will regularly be exposed to harmful, even fatal heat. Last October, the United Nations warned that there is "no credible pathway" to stop the planet from blowing past 1.5 degrees of global heating, potentially within the next few years.

Reefs will contract into patches, then specks, and then, perhaps, vanish altogether. Individual corals, however, will linger on. Hardy species can eke out a living in sun-scalded tide pools, or in the ocean's chilly, lightless depths. This go-it-alone strategy is how stony corals, the kind that build reefs, survived after a meteor put an abrupt end to the age of dinosaurs 55 million years ago. But if the world loses reefs now, millions of years could pass before these solitary survivors re-evolve their almost magical ability to transform barren tropical shallows into teeming, technicolor gardens.

The difference between that distant apocalypse and now is us. Humanity has sparked this mass extinction, and we may be able to quench it. One day, perhaps in a few decades, maybe much, much longer, the climate will settle into a new equilibrium. The ocean will once again become habitable. Tropical corals will revive, if they're still around — and that 'still around' is what reef advocates across Florida have been fighting for since 2018.

Their idea was to make a Noah's Ark turned inside out, evacuating corals from an inhospitable ocean, and raising, breeding and propagating them on land, with the quixotic hope that the reef can one day be rebooted from its backup copy. To do so, they needed to collect thousands of corals, find places to warehouse their charges, and figure out ways to grow big, genetically diverse captive populations. And with a cataclysmic disease cutting a swath through the state's reefs, they needed to act fast.

This may be the most audacious conservation plan ever attempted — not just to save a species here and there, but to rescue the basis of an entire ecosystem, and to keep it alive through everything the future has in store. And where Florida's beleaguered reefs go, the rest of the world will follow. Sooner or later, but most likely sooner, corals everywhere will be in need of their own inside-out arks, ferrying them towards some hoped-for future. Improbable as it seems, it just might work. The willpower, know-how and technology exist. But as Hurricane Ian showed, rescuing an entire ecosystem while the climate comes crashing down is no easy task.

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Five months after Ian, on an unusually brisk February morning, O'Neil passes the sea turtle hospital tanks at the Florida Aquarium's conservation campus, and enters a dim, humid room. She wrestles with unwieldy black particleboards to reveal a bank of aquariums, bathed in the light of indigo LEDs. Along one side sprawl the antler-like branches of elkhorn and staghorn corals, once the Caribbean's dominant reef-building species, now reduced to a few percentage points of their former abundance. On the other side are the pillars, squat, lumpy, and covered in a pelt of furry, grayish tentacles.

“We actually have more genetic individuals here at the Center for Conservation than are alive in the wild in Florida,” O’Neil says. She estimates that by now only two dozen or so pillar corals remain along the entirety of the state’s 350-mile barrier reef. Too few, too far apart and too sickly to reproduce, the species is now functionally extinct in Florida.

In the greenhouse next door to the pillars, a wide, shallow tank holds clues to what landed the species in such hot water. A laminated sign hangs on its side: PRE-INVASION CORALS. Beneath the rippling surface lie living relics: corals collected over a decade ago, before the arrival of a mysterious disease that has turned the state’s reefs into graveyards.

The disease, like many unfortunate events, begins in Miami. Just as humans can catch a cold, corals can catch a hot, and in in the summer of 2014, Florida was sweltering. Pushed beyond their thermal limits, the region’s corals faded from their healthy colors of mahogany, ochre, and khaki green, turning an almost phosphorescent shade of white. This phenomenon, called bleaching, is becoming more frequent and severe as the planet warms.

Corals bleach when they spit out the single-celled algae that live inside their bodies. A coral colony consists of numerous tiny animals called polyps, all of them genetically identical copies of each other, and of the colony’s single founder. In exchange for shelter, the polyps’ algal roommates supply the colony with up to 95% its nutritional needs. Corals likely evict their algae as a last-ditch strategy to make room for more heat-tolerant replacements. Depending on the species, bleached corals can cling to life for a few days to a few weeks, surviving on the plankton their tentacles pluck from the currents. If temperatures return to normal within a certain time frame, the corals will welcome a new set of algae and regain their color. If not, they starve.

In Florida, many corals recovered as the heat wave subsided, but their health had taken a blow. None, perhaps, were worse off than those around Virginia Key, an island in the port of Miami. There, a leaking pipe oozed raw sewage into the water, a major dredging project stirred up clouds of sediment, and the run-off from a metro area of 6 million people laced the water with fertilizers and other pollutants. Bathed in a hot, unhealthy soup, the corals did what you’d expect them to do. They got sick.

The disease killed ruthlessly, with white necrotic lesions that gave the ailment its name: stony coral tissue loss. Though pillar corals counted some of the worst casualties — 93% of infected colonies died — the pathogen dispatched boulder, brain, star and maze corals too, roughly half of the Caribbean’s 40-odd reef-building species.

Despite some early warnings, the state’s conservation community largely assumed the disease would “blow up, and then die back down,” says Erinn Muller, who manages the coral health and disease program at Mote Marine Laboratory in Sarasota, Florida. Disease is nothing new to

Florida's reefs, and for the most part, outbreaks are short-lived. "I don't think as a community we realized this was going be different," Muller says. "And obviously, it was."

The pathogen quietly traveled north and south, hitching rides on currents and in ships' ballast water. In 2017, it reached the northernmost of the Florida Keys, the chain of islands that curves off the state's southern tip. "Once we realized it was moving down into the Keys, that's when the red flags started going," Muller says. By the time Muller, O'Neil, and other reef experts met in 2018 to iron out a plan for the disease, it was clear that Florida was facing down an extinction-level event.

There was little the scientists could do to stop the spread of stony coral tissue loss, short of turning off ocean currents and shutting down ship traffic. Instead, a coalition of state and federal agencies, with help from universities, nonprofits and public aquariums, decided to attempt a last-minute mission to get corals out of the ocean and into tanks on land. But time was running out. If the rescue squad didn't get to the corals before the disease did, there would be little left to save.

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While stony coral tissue loss is widely considered the worst known coral disease, it's only the latest in a long line of marine plagues that have, within the span of a human lifetime, pushed Caribbean reefs to the edge of collapse and beyond. How microbes could topple an ancient, vast, and vibrant ecosystem, threaded across an entire ocean basin, is a story best told not through pillar corals, but their distant cousins, the elkhorn and staghorn corals.

Growing five to ten times faster and taller than other Caribbean corals, these two species have been the region's dominant reef engineers for at least half a million years. During this time, atmospheric CO2 levels ping-ponged between 180 and 300 parts per million, while ice sheets advanced and retreated in lockstep. At peak glaciation, 20,000 years ago, the sea's surface lay 400 feet lower than it does today. Still, whether the strand was patrolled by mastodons or modern vacationers, the reef would have looked much the same: a golden-orange hedgerow of elkhorn in the shallowest waters, followed by a dun-colored ribbon of staghorn.

Beginning in the middle of last century, reefs faced an enemy far more ferocious than any ice age: a booming human population. Farms multiplied on land, washing plowed-up dirt and fertilizers into the ocean, and clouding the water with sediment. Sun-seekers flocked to coastlines, ripping out mangrove forests, dredging up corals, and dumping raw sewage into the sea. In the Florida Keys, up until the mid-2000s, septic tanks and cesspits serving tens of thousands of residents oozed untreated waste into the ocean. Even now, after major infrastructure upgrades, raw sewage still bedevils south Florida waters, and regular 'no swim' advisories warn beach-goers not to venture into the waves.

Anchored to the sea floor, corals don't have the luxury of packing up and moving when conditions get bad. An individual coral polyp is tiny, only a few millimeters across. Constantly shrugging off sediment drains its strength, and shades its symbiotic algae, like dust on a solar panel. Worse still are sewage and fertilizer. Reefs grow in the marine version of a desert, where the crystal-clear water is almost entirely devoid of nutrients. Cranking up nitrogen and phosphorus effectively turns a reef from Arizona to Amazonia, supercharging the growth of macroalgae — large, fast-spreading seaweeds, the kind that elicit a shudder when they brush a swimmer's bare foot. These weedy plants can swiftly smother corals if not kept in check by grazers such as sea urchins.

In 1970, as the world celebrated the first Earth Day, atmospheric carbon climbed to 325 parts per million, its highest level in 2.5 million years. The seventies saw the first "pronounced" warming in Caribbean waters, further stressing corals, and creating ideal conditions for disease-causing microbes. In 1977, divers in the U.S. Virgin Islands began noticing dead tissue peeling off the branches of elk- and staghorn corals, revealing pale rings of lifeless skeleton. Over the next five years, white band disease would go on to annihilate billions of colonies of each species, with only 5 out of every 100 surviving the onslaught.

White band disease was only the first major explosion[1] in a warehouse full of dynamite. In 1983, as the first wave of white band was petering out, a different plague took its place. This one assailed long-spined sea urchins, the dominant herbivore on Caribbean reefs. Within a few years, 98% of the urchin population had died off. To this day, their numbers have not recovered. In the coming decades, disease after disease would hammer stony corals — white pox, white plague, yellow band, black band — and decimate other reef species, including sea fans and giant barrel sponges, some of which had been growing since the birth of Christ.

With the collapse of urchins, corals had lost their most powerful ally in the battle against invading algae. Across Florida, live coral cover has plunged to 2%, down from a historical average of 60%. On many parts of the reef, you'd be hard pressed to find a single living colony amid the drab seascape of dead coral and slimy brown seaweed.

The damage to Florida has been punishing. Algae provide scant shelter for fish and crustaceans, and they present dreary vistas for snorkelers, divers and other tourists, who spend well over $2 billion annually in the Florida Keys alone. Florida's corals act like a self-building seawall, averting $675 million in potential storm damage each year. Without trillions of polyps fabricating the reef layer by layer, the seawall erodes away, leaving coastal communities vulnerable to increasingly fierce storms.

[1] Black band disease was first observed in the Caribbean in the early 1970s, but was nowhere near as devastating as white band disease, and did not affect elkhorn or staghorn corals.

For all the destruction these diseases have wrought, remarkably little is known about the microorganisms that cause them. The lesions of stony coral tissue loss, for example, respond to the antibiotic amoxicillin, but a causative bacterium has yet to be identified. Erinn Muller and other coral pathologists suspect the disease may involve an alliance of several different bacteria, even viruses and fungi.

"Corals have super-weird microbiomes," says Grace Klinges, a microbiologist at Mote Marine Laboratory's Summerland Key facility. An ex-dentist turned Mote intern, Klinges says, found perfectly healthy corals infested with pathogens of the human mouth. This wild diversity of microbes makes it hard to tell friend from foe, and foe from opportunistic newcomers drawn by the coral's dying flesh.

Adding to the confusion, says Muller, is the fact that many named coral diseases are just descriptions of symptoms, rather than specific pathogens. At least some cases of white pox are caused by *Serratia marcescens*, a bacteria found in human feces, but that doesn't mean that all corals with pale, sickly blotches are dying from that particular microbe, she explains.

At least for now, stony coral tissue loss is winning out. But even if the disease had never reared its necrotic head, the Caribbean's corals would still be in deep trouble. Between the climate crisis, coastal pollution and other threats, Florida would eventually have needed to rescue its corals, one way or another.

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After the 2018 meeting about stony coral tissue loss, the program to evacuate Florida's corals began in earnest. Thanks to a government monitoring program dating back to the '90s, the rescue squad knew where and how deep their target corals dwelled — places where they could get "the most bang for our buck," says Jennifer Moore, the coral recovery coordinator at the National Oceanic and Atmospheric Administration.

The challenge wasn't finding the corals, but finding enough of them. To guard against inbreeding, the team would need to collect at least 50 genetically distinct individuals of the 15 priority species they'd identified. Corals, however, have a penchant for creating exact copies of themselves via a process called fragmentation. When waves or wayward anchors smash a coral into bits, the scattered pieces can re-attach to the reef's bare surface, creating genetically identical replicas of the mother colony. Out in the ocean, there would be no way for the rescue squad to know which corals were clones, and which ones weren't. Nor was there time to send samples to a lab for DNA testing.

“The disease front was moving so fast that we were losing ground in terms of areas where there were unaffected corals,” Moore says. The solution was to overshoot the 50-coral target, and aim for 200 specimens of each species, or 3,000 overall. “The majority of these had never been kept in human care before,” Moore says. “We were like: This is going to be huge.”

After the first collecting trip in September 2018, it quickly became clear that day-long jaunts from the coast were taking too long. The next year, in May, the team hired a live-aboard dive boat, boosting collection capacity to several hundred specimens per five-day cruise. Rescued corals were kept in a jury-rigged life support system of shade tarps, laundry baskets, and seawater-filled plastic tubs. By then, however, the disease had already spread to the farthest reaches of the Keys. Divers targeted areas that were relatively unaffected, to greater or lesser effect. After scouring 200 sites, for example, fewer than 20 rough cactus corals were found alive.

Still, the operation was a success. They had the species they wanted, and in most cases, the numbers they needed too. With 2,400 corals in temporary holding tanks, it was time for the team to tackle the next hurdle: getting the evacuees into permanent homes. State-owned facilities in Florida did not have enough space to host all of the corals, so a plea was sent to members of the Association of Zoos and Aquariums, or AZA. Responses poured in from across the country.

“We’ve got corals in mile-high Denver, Colorado,” says Beth Firchau, the coordinator for the AZA Florida Reef Tract Rescue Project. “We’ve got corals in the inner city of Camden, New Jersey. We’ve got Jersey Shore corals.” Within the first 16 months of the rescue operation, AZA members had volunteered $14.2 million, both in cash and in-kind — everything from veterinary care and staff time, to empty tanks and space in storage closets. Overall, Firchau says, 80% of the project’s total investment “has come just from AZA facilities.”

The biggest of these facilities is tucked in a small office park in Orlando, just off a sun-seared highway lined with strip malls and fast-food joints. An unmarked entrance opens into a warehouse saturated in the disorientating light of blue and purple LEDs. Tank after burbling tank is home to neatly arranged corals — 700 in total, of 18 different species.

This is the Florida Coral Rescue Center, and the fact that it’s home to anything at all is a minor miracle. In February 2020, a month before the rescued corals were due to arrive, a commercial coral store had happened to vacate the space — leaving behind its tanks, pumps, lights and so on. Then, in early March, when the last collection cruise docked at Nova Southeastern University in Fort Lauderdale, the rescue team found itself racing against an entirely different pandemic.

Nova Southeastern sits on a small peninsula, Firchau says, next to a massive harbor for cruise ships. Normally, the cruise liners are out at sea, and the port is empty. That morning, however, things were different. “It was eerie,” Firchau says. The harbor was “packed with cruise ships.

Cruise ships filled with people with Covid."

By the time Firchau and the corals had arrived in Orlando, the scene was chaotic. Nobody had masks, or any idea of what was to come. "Miraculously, none of us got sick," says Sara Spangler, one of the rescue center's biologists. If the delivery had been scheduled even a week later, she adds, "no corals would be here right now."

Since then, the center has settled into a comfortable routine. Starting at 6 AM, the staff begin their daily rounds of feeding the corals powdered krill, testing water chemistry, and cleaning out filters. Every five days, the residents are gently lifted from their homes and given a toothbrush scrub down. Their growth and health are closely monitored, and reported to the Florida Fish and Wildlife Conservation Commission. With two full-time and two-part time staff, these corals might be the most coddled invertebrates on earth. "We only really see these four walls all day," says Spangler, laughing. "This is all we look at."

These colonies are here for a single purpose: to act as an insurance policy. In case disaster befalls other holding facilities and their corals die, the idea is that the Florida Coral Rescue Center can step in to supply backup copies of whatever was lost.

Some corals, however, haven't been content with retirement. One morning last April, the center's eight rough cactus corals surprised the team by burping up fully formed, free-swimming babies, known as larvae. A few days prior, under cover of darkness, the hermaphroditic colonies had spawned with one another, brooding the fertilized eggs inside of their bodies. Over the next few weeks, several hundred more larvae would follow.

It's "kind of groundbreaking" for these corals "to want to do their thing here in our facility," says site manager and Sea World aquarist Justin Zimmerman. It's proof, he says, of a return to health[2] after the corals' sickly (and likely sexless) early lives. Most of the larvae were sent to partner institutions, but a few rebellious ones stuck around, chocolate-brown buttons tucked in corners of the tank. Life finds a way, if given half a chance.

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The team at the Florida Coral Rescue Center lucked into something that aquarium keepers have noticed on and off for a few decades: that with expert care and perfect lighting, corals will spawn in captivity. The trick, however, has been getting them to spawn intentionally, on cue. And that's what Florida's coral community would need to figure out for the third and final act of the rescue plan, the restoration phase. This will involve returning hundreds of thousands — even millions

[2] The Florida Coral Rescue Center's corals developed more vibrant coloration and "puffed up" — appearing pudgier — after they arrived, an indication of a healthier state.

— of captive-raised corals to the ocean, in hopes of bringing the state's reefs back to life.

For the transplanted corals, genetic diversity will be the key to their populations' long-term health. A genetically diverse population ups the odds that any given individual will luck into genes that confer resistance to disease, heat, or other threats. Conversely, closely related populations wind up sickly and weak. Mary Hagedorn, a coral conservationist at the Smithsonian Conservation Biology Institute, relates the cautionary tale of the black-footed ferret, reduced to just seven founders. Their descendants are inbred and disease-prone, and must be rounded up each year for vaccinations. For Hagedorn, the calculus is simple. "If we have genetic diversity, we can rebuild populations," she says. "If we don't have genetic diversity, we can't."

Coral keepers can easily grow their collections in sheer numbers via fragging — clipping off fragments from a parent colony to make a clone. But if they wanted to foster genetic diversity, sexual reproduction, or spawning, would be essential.

When it comes to spawning, rough cactus corals and their larvae-brooding relatives are a bit of an outlier. Most reef-building corals, both in Florida and around the world, reproduce in a far more spectacular fashion. For only a few minutes a year, a few nights a year, some silent signal puts these corals, called broadcast spawners, in the mood for love. Against the inky backdrop of the sea, eggs and sperm spurt forth from their parent colonies, rising to the surface and glazing the waves with a slick of gametes. Somehow, in this festival of sex, eggs and sperm from their respective species manage to meet up and merge together. The resulting larvae will drift in the open ocean for days to weeks, before following chemical cues towards a reef and settling down.

We've known about these midnight orgies since 1981, but until the mid-2000s, no one had thought to figure out how to purposefully trick broadcast spawners into doing their thing in captivity. It took Jamie Craggs, the head aquarist at London's Horniman Museum, to crack the code of coral sex. From his work with jellyfish and brooder corals, he knew that seasonal changes in temperature and light play a big role in the reproductive lives of marine animals. In 2012, he says, the "penny sort of dropped" when he noticed a tweet from Fijian dive shop offering nighttime trips to watch the reef spawn. Craggs looked up the water conditions in Fiji, and decided to tune a few of his experimental tanks at the Horniman to match.

Lighting, he knew, was crucial. The period of absolute darkness between sunset and moonrise is one of the main prompts corals use to sync up their spawning. Advanced lighting technology, borrowed from the coral hobbyist world, allowed Craggs to precisely mimic a Fijian sky — sunrise, moonset, even cloudy days or nights. Eight months later, right on cue, the tanks filled with a confetti of bubblegum pink gametes.

In 2017, after a few years perfecting his spawning set-up, Craggs posted an offer of his expertise on a marine biology messaging board, and quickly got a response from O'Neil. She'd recently found herself caretaker to the last of Florida's pillar corals, collected as an unwitting rehearsal to the larger rescue effort, back before the full scope of stony coral tissue loss had come into focus. Eager to help, Craggs flew to Tampa, where he spent a week designing a spawning system for the pillars, and training staff how to use it.

In August 2018 — roughly 100 minutes after sunset, on the second night after the full moon — Florida's population of pillar corals exploded from two dozen to several hundred. Working by the glow of red flashlights, so as not to disturb the honeymooners, O'Neil and her colleagues watched as the colonies sucked in their tentacles and sneezed out clouds of eggs and sperm.[3] That balmy Tampa evening witnessed the first-ever captive spawn of a Caribbean coral, and likely the first time in decades that new pillar babies had graced Floridian waters.

Ridged cactus corals followed in 2020, grooved brain coral in 2021, and elkhorn in 2022. All the while, ever since that first spawn, the aquarium's pillar corals have gamely spat out gametes every August. The week before my visit with O'Neil, the aquarium's staff had bid farewell to 1,700 pillar corals, grown from larvae into small adult colonies, and sent off to the Florida Keys to begin a new life in the sea.

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It's February 2023 at the aquarium's conservation campus, and a fresh batch of cactus coral babies are about to embark on the first phase of their journey from captive babyhood to reef-dwelling adult.

Amid the roar of protein filters, expectant parent colonies wait in buckets, where their babies float to the surface and travel via the "larvae water slide," as O'Neil describes it, into a separate container. A few scattered larvae — the size and color of roasted sesame seeds — meander around the water, propelled on microscopic, wiggling hairs called cilia.

O'Neil pipettes up one of the wandering embryos and squirts it into a dish under a microscope. Under magnification, its uniform tahini-tan coloration splits into bold tiger stripes. Despite having no eyes or brain, its movements seem full of purpose. Right now, it's looking for an ideal spot to settle down — which the aquarium's staff will provide in the form of a small ceramic tile. Hunkered down on its tile, the larvae will grow a cup-shaped skeleton and transform into an adult polyp, roughly the size and color of a mini chocolate chip. It will grow by budding off another polyp, and another. Within two or three years, the young colony will expand to the size of a muffin top, and be ready to move from the land to the ocean.

[3] While most reef-building corals are hermaphrodites, individual pillar colonies are usually, but not always, either male or female.

Many of the Florida Aquarium's graduates, such as those 1,700 pillar corals, are handed off to the Coral Restoration Foundation in Key Largo. There, they join several other species living in the organization's ocean nurseries, where corals dangle like Christmas ornaments from floating, PVC-pipe trees. When an individual coral grows large enough, staff and volunteers will cut it into smaller fragments, and cement those pieces to the reef's limestone surface.

At the Coral Restoration Foundation's small, spotlessly white visitor center in Key Largo, outreach coordinator Madelen Howard demonstrates how to attach one of these fragments. First scrape a patch of the reef clean with the back of your hammer, then glue it in place with a marine epoxy. For the final step, furiously fan the coral with your hands — if it stays in place, you're good to go. Repeat until your scuba tank runs low on air. The average volunteer can plant about 30 frags per dive. In 2022, the Coral Restoration Foundation returned 45,000 corals to sites up and down the Florida Keys. Mote Marine Laboratory, the Keys' other major coral restorer, added an additional 50,000.

Restoration is the biggest unknown in the entire rescue process. Scientists know how to keep corals happy and healthy on land. What they don't know, at least not right now, is how they'll fare in an ocean where conditions are already bad, and getting worse.

Seventy-five miles south of Key Largo, on a hiccup of land called Summerland Key, a Caribbean king crab known as Big Red is doing his part to revive his native habitat. Friendlier than his next-door neighbor, Diablo, Big Red doesn't protest when biologist Alicia Manfroy lifts him from the water to say hi. "These guys are kind of the goats of the sea," she says. "They don't really care about what type of algae they're eating."

Housed with dozens of mud-brown female crabs in a tank at Mote's Elizabeth Moore International Center for Coral Reef Research & Restoration, Big Red's job is to produce a lot of offspring — offspring that, with luck, could stand-in for the reef's vanished sea urchins, which suffered another mass die-off in 2022.

Scientists at Mote hope that the hardier crabs will mow down seaweed and clear the way for corals to regrow. But nothing on this scale has ever been attempted. While Caribbean king crabs naturally occur at a density of one per square kilometer, Mote's researchers anticipate that one per square meter are what's needed to help revive the reef. The Florida Keys will require millions of crabs to be raised and released, while the greater Florida reef tract will require tens of millions.

These crabs are part of an umbrella initiative called Mission: Iconic Reefs. Helmed by NOAA, and crewed by a variety of government agencies, nonprofits, and universities, it will be one of the largest marine restoration projects ever attempted. The goal is to revitalize seven ecologically and culturally important reefs along the Florida Keys by 2035, boosting live coral cover from 2% to 25% over a total of 70 acres. This work will involve not only outplanting 500,000 corals, but restoring herbivores such as king crabs, and manually removing algae and invasive species. With luck, the corals will thrive, spread and spawn, producing a crop of larvae that can ride the currents and reclaim other parts of the barrier reef, kickstarting the comeback of the ecosystem at large.

Mote is one of the main players in Mission: Iconic Reefs, and its ambitions aren't limited to crustaceans. Like the Florida Aquarium, it also hosts a sizable population of rescued corals, and is breeding them as well. Manfroy explains that Mote is beginning to focus less on pure volume and more on targeted breeding. A primary aim is to identify corals that are resistant to stressors such as disease, heat, and acidification. "We're not going after one super coral," Manfroy says. "We want to have a lot of corals that are able to handle a lot of different conditions." The organization stress tests their prospective broodstock by exposing the corals to heat, acidic water, then both at once, with disease testing occurring separately. These trials, however, are time-consuming, and Mote researchers are now trying to identify genetic markers that can replace them.

In the underfunded world of conservation, Mission: Iconic Reefs carries a relatively hefty price tag. Each frag costs between $60 to $80 to grow on land, and more to grow to a reef-ready size in ocean nurseries. A tank that can house 1,000 young corals, or 30 adult colonies, costs around $10,000, not including staff time, food, water, and electricity. Of the outplanted corals, only three or four out of every 10 will survive their first few years on the reef, according to Zimmerman. Overall, Mission: Iconic Reefs will cost an estimated $100 million, just to revive seven specks of a once-vast ecosystem.

But for scientists, the benefits of the rescue and restoration mission are worth the costs. Besides the obvious benefits of staving off extinction and reviving a vital habitat, Muller, Moore, Firchau, and others praised the program for knocking down scientific siloes, fostering collaboration, and revealing new information about basic coral biology. "The researchers are going, holy smokes … we thought we knew these animals, but every time we turn a corner, we're learning something new," Firchau says. Aquarists caring for the captive corals, she notes, have noticed seasonal bleaching, suggesting that at times it's a healthy response to a subtropical climate, with its annual extremes of heat and cold. "It's incredible how this project has not only helped Florida corals," Firchau says, "but has advanced coral science by leaps and bounds."

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As world's reefs begin to follow Florida's into oblivion, the state's rescue response offers methods and lessons for coral advocates beyond the Caribbean. One of them being: You better start soon.

Despite a series of cataclysmic bleaching events in recent years, Australia's Great Barrier Reef is nowhere near as sickly as its counterpart in the United States. Yet the mounting threat of climate change means it's likely living on borrowed time as well. The scale of a potential rescue is staggering: the Great Barrier Reef stretches for 1,500 miles, and is home to 400 species of stony coral, an order of magnitude more than Florida.

Paul Myers has seen the future firsthand. When sweltering water temperatures turned two-thirds of the Great Barrier Reef a skeletal white in 2016 and 17, Myers was in his fifteenth year as a dive instructor in Port Douglas, a town on the northern tip of Australia's east coast. "For a while there it was embarrassing," he says. "Customers coming and paying $200 to go to the reef, and I'm struggling to find them a living coral."

Myers now manages the operations of Great Barrier Reef Legacy, a nonprofit that has set itself the lofty goal of making a Florida-style gene bank for the planet's 800 species of reef-building coral. The hope is to one day house them in a $70-million, carbon-neutral ark, built in the shape of a humungous mushroom coral. For now, the organization cares for 181 colonies of 181 species. The initial goal is one genetic individual of each kind, eventually bumping that up to ten to 30 individuals — the number the group's scientific advisory panel recommends. Great Barrier Reef Legacy's current facility can house 8,000 colonies, while a new one at the Cairns Aquarium, slated to open in 2023, can host an additional 12,000.

The United States and Australia aren't alone — Saudi Arabia is eager to get in on the coral rescue game, with plans to restore 250 acres of reef in the Red Sea, and to build the world's largest in-ocean nursery. But for most nations, programs like these are beyond the limits of budgets and expertise. The Philippines, for example, boasts 600 species of coral, but the country lacks most of the resources that made Florida's rescue program successful, from a well-financed network of aquariums to a stable political climate.

A potential solution to this is one that Mary Hagedorn, the Smithsonian Conservation Biology Institute researcher, has spent the last 14 years perfecting: cryopreservation. Hagedorn has successfully frozen and revived first coral sperm, then eggs, then entire larvae and bits of adult tissue. At present, the adult polyps come out of the freezer battered and barely make it alive to the 24-hour mark. By the end of the summer, Hagedorn hopes that tweaks to the process will see the adult tissue surviving to three weeks. "Once we get to three weeks, we know they're going to be fine," she says. In theory, these adult specimens can be thawed, grown, and ready to spawn in just a few years.

Hagedorn and her collaborators have cryopreserved 53 coral species, and are working with partners around the globe to add hundreds more. In 2021, Hagedorn helped launch the Coral Biobank Alliance, which counts Mote, Great Barrier Reef Legacy, and the AZA among its members. By 2026, the alliance aims to have 1,000 species of coral cryopreserved or kept in aquariums. This number is higher than the number of coral species currently known to science, under the assumption that many have yet to be discovered.

There are big benefits associated with cryopreservation. For the same number of corals, freezers are cheaper, and take up less space. Compared to the eye-watering complexities of maintaining a tank's delicate water chemistry, water flow, and so on, just about anyone with some scientific background can learn cryopreservation, Hagedorn says. Larvae can be frozen and thawed as their caretakers see fit, averting the mad dash during spawning season to settle tens of thousands of baby corals on their little white tiles. Cryopreservation also makes improbable couplings possible: the elkhorn corals in O'Neil's spawning room at the Florida Aquarium, for example, are the product of fresh Florida eggs and frozen Curaçao sperm.

The biggest gift of cryopreservation, however, is time. "The frozen fragments can last for 50 years, easily 100 years," Hagedorn says. The theoretical upper limit is a whopping 1,000 years. At the biting temperatures used, the only threat of tissue damage comes from outer space. "You can live forever," Hagedorn says, "as long as you're protected from cosmic rays."

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In April 2023, scientists sighted stony coral tissue loss for potentially the first time in Curaçao, an island 40 miles north of the South American coast, and home to some of the Caribbean's healthiest remaining reefs. Curaçao joins 28 other countries in the region that the disease has now invaded.

On the climate front, the news is no better. Atmospheric carbon has surpassed 420 parts per million, the highest it's been in 4 million years — back when global temperatures were 4 degrees Celcius warmer than today, and sea levels 80 feet higher. Barring a brief dip in the early pandemic, global carbon emissions have increased every single year since Florida rescued its first batch of corals. "It doesn't take a rocket scientist to figure out that unless we change what we're doing," Hagedorn says, "everything in the ocean is just going to get worse."

Reefs may still have a few tricks up their sleeves. Corals could adapt, particularly with scientists selectively breeding them for heat resistance and other traits. Hardier species might endure and spread. And some reefs might perform entirely counter to expectations. Despite the polluted waters of Tela Bay, Honduras, a dive here is like boarding a time machine a hundred years into the past. Urchins bristle from every nook. Luxuriant gardens of elkhorn branch like fractals in the shallows. Live coral cover approaches 70%, while stony coral tissue loss is, for some reason, absent.

But the crushing march of the climate crisis could one day flatten Tela too. If scientific predictions hold true, a child born today will live to see the world's remaining reefs decay from bustling metropolises into ragged bands of survivors, and then, maybe, into nothing. Yet captive reefs will linger on, reaching towards the light of LED suns, frozen in humming steel chambers, branching within the synapses of their human caretakers — the strangest ecosystem of all, haunted by the ghosts of what once was, and what could come to be.

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